“Interstellar Shock Fluorescence”

by
Ralph S. Sutherland

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Mount Stromlo and Siding Spring Observatories,
Institute of Advanced Studies,
The Australian National University, Canberra.

Declaration of Authorship

The work in this thesis is that of the candidate alone, except for some joint research with co-authors, who are acknowledged here and in the main text.

Chapters 1 and 2 are entirely my own work.

Chapter 3, on cooling functions, is almost entirely my own work with assistance in discussion and preparation by M. A. Dopita, at a level that warranted co-authorship in the published paper. This Chapter is in the form of a paper that has been accepted for publication in *The Astrophysical Journal Supplement Series*.

Chapter 4 is also in the form of a paper submitted to the *Astrophysical Journal*, which was based on the joint research done by myself, G. V. Bicknell and M. A. Dopita. I performed the detailed shock and photoionization modeling of §4.3 and §4.4, while G. V. Bicknell developed most of the detailed hydrodynamic arguments of §4.2. In particular, §4.2.3, on the Kelvin-Helmholtz instability, is largely the work of G. V. Bicknell. All three authors worked to develop the overall model structure.

Chapters 5 and 6 are my own work. The narrow-band imaging was taken during a joint observational program with M. A. Dopita, S. D. Ryder and myself.

The original idea of the shock driven ionization front in Chapter 6 is due to M. A. Dopita, but the development, modeling and testing of this model is my own work.

Ralph S. Sutherland

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Acknowledgements

I am in awe of my wife Denise, who has somehow held our little family together, and given me "leave of duty" for the duration of my thesis work. She also bravely assisted in the proof reading of this thesis. She has my deepest love and gratitude.

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“Interstellar Shock Fluorescence”

Ralph S. Sutherland

'... Light is a confused aggregate of Rays indued with all sorts of Colours, as they are promiscuously darted from the various parts of luminous bodies. A naturalist would scarce expect to see ye science of those colours become mathematicall, and yet I dare affirm that there is as much certainty in it as in any other part of Opticks.'

Sir Isaac Newton, in a letter to the Royal Society, 1672

*Dedicated to the memory
of
my brother*

FRONTISPIECE: (Opposite) This image is a composite narrow-band, continuum subtracted CCD image of the supernova remnant N132D. It consists of an $H\alpha$ emission image in red, and a forbidden $[OIII]\lambda 5007$ image in green. The overall excitation of the nebula is high compared to the nearby dark red HII regions, resulting in an overall orange color. In the central regions some oxygen-rich material emits only in the green $[OIII]$ line and therefore appears as green in the image. Some of the oxygen-rich material present has been excluded from the image due to large radial velocities that move the emission out of the narrow filter bandpass. See Chapter 5 for details.

Thesis Abstract

In this thesis, a description of the development of a new spectral synthesis code is given. The new code, MAPPINGS II, expands upon the existing code MAPPINGS (Binette 1982). It incorporates recent atomic data, published up to 1992, and provides for an extended range of plasma ionization conditions. It is capable of modeling up to 16 species in all stages of ionization. New, more rigorous methods of calculating collisional ionization and hydrogenic recombination are developed. Initial results include self-consistent non-equilibrium cooling functions for a wide range of temperatures and abundances. The cooling functions are presented in Chapter 3.

In Chapter 4 the feasibility of an alternative model for extended emission line excitation in active galaxies is explored. In this model the exciting nuclear energy is transported by a mechanical flux in the form of high velocity plasma radio jets, rather than narrow, relativistically beamed, ionizing radiation.

The mechanical interaction of such a radio-jet and an extra-galactic dense cloud is invoked to account for the extended emission line filaments of Centaurus A. The resulting cloud collisions and shockwaves are modeled, and shown to be capable of producing sufficient ionizing radiation to account for the observed emission luminosity and line ratios. The model also makes important predictions about the velocity dependence and UV characteristics of the emitted spectrum. The emission spectrum of the cloud-cloud collisions, which are produced in the interaction, is quite characteristic of the physical processes involved, and the model has general application wherever large-scale turbulent motions of $200\text{--}500\text{ km s}^{-1}$ are encountered. This may include the narrow line regions of Seyfert galaxies and elliptical LINER galaxies.

In Chapters 5 and 6 the MAPPINGS II code is used to analyze the emission from oxygen-rich supernova remnants (OSNRs). Three remnants, N132D, Puppis A and SNR G292.0+1.8, were observed and the results are subject to an initial analysis in Chapter 5. A structural model for N132D is presented. In the case of N132D the interaction of the stellar ejecta with the local circumstellar environment is likely to be responsible for the ongoing excitation of the oxygen-rich material.

In the final chapter, the observations are combined with data from the literature for other OSNRs, and an emission mechanism for the observed the oxygen-rich spectra is tested. In this model a time-dependent photoionization computation is used to calculate the emission from a shock induced R-Type ionization front propagating through an individual cloud of oxygen-rich material. The cloud shock is the product of the collision of the high velocity cloud with a density discontinuity. The comparison between the synthetic spectra and the observations is encouraging.

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Chapter 1

Thesis Overview

1.1 Introduction

The thesis title “*Interstellar Shock Fluorescence*” was chosen to encapsulate the concept of the reprocessing of bulk kinetic energy in the interstellar medium, through the formation of strong shocks and the generation of ionizing radiation, to ultimately produce the observed emission spectra. This can be considered as a generalized fluorescence mechanism applicable to interstellar shocks.

Self-consistent shock models (*i.e.* Shull & McKee 1979; Binette 1982) have already shown that shocks with velocities of $\sim 100\text{km s}^{-1}$ or more create sufficient upstream ionizing radiation to produce an ionized zone ahead of the shock front. In this work, it is further shown that as the shock velocity exceeds $150\text{--}200\text{km s}^{-1}$ the ionizing radiation is strong enough to generate an emission region ahead of the shock which is both larger than and of comparable luminosity to the shocked structure itself.

In order to pursue this concept, and its application to a number of astrophysically interesting phenomena, a new photoionization and shocked flow spectral modeling code has been developed. The new code, MAPPINGS II, is used here to investigate a series of related phenomena, in order of increasing complexity. However the MAPPINGS II code is quite general in nature and is intended to be used in many other areas such as in the study of HII regions, Planetary Nebulae, Nova Shells, Herbig-Haro Objects, radiative Supernova remnants, and various Active Galaxy phenomena.

The development of a single code to consistently model both high temperature, collisionally ionized, plasmas and low temperature, photoionized, plasmas using a common model structure and atomic data set, is an ideal that many have been

working towards. The original MAPPINGS code (Binette 1982; Binette *et al.* 1985), was constructed with this aim in mind, but the code lacked the necessary treatment of highly ionized species required to describe plasmas hotter than 10^5 K. A number of astrophysical situations could not therefore be modeled in a fully self-consistent way. MAPPINGS II is the next step in the development of the Dopita and Binette code, addressing in particular a treatment of highly ionized species and the processes of collisional ionization, hydrogenic recombination and continuum emission mechanisms.

1.2 MAPPINGS II Development

1.2.1 Photoionization and Shock Model Structures

The details of the numerical treatment of the photoionization, shockwave and flow models in MAPPINGS II are given in Chapter 2. This presents the basic equations and methods, as well as some of the practical computational optimizations used to make the code efficient.

The areas covered include:

- A photoionization model with an adaptive integration step size.
- Other photoionization optimizations.
- Ionization balance species sub-sampling.
- An explicit time coordinate system for shocked flows without monotonic temperature profiles.
- An adaptive integration mesh for time-dependent flow models using thermodynamic and atomic timescales.

Test models are made and compared with published models to verify the new code.

1.2.2 Atomic Physics

The details of the atomic processes calculated in MAPPINGS II are discussed in Chapter 3. The electron collisional ionization methods of Younger (1981,1982,1983) and the data of Arnaud & Rothenflug (1985) have been adapted and made more robust to allow their application far from equilibrium conditions. The recombination of the critical hydrogenic species has been made more accurate and valid

over a wider range of temperature than before. The radiative processes of line emission and continuum emission have been made more detailed and complete. The photoionization processes are handled with a radiation vector method that is optimized to handle sharp ionization edges. Processes previously used in solar coronal modeling (Mewe, Gronenschild and co-workers 1978, 1981, 1985, 1986) have been incorporated, as well as the detailed modeling of low temperature species such as FeII with data from Nussbaumer and Storey (1980,1988) and Fuhr *et al.* (1988). This combines to give MAPPINGS II a wide operating range in temperature and density (see figure 1.1).

The new code now provides for 16 species: H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Cl, Ar, Ca, Fe & Ni. The emission line list extends from a NiXXVIII λ 1.24 transition to the fine-structure [CII]157 μ and [NII]205 μ lines, totaling 1,683 transitions. Of the 225 ions, 29 are treated in a five level atom approximation to give 290 transitions sensitive to temperature and density. The FeII ion is treated separately as a 14 term atom. Resonance lines are treated as two level atoms, collisionally excited from the ground state. Some 940 resonance lines are included, and the remainder of the emission lines are from hydrogen and helium recombination lines, as well as other fine-structure and inter-system transitions.

As can be seen from the schematic figure (1.1), the new operating range permits self-consistent modeling of a new range of phenomena compared to the older MAPPINGS code.

1.2.3 Cooling Functions

The results of the work on MAPPINGS II up to this stage were prepared for publication in the form of a paper presenting a grid of cooling functions for astrophysical plasmas. The paper is to appear in *The Astrophysical Journal Supplement Series* in 1993. In this thesis version of the paper, the extensive tables produced for the published paper are collected in appendix A, and only the figures remain in the body of the text.

The results include the presentation of the collisional ionization equilibrium (CIE) ionization balance as a function of temperature. Using this balance, cooling functions for the CIE case are calculated, and are given in a normalized form along with a number of useful plasma properties such as the isothermal sound speed and cooling timescales. The functions are given for a range of abundances from a zero metal (H & He) primordial case, up to solar and mildly super-solar.

An analogous set of non-equilibrium (NEQ) cooling functions are also pre-

FIGURE 1.1: The operating range of MAPPINGS II compared to the low density non-relativistic universe. The characteristic densities, temperatures and sizes for a range of astrophysical phenomena are shown along with the approximate operating range (shown by the inset rectangle) that can be modeled with the expanded atomic data set of MAPPINGS II. The range of the old MAPPINGS code is shown with the gray rectangle.

sented. These are in a normalized form to allow comparison with the CIE curves. The results may be scaled to different pressure regimes up to $\log(p/k) \sim 8 \text{ cm}^{-3} \text{ K}$. The NEQ tables cover a range of initial temperatures as well as a series of abundance levels.

In this chapter some general effects of NEQ cooling are discussed, including the reduced cooling efficiencies and lagging recombination compared to the CIE case. Most of the ionization effects may be traced to the inherent stability of H and He-like ions, causing a bottleneck in the ion recombination process. These effects are more pronounced for the light C, N and O ions, than for the heavier ions such as Fe.

1.3 Shock Excited Equilibrium Photoionization

The second stage of this thesis is Chapter 4. This the first direct observational application of the new MAPPINGS II code, and it concerns the modeling of the extended emission line regions (EELR) of Centaurus A. In this stage, MAPPINGS II is applied to the case where the shock fluorescence may be treated in an equilibrium approximation.

The Centaurus A EELR display characteristic strong [OIII] and [NeIII] emission lines and can be classed as high excitation nebulae. However, they also simultaneously display strong emission from low ionization species such as OI and SII. With the shock excited ionization models developed here, the distinctive high and low excitation lines are reproduced. The models presented also correctly predict the total luminosity and nebula dimensions within factors of two of the observations.

The shock excitation model used is the predicted result of a radio jet – dense cloud interaction, proposed by Bicknell (1991). This interaction and excitation, due to an energy flux transported by a plasma jet from the AGN nucleus, is an alternative to the relativistically beamed ionizing radiation model that has been proposed for these filaments by Morganti *et al.* (1991). The interaction of a typical Fanaroff–Riley Class I radio jet with a dense extra-galactic cloud is examined semi-quantitatively, and the results are applied in a detailed cloud–cloud collision, shock excited, equilibrium photoionization model. Both the general jet–cloud interaction and the resulting cloud–cloud collision models have implications for other AGN narrow–line emission phenomena.

Chapter 4 is a self-contained paper submitted for publication in *The Astrophysical Journal*. As such it is not heavily cross-referenced with the rest of the

thesis. It therefore contains some minor reiteration of material presented in Chapters 2 and 3. The text of the paper has been modified slightly for inclusion in the thesis.

1.4 Shock Excited Time-Dependent Photoionization

The third and final investigation of this thesis is represented by Chapters 5 and 6. In these Chapters, a self-consistent, time-dependent, shock-excited photoionization model for the emission from the oxygen-rich supernova remnants is developed.

Chapter 5 presents the modest observational program undertaken in the course of this thesis. A brief review of oxygen-rich supernova remnants (OSNRs) is given, followed by the results of observations of three OSNRs. Relative optical spectrophotometry of two of the galactic remnants, Puppis A and SNR G292.0+1.8 was obtained, while the remnant N132D in the Large Magellanic cloud was subjected to 2 dimensional spectrophotometry. The observed oxygen-rich spectra are presented and a more detailed structural analysis of N132D is made. An expansion age of $\sim 2,350 \pm 520$ years is derived for N132D. This is significantly older than the 1,300 years estimated by Lasker (1980). In N132D the oxygen-rich emission is seen to be generally spatially associated with slow-moving, normal composition material, suggesting that interactions with the slow-moving material is responsible for the observed excitation of the oxygen-rich material.

In Chapter 6 a detailed ionization front emission model for the oxygen-rich material in OSNRs is developed, based on the initial study of Dopita (1987). The emphasis in the present work is to determine if the proposed ionization front model is feasible, using a more self-consistent physical model, albeit still with a number of simplifying assumptions. In this chapter the plasma properties of the oxygen-rich material are discussed in terms of a model where a shock wave is driven into a rapidly moving cloud of oxygen-rich material, which in turn powers a photoionization zone ahead of the shock.

The relationship between the shock temperature, T_s , the mean plasma molecular weight, μ , and the shock velocity, v_s : $T_s = (3\mu v_s^2/16k)$ K, indicates that oxygen plasma shocks will be shocked to very high temperatures. This, coupled with the large X-ray emissivity of the oxygen plasma, implies that shocks of even

moderate velocities will produce copious quantities of ionizing radiation. This radiation is used as the source in the photoionization models of the shock precursor zone.

In some cases, the resulting equilibrium photoionization electron temperature is as low as 200 K, and even though the plasma is highly ionized, it does not produce any optical forbidden line radiation. However, the time-dependent photoionization front process may produce such optical emission. Therefore, a time-dependent R-type ionization front, that is supersonic before and after the front, is modeled to examine the optical and UV emission from the leading, super-heated ionization zone, before it cools to a cold equilibrium. The photoionization model is time-dependent, although the overall model structure achieves a steady-state with a non-equilibrium ionization and temperature structure. In this model, both the spectrum of the shock and the ionization front spectrum must be combined in order to model the observed spectrum. The shock is found to contribute strongly to the [OIII] λ 5007, [OIII] λ 4363 and [NeV] λ 3426 lines while the ionization front provides the [OII] λ 3727 and other emission lines from lower ionization species.

A plasma composition based loosely on the oxygen-neon-carbon layers of massive star evolution models (Weaver *et al.* 1978; Woosley *et al.* 1984; Johnston & Yahil 1984) is found to be generally satisfactory, although the magnesium abundances may have been overestimated. At this stage the observations do not constrain the models well enough to justify detailed abundance estimates. Having said this, the overall model spectra give a sufficiently good fit to the observations to encourage the effort required for more detailed, rigorous, modeling in the future.

Special Note: For the sake of consistency with the published material in some chapters of this thesis which have been prepared for American journals, American English spelling has been adopted for the entire thesis.

Chapter 2

Methodology

2.1 Introduction

In this chapter some of the modeling procedures developed for this thesis are related. Some aspects of the code, particularly the atomic physics, are presented in Chapter 3. This chapter describes the modeling methods relating to the physical model structures and the important optimizations used. It is divided into four sections: the low level optimizations in the ionization balance calculations, the design of a photoionization model with an adaptive integration mesh, the details of a one dimensional steady-flow shock model with another highly adaptive integration mesh, and finally, the comparison of test models with those published in previous works.

2.2 Ionization Balance Optimizations

The calculation of a complete set of ionization stages for all ions in each model step would represent a very inefficient approach to the modeling procedure. With up to 225 ions, the need to calculate all the associated recombination, collisional ionization, autoionization, photoionization, dielectronic recombination, Auger, secondary ionization and charge exchange rates, the time-dependent calculations could become a computationally intensive process. The computations can be made significantly more efficient by making optimizations, primarily by choosing the most significant subset of the ion populations to concentrate on at any given time.

At the heart of the MAPPINGS codes is the time-dependent ionization bal-

ance method. This is described in detail by Binette (1982) and Binette *et al.* (1985). A summary of the method is given here.

2.2.1 Time-Dependent Ionization Balance

The ionization populations as a function of time can be written in differential form:

$$\frac{dn}{dt} = \mathbf{Rn} \quad (2.1)$$

Here the vector $\mathbf{n}$ represents the ionization stages of the atomic species considered. The matrix $\mathbf{R}$ is the rate matrix for all the atomic processes.

If we can choose a sufficiently small time step over which the rates remain constant, (*i.e.* the density and temperature do not change significantly), then the balance at the end of the timestep, $\mathbf{n}_{i+1}$, can be given with respect to the balance at the start of the step, $\mathbf{n}_i$:

$$\mathbf{n}_{i+1} = \exp[\mathbf{R}t] \mathbf{n}_i \quad (2.2)$$

This may be expanded:

$$\mathbf{n}_{i+1} = \left\{ \mathbf{I} + \mathbf{R}t + \frac{(\mathbf{R}t)^2}{2!} + \frac{(\mathbf{R}t)^3}{3!} \dots \right\} \mathbf{n}_i \quad (2.3)$$

When t is large this series may diverge. This problem is avoided by renormalizing the rate matrix:

$$\mathbf{n}_{i+1} = \mathbf{T}^m \mathbf{n}_i = \exp[\mathbf{O}t]^m \mathbf{n}_i \quad (2.4)$$

where: $\mathbf{O} = \mathbf{R}\delta$, $m = t/\delta$ and m is an integer > 0 . If a δ is chosen so that no rate in $\mathbf{O}$ is greater than 1.0, a series expansion for $\mathbf{O}$ analogous to equation (2.3) will converge.

Finally, rather than directly raise the matrix $\mathbf{T}$ to the m^{th} power through matrix multiplication, the matrix $\mathbf{T}^m$ is expressed in terms of a lower power matrix $\mathbf{U}$:

$$\mathbf{U}^l = \mathbf{T}^{kl} = \mathbf{T}^m \quad (2.5)$$

where l, k , and m are integers and $l \ll k$, so that:

$$\mathbf{n}_{i+1} = \left(\prod^l \mathbf{U} \right) \mathbf{n}_i \quad (2.6)$$

This allows the result of the power raising process to be accumulated at each stage directly into the result by performing this product from right to left. This

also makes use of faster matrix–vector multiplications and has better numerical stability in a finite precision system.

This method has been shown to be stable for timesteps as long as $10^{15}/r_{max}$ where r_{max} is the fastest rate in $\mathbf{R}$, using IEEE double precision.

The benefits of a very large dynamic range and good stability that this method gives are balanced by its relatively slow performance, compared to the matrix inversion methods which are commonly used. The execution time of the routine that performs this method displays a $n^{\sim 3.5}$ time dependence, where n is the number of ionization stages considered at one time. Profiling tests showed that as much as 60% of the execution time of the code was spent in the ionization balance routine. The old MAPPINGS code, which used only 6 stages of ionization did not suffer badly, but when up to 27 stages for Fe and 29 stages for Ni were introduced into MAPPINGS II, performance problems were encountered.

As a solution, a system of ionization vector sub–sampling is used. For a given ionization vector $\mathbf{n}$ a subset of ionization stages, $\mathbf{u}$, is chosen for the balance calculations by taking into consideration the existing distribution in $\mathbf{n}$ and the current set of rates in $\mathbf{R}$. The subset, $\mathbf{u}$, is taken as the union of the those stages in $\mathbf{n}$ with population fractions greater than 1 part in 10^6 , and those stages of $\mathbf{n}$ which are influenced by net ionization and net recombination rates within a dynamic range of 10^6 of the rates for the dominant equilibrium ion stage. In this way $\mathbf{u}$ includes all significant populations, even if they are far from the equilibrium distribution, such as the case of low ionization species entering a hot shock. At or near equilibrium, only those stages with significant rates are considered. After the balance calculations, $\mathbf{u}$ is placed back into $\mathbf{n}$ and a different subset may be chosen in subsequent model steps.

A non–adaptive version of this method was suggested independently by Gaetz (1990), but in that case a fixed subset of 3 or 5 stages is chosen, which would be useful in near equilibrium calculations as it does not take into account gross non–equilibrium ion population distributions, such as occurs in the shock case mentioned above. The method used here reduces to a similar treatment under equilibrium conditions. Under general non–equilibrium conditions, the present method dynamically adjusts to rate and distribution changes on a species by species basis, thereby choosing the optimum subset, $\mathbf{u}$, at all times.

In practice, $\mathbf{u}$ varies between 2 stages, when neutral or fully ionized at equilibrium, to as many as twelve stages for ions such as Fe and Ni because of their multiplicity of significant stages of ionization. Gaetz (1990) noted the difficulties that the fixed sub–vector sampling method has with accuracy in individual

ions of species like iron. In the present modeling with the adaptive system, no significant differences in the ionization balance were detectable when compared with complete ion stage vector calculations. This optimization, based on the actual physical processes being modelled, was found satisfactory in all the modeling cases tested. The performance gain, especially in the low ionization stages of the models, was as much as 30–100 fold in a typical HII region photoionization model with 16 atoms and all stages of ionization permitted (but not necessarily used).

2.2.2 Photoionization Optimizations

The photoionization calculations in their explicit form require the photoionization cross-section for all ions, for each energy bin in the ionizing radiation vector (*c.f.* Chapter 3 §3.3, equation (3.1)). Even allowing for consideration of only those bins greater than a given ion edge threshold, the occurrence of multiple edges per ion means that the the photoionization heating calculations have of order an n^2 dependence since there are a similar number of bins as there are ionization edges. The optimization used here is to take the frequency-dependent total photoionization cross-section for the model step, which is calculated during the radiation source computations, to estimate which energy bins will be significant in photoionization heating. A simplified and conservative first order linear approximation is used:

$$\sigma_\nu \varphi_\nu > 10^{-20} \text{ s}^{-1} \quad (2.7)$$

If the product of the photons in a bin, φ_ν , with the the cross-section, σ_ν , of the bin is larger than 10^{-20} s^{-1} , then the bin is marked for inclusion in the detailed photoionization heating calculations. The detailed calculations use more sophisticated power-law interpolations to estimate the rates, and include Auger and secondary ionization. This rate estimate is chosen as being significantly smaller than the typical total photoionization rate ($\sim 10^{-12} \text{ s}^{-1}$).

2.3 The Photoionization Model

The photoionization modeling procedure is similar to the treatment by Binette (1982). The principal differences here are the more detailed photoionization atomic physics outlined in Chapter 3, the optimization in 2.2.2 above, and the more efficient integration step size determinations described below.

2.3.1 The Absorption Step Size

The natural length scale in a photoionization model is the distance over which a given fraction of the current photon field will be either absorbed or diluted.

Summing over the i radiation field bins used (as described in Chapter 3) we have:

$$x = \frac{\sum_i (1 - \exp[-\sigma_i d_{abs}]) \varphi_i}{\Phi} \quad (2.8)$$

where

x = the fraction of the total ionizing photons absorbed

φ_i = the number of photons in bin i at frequency ν ($\text{cm}^{-2} \text{s}^{-1}$)

σ_i = the absorption cross-section for bin i at ν (cm^2)

Φ = $\sum s_i \varphi_i$ (the weighted number of photons)

and

s_i = $\frac{\sigma_i}{\sum_i \sigma_i}$ (the fractional cross-section of bin i)

Equation (2.8) is solved iteratively for a given absorption fraction x and the absorption distance d_{abs} until x is equal to the absorption weighted fraction desired. Typical values used for x are 0.05 – 0.15.

This defines an optical depth step, weighted by the frequency dependence of the absorption cross-section and the total number of photons at that frequency. It dynamically concentrates on the frequencies where the current ionizing spectrum is most likely to produce photoionization, and therefore provides an efficient adaptive step length. The product of the cross-section and the number of photons is more directly related to the actual atomic photoionization rates, in ionizations per second, and hence to the ionization balance, than a simple total optical depth quantity.

Barring significant changes in the radiation field due to purely geometric effects as outlined below, the photoionization model uses a predicted integration step length given by the absorption length for a given fraction x , for a particular model. The test PN model in the §2.5.1 using a fraction value of $x = 0.1$, produced a 140 zone model with a spatial size ranging from $8.36 \times 10^{15} \text{cm}$ in the optically thin regions, down to $1.12 \times 10^{14} \text{cm}$ in the recombination zone at high optical depths.

The thermal and hydrogen ionization structure of the test model SP92 from §2.5.1 is given in figure 2.1, along with the step sizes determined with the methods presented here.

2.3.2 Spherical Geometric Dilution

In the case of spherical geometry, the dilution factor, or the fraction of the sky covered by a sphere of radius r at a distance R , is given by:

$$g = \frac{r^2 - R^2 (1 - \cos \phi)}{2R^2 \cos \phi} \quad (2.9)$$

where

$$\sin \phi = \frac{r}{R}$$

Equation (2.9) is valid all the way from the surface of the spherical source out to infinity. It tends to a limit of $r^2/(4R^2)$ for large R as is commonly assumed. As the precision of the trigonometric functions in equation (2.9), fail the code changes over to this simpler approximation.

If the geometric dilution varies strongly over a model step, the step length is reduced below the pure absorption distance of equation (2.8) until the geometric dilution does not change by more than a predetermined fraction, which is a parameter in the modeling process. This effect is apparent in the initial steps of the test model in figure 2.1 where geometric dilution is the limiting factor.

By choosing a step length determined by the absorption distance and the changing dilution fraction, an efficient integration is possible, one that takes good advantage of the *a priori* knowledge available from the physics of the problem.

2.4 The Shock/Flow Model

Shock structure models have been computed by many authors (*i.e.* Dopita 1976; Raymond 1977; Shull & McKee 1979; Binette 1982; and Innes 1987a), and most have used similar treatments to that of the pioneering work of Cox (1972).

The equations that relate the physical conditions between points in a one dimensional flow are given by the Rankine–Hugoniot conditions:

$$\rho v = \rho_0 v_0 \text{ (conservation of mass)} \quad (2.10)$$

$$\rho v^2 + P + \frac{B^2}{8\pi} = \rho_0 v_0^2 + P_0 + \frac{B_0^2}{8\pi} \text{ (conservation of momentum)} \quad (2.11)$$

$$\frac{B}{\rho} = \frac{B_0}{\rho_0} \text{ (frozen in magnetic field)} \quad (2.12)$$

where v is the flow velocity, U is the internal energy, P is the gas pressure, ρ is the mass density, B is the magnetic field. The subscripted P_0 , ρ_0 and B_0 refer to

FIGURE 2.1: The Test Planetary Nebula Model SP92. In the upper panel the thermal & hydrogen ionization structure for the model is shown. The lower panel shows the model step mesh chosen using an absorption fraction of 0.1, resulting in ~140 steps. See text for details.

some reference point in the flow, usually, but not necessarily, taken as the point just after a shock jump.

Conservation of energy requires that, between two points in the flow separated by a time interval Δt :

$$\frac{v^2}{2} + U + \frac{P}{\rho} + \frac{B^2}{4\pi} + \bar{\Lambda}\Delta t = \frac{v_0^2}{2} + U_0 + \frac{P_0}{\rho_0} + \frac{B_0^2}{4\pi} \quad (2.13)$$

where $\bar{\Lambda}$ is the mean plasma cooling rate.

Assuming the equation of state PV^γ is a constant, and $\gamma = 5/3$ for the ratio of the specific heats of a monatomic gas, U can be written as:

$$U = \frac{1}{1 - \gamma} \frac{P}{\rho} \quad (2.14)$$

Equations (2.10) to (2.14) provide a set of five equations and five unknowns, so the flow equations can be solved.

Previous workers (*i.e.* Cox 1972; Dopita 1976) have used a solution that gives the density in the flow as a function of T and the ratio of n_e/n .

$$\left\{ \frac{B_0^2}{8\pi} (q^2 - 1) + P_0 \frac{T}{T_0} \frac{\mu_0}{\mu} (q - 1) \right\} q = (q - 1) \rho_0 v_s^2 \quad (2.15)$$

where:

$$N = n_e + \sum_i n_i \quad (\text{the number of particles, electrons and ions}) \text{ cm}^{-3}$$

$$\mu = \frac{N}{\rho} \quad (\text{the mean molecular weight})$$

$$q = \frac{N}{N_0} \quad (\text{the compression factor})$$

$$v_s = \text{the shock velocity}$$

In this work, the integration variable is changed so that the velocity is derived directly as a function of time. This permits a more direct physical interpretation of the model structure, and allows for the simple treatment of the situation where the temperature may become constant or increase. Integration along a temperature coordinate means that as the temperature slope becomes very shallow, the integration step size is unstable for a given temperature decrement. When the temperature increases due to photoionization, the solution can become two valued and considerable care is required to integrate along the correct path. By integrating along the guaranteed monotonic time variable these difficulties are avoided.

Using equations (2.10), (2.11), (2.13) and (2.14) , in the absence of magnetic fields, we can write:

$$v^2 [\Gamma - 1] - v \left[\Gamma \left(\frac{P_0}{\rho_0 v_0} + v_0 \right) \right] + \left[v_0^2 + \Gamma \frac{P_0}{\rho_0} - 2\bar{\Lambda} \Delta t \right] = 0 \quad (2.16)$$

where

$$\begin{aligned} \Gamma &= \frac{2\gamma}{\gamma - 1} \\ &= 5 \text{ for a monatomic plasma} \end{aligned}$$

This quadratic equation may be solved exactly for v for a given loss ($2\bar{\Lambda} \Delta t$). The presence of a magnetic field using equation (2.12) results in a quartic expression:

$$v^4 [\Gamma - 1] - v^3 \left[\Gamma \left(\frac{P_0}{\rho_0 v_0} + v_0 + \frac{\beta}{4\rho_0 v_0} \right) \right] + v^2 \left[v_0^2 + \Gamma \frac{P_0}{\rho_0} - 2\bar{\Lambda} \Delta t + \beta \right] + v \left[\Gamma \frac{\beta v_0}{4\rho_0} \right] - \beta v_0^2 = 0 \quad (2.17)$$

where $\beta = \frac{B^2}{2\pi}$

Equation (2.17) reduces directly to equation (2.16) as β goes to zero.

For reasonable values of B , typically 1.0 μG per unit particle density, this quartic equation may be treated as a perturbed form of the quadratic equation (2.16). The quadratic root is used as the initial guess in a standard Newton-Raphson root polishing routine. The polynomial is quite steep near the root, and the root is isolated and real, so convergence is rapid and well behaved.

This time variable formalism allows the shock model to use the physical timescales of the plasma to make efficient step size choices. The following timescales are calculated at each step:

$$\tau_{cool} = \frac{U}{\bar{\Lambda}} \quad (2.18)$$

$$\tau_{equ.} = \frac{1}{\sum (S_{coll.} + \alpha_{phot.} + \alpha_{rec.}) A_{el} X_i} \quad (2.19)$$

$$\tau_{at.} = \frac{1}{\sum (S_{coll.} + \alpha_{phot.} - \alpha_{rec.}) A_{el} X_i} \quad (2.20)$$

$$\tau_{abs.} = \frac{d_{abs.}}{v} \quad (2.21)$$

Where A_{el} is the abundance of element el and X_i is the fraction of ion i .

The atomic timescale $\tau_{atm.}$ depends on the plasma properties and is calculated using the atomic rates as described in Chapter 3 section 3.3. Briefly:

- $S_{coll.}$ is the electron collisional ionization rate for element el and ion i . This includes autoionization rates. This is calculated as described in Chapter 3 §3.3.2.

- $\alpha_{phot.}$ is the photoionization rate for element el and ion i . This is calculated from the photoionization cross-sections described in Chapter 3 §3.3.1.
- $\alpha_{rec.}$ is the recombination rate for element el and ion i including dielectronic recombination. This is calculated as described in Chapter 3 §3.3.4.

The quantities $\tau_{at.}$ and $\tau_{equ.}$ indicate the response and equilibration timescales of the atomic ionization balance of the plasma respectively. The $\tau_{equ.}$ scale is dominated by the fastest atomic rate among the collisional ionization, recombination and photoionization rates. The scale, $\tau_{at.}$, indicates the balance between ionization and recombination. The timescale τ_{cool} is the cooling timescale based on the current mean loss rate $\bar{\Lambda}$.

If equilibrium is achieved, and the flow becomes dominated by photoionization and recombination processes, the flow velocity v becomes almost constant, and the mean loss rate $\bar{\Lambda}$ is nearly zero. The model is effectively an isobaric equilibrium photoionization model, and the model step length is determined by the absorption length (equation (2.8)). The time for the flowing gas to cover this distance at velocity v is given by $\tau_{abs.}$.

By choosing a fraction of the geometric mean of the timescales $\tau_{at.}$, $\tau_{equ.}$, τ_{cool} and $\tau_{abs.}$, a smoothly varying step is determined which will assure a step size appropriate to the physical conditions of the plasma.

With the chosen time interval, a new ionization balance is determined and an average loss rate is calculated. This loss rate is used to determine a new velocity after the time interval, allowing the physical step size to be found and the diffuse field contribution to be estimated. A revised loss rate is calculated and the whole process is iterated until a consistent step size, loss rate, and ionization balance is determined for the chosen time step. With reasonable fractions of the timescales in equations (2.18-2.20) of ~ 0.1 , convergence is achieved in 3 or 4 iterations to 1 part in 10^6 . Under extremely variable conditions, such as when Λ is rapidly changing as neutral gas enters a shock front, a step size reduction is used if convergence fails.

An added refinement allows for the specification of different fractions of the collisional ionization, recombination and photoionization timescales, so that specific regions of a shock, such as the initial collisional ionization zone, can be treated with more or less detail as required.

The behavior of these timescales throughout the evolution of two shock models is shown in figure 2.2. The 130 km s^{-1} test model of §2.5.2 is shown along with an arbitrary 500 km s^{-1} steady flow test model with the same composition and

preshock density and magnetic field. Both shocks used a self-consistent pre-ionization.

The timescales plotted in figure 2.2 as a function of the plasma temperature clearly demonstrate the physical processes of the shock and subsequent flow. The initial steps are limited by collisional rates, and the ionization occurs before any significant temperature drop. The balance between ionization and recombination is measured by the atomic rate $\tau_{at.}$, which peaks early in the models. This balance is maintained for a long time in the faster shock model, whereas balance is achieved only in a narrow temperature zone for the slower shock.

The models both cool monotonically until the rapid onset of photoionization heating. The 130 km s^{-1} model displays a smooth halt to the cooling, which then resumes as the ionizing field is reduced by absorption faster than an equilibrium between heating and cooling can be achieved. The plasma remains slightly over-ionized with respect to the local ionizing field, and it therefore continues to recombine and cool.

The 500 km s^{-1} model heats the plasma to $\log(T) \sim 6.5$, and is similar to the full-field NEQ $\log(T_0) = 6.5$ cooling function model of Chapter 3. It displays a rapid onset of photoionization at $\log(T) = 4.0$, and in this case photoionization equilibrium is achieved. Finally however, the flow again reaches a point where it cools rapidly compared to the rate of field absorption and the model displays non-equilibrium recombination. This model was terminated at 6% ionized hydrogen when the temperature was still 7,000 K. The rapid onset of photoionization defines the point at which the full-field NEQ cooling functions were terminated in Chapter 3, since at this point the cooling function becomes two valued.

2.5 Test Models

The complexity and non-linear nature of this type of modeling makes a detailed performance analysis very difficult. The best that can be done is to make a comparison with existing standard models to cross-check the global properties of the various codes.

Firstly, the low-level atomic physics used in the calculation of collisional ionization equilibrium, presented in Chapter 3, §3.4, give results that compare very satisfactorily with the results of Arnaud & Rothenflug (1985) and Shull & van Steenberg (1982).

A test photoionization model was made for a planetary nebula and the results

FIGURE 2.2: Timescales in test shock models. The timescales τ_{cool} , τ_{at} , τ_{equi} , and τ_{abs} are described in the text. Also shown are τ_{coll} , τ_{rec} and τ_{phot} representing the individual collisional, recombination and photoionization timescales respectively. The heavy lower curve represents the modeling time step used throughout the model. In the 130 km/s model the points marked A, B, C and D indicate in turn the zones where collisional ionization, recombination, photoionization and again recombination dominate the atomic rates. Photoionization only exceeds the cooling rate at C, forming the photoionization zone in the shock tail. See text for more details.

are compared to models produced using the same input parameters by other independent codes, as well as the older MAPPINGS code. The element set was initially restricted to a subset of those available in MAPPINGS II so that detailed comparisons with the other models are more meaningful.

A steady-flow 100 km s^{-1} shock model is compared with the standard model from the workshop held by Pequignot (1985). This model specifies a restricted set of elements and uses a pre-determined pre-ionization balance.

After general verification of the new code here, a self-consistent 130 km s^{-1} model is made with the full element and data set of MAPPINGS II. This is compared with models by Raymond & Smith (1979), Shull & McKee (1979) and Innes *et al.* (1987). The purpose in this case is to both confirm the general model structure and to approximately gauge the degree to which the additional atomic physics affects the results.

2.5.1 A Spherical Planetary Nebula

The test planetary nebula model from the workshop of Pequignot (1985) was constructed using the parameters given in table 2.1a and the chemical abundances in table 2.1b.

The resulting spectra are given in table 2.2. Comparison is made with the model results of Harrington (HP85), Neutzer (NP85), Pequignot (PP85) and Binette (BP85) from the Pequignot workshop. The BP85 model used an older version of the MAPPINGS code. A model using the current version of MAPPINGS was also run (BP92), and the results of the current MAPPINGS II model (SP92) are compared with all of these.

The total $H\beta$ luminosities are in good agreement, verifying the global energy accountancy of the new model. The detailed line strengths are in good general agreement. The effects of the new charge exchange reactions can be seen, and the [OIII] and [OII] line ratio is strongly affected. The cases where the line ratios between different ion stages vary, are most easily accounted for by the changed ionization fractions resulting from differences in the charge exchange and dielectronic recombination rates. Line ratio changes within an ion stage, such as the [NeV] lines, are due to changes in the transition data since 1985, and the newer models (BP92 and SP92) are in close agreement for those lines which are discrepant with the older models.

A comparison of the average ionization state of models SP92 and BP92 is given in table 2.3. The ionization in the two models is similar, and the MAPPINGS II

TABLE 2.1A: TEST PN MODEL PARAMTERS

Source	150,000 K BlackBody
Source Radius	1.0×10^{10} cm
Density	Isochoric, $n_0 = 3,000 \text{cm}^{-3}$
Filling Factor	1.0
Empty Zone	1.0×10^{17} cm
Integration	Radiation Bounded, Outward only.

TABLE 2.1B: TEST PN MODEL ABUNDANCES
LOG NUMBERS RELATIVE TO H = 0.00

H	0.000	C	-3.523	Ne	-3.824
He	-1.000	N	-4.000	Mg	-4.523
		O	-3.222	Si	-4.523
				S	-4.824

TABLE 2.2: TEST PN MODEL SPECTRUM COMPARISON.

Property		HP85	NP85	PP85	FP85	BP85	BP92	SP92
$H\beta \times 10^{35}(\text{ergs s}^{-1})$		2.64	2.51	2.67	2.29	2.01	2.13	2.44
$T_{\text{inner}} (\text{K}^a)$		17400	14800	18800	...	17900	20780	19874
		FLUXES RELATIVE TO $H\beta = 1.00$						
Transition		HP85	NP85	PP85	FP85	BP85	BP92	SP92
H α	$\lambda 6563$	2.89	2.87	2.86	2.80	2.83	2.83	2.83
HeI	$\lambda 5876$	0.10	0.11	0.11	0.10	0.09	0.09	0.09
HeII	$\lambda 4686$	0.34	0.35	0.32	0.35	0.43	0.40	0.38
CII]	$\lambda 2326$	0.50	0.31	0.32	0.44	0.32	0.23	0.19
CII	$\lambda 1335$	0.09	0.11	0.11	0.12	0.00	0.04	0.07
CIII]	$\lambda 1909$	1.67	1.73	1.70	2.26	2.91	3.92	2.07
CIV	$\lambda \lambda 1549$	1.70	1.19	2.02	2.12	2.07	4.32	4.53
[NI]	$\lambda 5198 + 200$	0.02	0.01	0.02	0.01	0.02	0.02	0.02
[NII]	$\lambda 6584 + 6548$	1.49	1.46	1.37	1.53	1.45	1.53	1.35
NIII]	$\lambda 1749$	0.12	0.09	0.11	0.15	0.14	0.06	0.14
NIV]	$\lambda 1487$	0.12	0.09	0.16	0.15	0.24	0.43	0.25
NV	$\lambda \lambda 1240$	0.08	0.04	0.15	0.12	0.14	0.32	0.364
[OI]	63.2μ	0.01	...	0.03	0.01	0.01	0.01	0.01
[OI]	$\lambda 6300 + 63$	0.16	0.15	0.13	0.15	0.18	0.12	0.10
[OII]	$\lambda \lambda 7320 + 30$	0.16	0.15	0.15	0.18	0.10	0.08	0.06
[OII]	$\lambda \lambda 3727$	2.28	2.24	2.18	2.52	2.56	1.17	1.01
[OIII]	51.8μ	1.44	1.42	1.43	1.49	1.36	1.61	1.57
[OIII]	$\lambda 5007 + 4959$	20.15	21.05	21.60	24.70	19.90	26.15	22.50
[OIII]	$\lambda 4363$	0.16	0.15	0.16	0.21	0.18	0.23	0.17
OIII]	$\lambda 1663$	0.24	0.20	0.25	0.35	0.26	0.38	0.17
[OIV]	25.9μ	3.87	3.62	3.27	3.36	3.97	1.40	1.32
OIV]	$\lambda 1403$	0.15	0.07	0.18	0.15	0.22	0.17	0.44
OV	$\lambda 1218$	0.07	0.03	0.18	0.13	0.24	0.46	0.32
[NeII]	12.8μ	0.02	0.03	0.03	0.03	0.05	0.14	0.09
[NeIII]	15.5μ	2.56	2.44	2.54	2.56	2.38	1.17	1.30
[NeIII]	$\lambda 3869 + 3968$	2.68	2.52	2.59	3.44	2.78	2.45	2.43
[NeIV]	$\lambda \lambda 2423$	0.62	0.43	0.62	0.53	0.84	1.25	1.09
[NeV]	24.2μ	1.58	1.85	1.58	2.20	1.85	0.36	0.21
[NeV]	$\lambda 3426 + 3346$	0.66	0.60	0.94	0.95	1.06	0.90	0.70
MgII	$\lambda 2799$	1.46	1.00	1.97	0.82	1.22	0.58	1.06
[MgIV]	4.5μ	0.07	...	0.10	0.10	0.19	0.37	0.25
[MgV]	5.6μ	0.04	...	0.07	0.10	...	...	0.05
[SiII]	34.8μ	...	0.12	0.15	0.15	0.09	0.05	0.14
SiII]	$\lambda 2335$	...	0.10	0.13	0.16	0.07	0.03	0.18
SiIII]	$\lambda 1892$	0.20	0.13	0.26	0.30	1.09	0.04	0.08
SiIV	$\lambda \lambda 1397$	0.14	0.11	0.20	0.26	0.07	0.27	0.17
[SII]	$\lambda 6717 + 31$	0.46	0.33	0.39	0.46	0.15	0.16	0.14
[SII]	$\lambda 4069 + 76$	0.08	0.06	0.06	0.08	0.02	0.02	0.02
[SIII]	18.7μ	0.49	0.52	0.45	0.43	0.54	0.57	0.54
[SIII]	$\lambda 9532 + 9069$	1.92	2.40	1.93	1.87	2.12	2.23	1.98
[SIV]	10.5μ	2.21	1.66	1.88	1.73	1.78	0.41	0.42

^a. Temperature on inner edge of model.

Models: xx85 models from Pequignot (1985)

HP85: P. Harrington

NP85: H. Netzer

PP85: D. Pequignot and G. Stasinska

FP85: G. Ferland (CLOUDY)

BP85: L. Binette (MAPPINGS)

BP92: MAPPINGS in 1992

SP92: Present Work (MAPPINGS II)

model confirms that the six stage limit of the older code is still adequate for in this type of PN model. Differences are due principally to the expanded set of charge exchange reactions, and possibly the new set of dielectronic recombination data for neon (see Chapter 3 §3.3.3 and §3.3.4). Differences in the neon, silicon and argon balances are the most significant.

The thermal and ionization structure of the model is shown in figure 2.1.

2.5.2 Plane Parallel Shock Models

The modeling of a self-consistent shock model is also a highly non-linear process. This makes verification and testing a difficult task. Here the basic shock structure and the photoionization/pre-ionization processes are separated using two test models.

The first model constructed used a predetermined pre-ionization for a 100km s^{-1} shock. The results are compared to the standard 100km s^{-1} model described in the workshop of 1985 (Pequignot 1985). In this model the atom set is restricted to the same subset used in the 1985 test models. The pre-ionization of the gas flowing into the shock front forms an important part of the work in the rest of this thesis. To test this model aspect, a self-consistent model of a 130km s^{-1} shock was constructed. Given the results of the 100 km s^{-1} model were in good agreement with the older codes, the full atom set and other features of MAP-PINGS II are used for the 130km s^{-1} shock model, to gauge the degree to which the more recent data affects the overall result.

The Standard 100 km s^{-1} Model, S100

A plane parallel steady shock model was constructed using the parameters given in tables 2.4a and 2.4b from Pequignot (1985). The pre-ionization is specified for the abundant hydrogen and helium species. The pre-ionization for the other elements was not specified, so a self-consistent pre-ionization was used for those ions. The details of this ionization are not very important to the overall shock structure due to the rapid post-shock ionization that takes place. The method used here, using equation (2.17), however, is very sensitive to rapid changes in the cooling function Λ_{net} . If the heavy elements are left in a neutral pre-ionization state for this test, the immediate postshock region has a very rapidly changing electron density, and the collisional cooling component in Λ_{net} is greatly affected. The code has difficulty converging on a solution under these conditions. If pre-ionization is used then the Λ_{net} is much more stable and while

TABLE 2.3: TEST PN MODEL AVERAGE IONIZATION BALANCE.
IONIZATION FRACTIONS $\geq 1 \times 10^{-4}$

MAPPINGS	I	II	III	IV	V	VI	
H	0.0389	0.9610	...	...	...	...	
He	0.0127	0.5980	0.3900	...	...	...	
C	0.0003	0.0793	0.6450	0.1320	0.1430	...	
N	0.0140	0.1430	0.4400	0.3280	0.0601	0.0152	
O	0.0251	0.0578	0.6200	0.1880	0.1030	0.0059	
Ne	0.0023	0.0397	0.6110	0.1980	0.1290	0.0211	
Mg	0.0045	0.0332	0.4920	0.2980	0.1660	0.0066	
Si	...	0.0351	0.0593	0.2750	0.6200	0.0100	
S	...	0.0264	0.3530	0.3140	0.1520	0.1550	
Cl	0.0002	0.0244	0.0903	0.4670	0.2940	0.1240	
Ar	0.0015	0.0123	0.0873	0.5910	0.1610	0.1460	
MAPPINGS II	I	II	III	IV	V	VI	VII
H	0.0356	0.9640	...	...	...	...	...
He	0.0120	0.6130	0.3750	0.0000	0.0000	0.0000	...
C	0.0003	0.0822	0.6410	0.1230	0.1540	0.0000	...
N	0.0128	0.1410	0.4550	0.3170	0.0551	0.0199	...
O	0.0230	0.0586	0.6350	0.1840	0.0936	0.0056	0.0001
Ne	0.0013	0.0289	0.7070	0.1810	0.0794	0.0030	...
Mg	0.0027	0.0697	0.6220	0.2150	0.0859	0.0043	...
Si	0.0002	0.1690	0.0838	0.3330	0.4050	0.0082	...
S	...	0.0249	0.3490	0.3280	0.1480	0.1340	0.0158
Cl	0.0002	0.0216	0.0860	0.4590	0.2980	0.1300	0.0044
Ar	0.0023	0.0309	0.3530	0.4620	0.0400	0.0861	0.0252

TABLE 2.4A: S100 TEST SHOCK MODEL PARAMETERS

Shock Velocity	$v_s = 100 \text{ km s}^{-1}$
Pre-shock Density	$n_o = 10 \text{ cm}^{-3}$
Pre-shock Magnetic Field	$B_o = 1.0 \mu\text{Gauss}$
Plasma Abundances	see table 2.4b
Pre-shock Temperature	$T_o = 10,000 \text{ K}$
Pre-ionization:	H II = 1.00
	He II = 1.00
	others unspecified

TABLE 2.4B: ABUNDANCES FOR S100
LOG NUMBERS RELATIVE TO H = 0.00

H	0.000	C	-3.523	Ne	-3.824	S	-4.824
He	-1.000	N	-4.000	Mg	-4.523	Cl	-6.398
		O	-3.222	Si	-4.523	Ar	-5.222
						Fe	-4.398

it still changes fairly rapidly, the code is able to follow the shock flow.

The results of the present code are in good agreement with the comparison models (table 2.6), verifying the basic physics of the treatment developed here. The difficulties encountered when artificially neutral species enter a rapid shock are inherent to the methods adopted here. The MAPPINGS II code depends on reasonable physics prevailing to operate efficiently.

A Self-Consistent 130 km s^{-1} model.

The 130 km s^{-1} shock model of Shull & McKee (1979) was calculated and the results compared with that work, along with similar models of Raymond & Smith (1979) and with the 130 km s^{-1} test model of Innes *et al.* (1987a). This model was chosen because it displays most of the important features of the shocks used in the remainder of this thesis. The upstream radiation field is significant, producing a photoionized precursor zone, and the downstream field produces a photoionized zone in the recombination tail structure. This model is a test of the shock dynamics, collisional ionization and cooling as well as the radiative transfer and the photoionization processes. It is important to have the global properties such as thermal structure, luminosity, timescales, and the emission spectrum, correctly accounted for.

In this test the complete self-consistent pre-ionization is calculated in three global iterations of the shock and its precursor zone. The precursor was treated as an isochoric photoionization zone with the preshock density. The principal objective here was to estimate the ionization state entering the shock front. In a stationary model, the Strömgren Length of the upstream field was calculated to be $\sim 1.5 \times 10^{19} \text{ cm}$. The time for the shock front to cross this distance is $\sim 1.2 \times 10^{12} \text{ s}$. As a first approximation, a single thin slab was subjected to the full radiation field for this length of time in a time-dependent model. This approximation assumes that the bulk of the photoionized zone is optically thin and effectively subject to the full field strength. This time-dependent model indicated that the plasma reached photoionization equilibrium in only $\sim 1.5 \times 10^{11} \text{ s}$, which is 10 times shorter than the crossing time. A further simplifying assumption can therefore be made, namely that the ionization balance entering the shock front has achieved the photoionized equilibrium of an optically thin plane parallel slab, subject to the full upstream field.

As long as the upstream field is strong enough, the crossing time of the shock through the precursor zone will be longer than the equilibration time. Material flowing across the precursor zone will reach equilibrium with the full field, well

TABLE 2.5: S100 MODEL DIMENSIONS.

Property	RS85	BS85	PS85	IS91	MS92
$H\beta \times 10^{-6}$ (ergs s ⁻¹ cm ⁻² sr ⁻¹)	5.12	4.99	7.96	5	5.009
$T_{0.5H}^a$ (K)	5970	6960	4770	...	6364
$d_4 \times 10^{15}$ (cm)	1.73	1.76	2.1	2.7	1.563
$d_3 \times 10^{15}$ (cm)	...	2.84	3.46	5	3.638
$d_{0.5H} \times 10^{15}$ (cm)	...	2.05	2.28	...	1.762

^a. Temperature at 50% H ionization

Models: xx85 models from Pequignot (1985)

RS85: J. Raymond

BS85: L. Binette (MAPPINGS)

PS85: D. Pequignot and G. Stasinska

IS91: D. Innes (1991)

MS92: Present Work (MAPPINGS II)

TABLE 2.6: S100 MODEL SPECTRUM COMPARISON.

		FLUXES RELATIVE TO $H\beta = 1.00$				
Transition		RS85	BS85	PS85	IS91	MS92
H α	$\lambda 6563$	3.03	3.05	3.18	...	3.019
HeI	$\lambda 5876$	0.28	0.17	0.21	...	0.105
HeII	$\lambda 4686$	0.03	0.15	0.04	...	0.029
CII]	$\lambda 2326$	3.13	2.99	2.44	...	1.722
CII	$\lambda 1335$	4.10	7.13	2.30	...	7.718
CIII]	$\lambda 1909$	6.15	6.20	4.60	6.80	3.073
CIII	$\lambda 977$	15.60	16.40	12.50	...	24.550
CIV	$\lambda 1\lambda 1549$	5.56	9.67	6.36	8.80	12.005
[NI]	$\lambda 5198 + 200$	0.30	0.28	0.05	...	0.244
[NII]	$\lambda 6584 + 6548$	2.73	3.31	1.65	3.00	2.036
[NII]	$\lambda 5755$	0.05	0.08	0.05	...	0.051
NII]	$\lambda 2141$	0.20	0.28	0.21	...	0.174
NIII]	$\lambda 1749$	0.75	0.27	0.57	0.25	0.511
NIII	$\lambda 990$	1.53	1.30	1.47	...	2.135
NIV]	$\lambda 1487$	0.27	0.21	0.24	0.25	0.190
NV	$\lambda \lambda 1240$	0.01	0.01	0.02	0.02	0.029
[OI]	63.2μ	0.91	0.23	1.24	...	0.285
[OI]	$\lambda 6300 + 63$	0.78	0.65	0.13	0.86	0.468
[OII]	$\lambda \lambda 7320 + 30$	0.21	0.30	0.37	0.55	0.344
[OII]	$\lambda \lambda 3727$	6.47	10.40	6.33	10.00	6.881
[OIII]	51.8μ	0.03	0.16	0.08	...	0.097
[OIII]	$\lambda 5007 + 4959$	4.39	4.61	3.18	3.70	2.565
[OIII]	$\lambda 4363$	0.28	0.29	0.19	0.25	0.135
OIII]	$\lambda 1663$	1.68	1.79	1.23	1.70	0.637
[OIV]	25.9μ	0.00	0.01	0.04	...	0.010
OIV]	$\lambda 1403$	0.54	0.11	0.37	0.61	0.539
[NeII]	12.8μ	1.43	3.23	1.36	...	2.596
[NeIII]	15.5μ	0.70	0.15	0.76	...	0.147
[NeIII]	$\lambda 3869 + 3968$	1.08	1.09	1.09	...	0.762
[NeIV]	$\lambda \lambda 2423$	0.13	0.11	0.12	...	0.103
MgII	$\lambda 2799$	0.87	1.56	0.38	...	0.735
[SiII]	34.8μ	5.10	5.09	4.80	...	6.248
SiII]	$\lambda 2335$	0.07	1.19	0.08	...	0.192
SiIII]	$\lambda 1892$	2.21	1.68	1.34	...	0.996
SiIV	$\lambda \lambda 1397$	1.72	0.09	1.57	2.10	2.387
[SII]	$\lambda 6717 + 31$	1.86	2.75	1.21	3.20	2.477
[SII]	$\lambda 4069 + 76$	0.19	0.18	0.08	...	0.132
[SIII]	18.7μ	0.20	0.51	0.13	...	0.222
[SIII]	$\lambda 9532 + 9069$	0.58	1.37	0.49	...	0.645
SIV]	$\lambda 1406$	0.84	0.09	0.07	...	0.116
[ArII]	7.0μ	0.14	0.30	0.15	...	0.365
[ArIII]	$\lambda 7135 + 7751$	0.17	0.32	0.15	...	0.137

Model identifications: see table 2.5

before entering the shock. In subsequent modeling in this thesis, this approximation is used whenever an initial time-dependent pre-ionization test indicates that it is appropriate. It is used in the shocks discussed in Chapter 4 in particular, where an equilibrium approximation is also used for the emission from the precursor zone. In the modeling there for shocks of 150 to 500 km s⁻¹, the precursor Strömgren Length increases as $\sim v^3$, so for roughly constant or increasing photoionization rates this approximation gets better for the more rapid shocks. This equilibrium photoionization model should be generally applicable to shocks of $\gtrsim 130$ km s⁻¹. Slower shocks, particularly below ~ 110 km s⁻¹, should strictly use a time-dependent treatment. The errors caused by assuming equilibrium ionization for the pre-ionization may be expected to predict an over-ionization compared to the fully time-dependent case.

In Chapter 6, the pre-ionization entering an oxygen-rich shock is also taken to be that of equilibrium, however, the optical emission of the precursor zone is treated in a time-dependent manner so that the emission from the super-heated leading edge of the ionization front may be modeled.

The equilibrium pre-ionization treatment used here is roughly equivalent to the second case of pre-ionization described by Shull & McKee (1979), where recombinations become important. The advantage here is that an estimate for the preshock temperature is also derived from the detailed photoionization modeling.

The present pre-ionization calculations (table 2.7c) are in very good agreement with the results of the more detailed time-dependent treatment of Innes *et al.* (1987a), which lends support to this approximation. The balance predicted here is less ionized than the time-dependent calculations of Shull & McKee (1979), contrary to the expected error trend of the present method. The reasons for this are not clear.

The free parameters of the 130 km s⁻¹ test model are given in table 2.7a. This specifies the preshock density, magnetic field and the shock velocity. The composition is nominally that of the ‘cosmic’ abundances of Allen (1973) (table 2.7b).

The presence of cooling emission by the FeII ion, using the detailed 14 term model (*c.f.* Chapter 3 §3.3.5), which gives emission for over 300 lines, was found to be an extremely efficient coolant in the low temperature regions of the shock model. This ion displays both strong UV lines at 2400 and 2600 Å as well as a large number of IR transitions such as [FeII]1.647 μ . The fine-structure transitions in particular become very strong below 10,000 K, and continues to be strong down to temperatures of a few hundred Kelvins. At normal ‘cosmic’ abundances

TABLE 2.7A: MS130 TEST SHOCK MODEL PARAMETERS

Shock Velocity	$v_s = 130 \text{ km s}^{-1}$
Pre-shock Density	$n_o = 10 \text{ cm}^{-3}$
Pre-shock Magnetic Field	$B_o = 1.0 \mu\text{Gauss}$
Plasma Abundances	see table 2.7b
Pre-shock Temperature ^a	$T_o = 5,514 \text{ K}$
Pre-ionization ^a	see table 2.7c

^a self-consistent solution, see text.

TABLE 2.7B: ABUNDANCES FROM ALLEN (1973)
LOG NUMBERS RELATIVE TO H = 0.00

H	0.00	C	-3.48	Ne	-4.08	Si	-4.48	Ca	-5.70
He	-1.07	N	-4.04	Na	-5.75	S	-4.80	Fe	-4.40
		O	-3.18	Mg	-4.58	Cl	-6.40	Ni	-5.70
				Al	-5.61	Ar	-5.20		

TABLE 2.7C: S130 PRE-IONIZATION

Atom	MS130				
	I	II	III	IV	V
H	0.011	0.989	...	...	...
He	0.036	0.902	0.062	...	...
C	0.00	0.36	0.64	0.00	...
N	0.00	0.47	0.52	0.01	...
O	0.00	0.21	0.78	0.00	...
Ne	0.00	0.48	0.52	0.00	...
Na	0.02	0.37	0.60	0.00	...
Mg	0.01	0.24	0.75	...	...
Al	0.00	0.40	0.44	0.16	...
Si	0.00	0.61	0.24	0.16	...
S	0.00	0.09	0.82	0.09	...
Cl	0.00	0.08	0.41	0.50	0.01
Ar	0.00	0.13	0.71	0.15	...
Ca	0.07	0.31	0.51	0.11	...
Fe	0.00	0.06	0.54	0.40	0.01
Ni	0.00	0.07	0.54	0.39	...
Atom	SS130				
	I	II	III	IV	V
H	0.005	1.00	...	...	...
He	0.00	0.804	0.196	...	...
C	0.00	0.00	0.94	0.06	...
N	0.00	0.00	0.83	0.17	...
O	0.00	0.00	0.62	0.38	...
Si	0.00	0.00	0.00	0.48	0.52
S	0.00	0.00	0.00	0.95	0.05
Atom	IS130				
	I	II	III	IV	V
H	0.00	1.00	...	...	...
He	0.00	0.92	0.08	...	...
Atom	RS120				
	I	II	III	IV	V
H	0.00	1.00	...	...	...
He	0.00	0.92	0.08	...	...
Atom	RS141				
	I	II	III	IV	V
H	0.00	1.00	...	...	...
He	0.00	0.83	0.17	...	...

Model identifications: see table 2.8

this cooling dominates completely below 5,000 K, preventing the formation of an extended photoionized zone in the shock tail. In addition, the resulting optical emission is inconsistent with general interstellar shock observations. For example the $[\text{FeII}]\lambda 8617$ transition was predicted to be 10 times the $\text{H}\beta$ flux using normal abundances. The typical observed range for this line is $\sim 0.1\text{H}\beta$ (*c.f.* Russell 1989). Accordingly, the gaseous phase of iron was depleted by a factor of 100 for the model MS130 presented here. A comparison model, NS130, was made with no FeII cooling. This model demonstrates the effect of this important ion on the model structure, as may be seen in table 2.8. The additional FeII cooling is the principal reason for the relatively short photoionization zone in model MS130 compared with model NS130 (see also figure 2.3).

The structures derived here for MS130 and NS130 are most similar to the structures shown by Raymond & Smith (1979). The model of Innes *et al.* (IS130) has a much longer primary cooling zone, whereas the Shull & McKee and Raymond models have similar cooling lengths to the models here. Also, the current models here do not reproduce the very high $\text{H}\beta$ luminosity of the IS130 model, and are more in line with the earlier models. The spectra are compared in table 2.9. The lines that vary significantly between the MS130 and NS130 models are shown in **boldface** in the NS130 column. The main difference with the NS130 model is with the low ionization species, as might be expected. In the MS130 model more of the cooling is achieved by the FeII ion, and in its absence other forbidden and fine-structure lines take up the cooling. The lines of [SII] and [NI] are strongly affected. The cooling from a selection of FeII lines and the total FeII cooling is given in the table for model MS130. The total cooling due to the FeII ion is 4.61 times $\text{H}\beta$. The total forbidden line emission apart from FeII cooling for this model is only 17.45 times $\text{H}\beta$, and much of that comes from hotter zones with emission by [OIII] lines. Even with the depletion factor of 100 used here, the FeII ion represents a significant coolant, particularly in the cooler zones.

The density in the photoionized zone is consistent with magnetic pressure support by the modeled field of $1.0\ \mu\text{G}$ in the preshock medium. It is in agreement with the value given in the Shull & McKee model (SS130). This confirms magnetic field treatment in equation (2.17).

TABLE 2.8: S130 TEST MODEL DIMENSIONS.

Property	SS130	IS130	RS120	RS141	MS130	NS130
$H\beta \times 10^{-6}$ (ergs s ⁻¹ cm ⁻² sr ⁻¹)	6.10	15.4	6.76	9.64	9.44	9.52
$T_s \times 10^3$ (K)	245.5	245.5	210.5	285.2	246.2	246.2
$\tau_4 \times 10^9$ (s)	3.16	4.83	2.05	2.49	2.06	2.08
$\tau_3 \times 10^9$ (s)	...	41.4	54.0	49.2	22.5	41.9
$d_4 \times 10^{15}$ (cm)	2.84	5.36	1.7	2.7	2.14	2.21
$d_3 \times 10^{15}$ (cm)	6.87	7.52	5.0	5.7	3.22	4.34
$d_2 \times 10^{15}$ (cm)	...	...	...	...	3.34	4.70
$n_3 \times 10^3$ (cm ⁻³)	3.16	...	...	...	3.17	3.18

Models:

SS130: Shull & McKee 1979

IS130: Innes *et al.* 1987RS120: Raymond & Smith 1979, 120km s⁻¹RS141: Raymond & Smith 1979, 141km s⁻¹

MS130: Present Work (MAPPINGS II)

NS130: Present Work (MAPPINGS II) No Fe II cooling

FIGURE 2.3: 130 km/s Test Model MS130. These semi-log plots show in turn from top to bottom: the thermal structure, the electron n_e and total ion n_i number densities, and the ionized hydrogen fraction as a function of distance in the lower panel. The solid curves represent the MS130 model. The NS130 model, without FeII cooling, is shown in gray.

TABLE 2.9: S130 MODEL SPECTRUM COMPARISON.

		FLUXES RELATIVE TO $H\beta = 1.00$					
Transition		SS130	IS130	RS120	RS141	MS130	NS130 ^a
H α	$\lambda 6563$	2.98	3.15	2.99	2.99	3.032	2.982
HeI	$\lambda 5876$	0.19	...	0.19	1.67	0.072	0.072
HeII	$\lambda 4686$	0.12	...	0.06	0.07	0.057	0.056
CII]	$\lambda 2326$	2.36	1.18	0.30	2.00	1.049	1.101
CII	$\lambda 1335$	0.93	0.86	2.67	1.69	4.546	4.534
CIII]	$\lambda 1909$	2.04	2.44	6.38	5.13	1.873	1.846
CIII	$\lambda 977$	7.39	13.00	11.40	10.10	14.450	14.25
CIV	$\lambda \lambda 1549$	8.60	9.74	16.10	25.80	21.430	21.28
[NI]	$\lambda \lambda 5200$	1.70	...	0.26	0.29	0.109	0.260
[NII]	$\lambda 6584 + 6548$	3.95	2.45	0.24	2.62	1.436	1.865
NII]	$\lambda 2141$	0.24	...	...	...	0.129	0.1333
NIII]	$\lambda 1749$	0.11	...	...	...	0.421	0.4118
NIII	$\lambda 990$	0.32	...	0.90	1.27	1.939	1.911
NIV]	$\lambda 1487$	0.40	0.51	...	...	0.416	0.4133
NV	$\lambda \lambda 1240$	0.56	0.74	0.10	1.20	1.657	1.187
[OI]	63.2μ	2.10	...	...	...	0.230	0.336
[OI]	$\lambda 6300 + 63$	2.42	0.37	0.21	2.43	0.320	0.762
[OII]	$\lambda \lambda 7320 + 30$	0.41	...	0.20	0.22	0.306	0.328
[OII]	$\lambda \lambda 3727$	8.55	6.56	5.93	6.07	5.155	6.037
[OIII]	51.8μ	0.98	0.06	...	...	0.086	0.082
[OIII]	$\lambda 5007 + 4959$	7.35	2.60	5.72	5.96	2.418	2.337
[OIII]	$\lambda 4363$	0.25	0.19	0.26	0.31	0.137	0.133
OIII]	$\lambda 1663$	2.18	...	1.80	2.29	0.676	0.660
OIV]	$\lambda 1403$	0.93	1.35	0.58	1.30	1.622	1.606
[NeII]	12.8μ	...	...	0.98	0.99	1.360	1.622
[NeIII]	$\lambda 3869 + 3968$	...	...	0.43	0.43	0.321	0.320
MgII	$\lambda 2799$	...	...	0.37	0.34	0.364	0.557
[SiII]	34.8μ	4.97	...	6.18	5.39	3.700	5.661
SiII]	$\lambda 2335$	0.45	...	...	...	0.120	0.149
SiIV	$\lambda \lambda 1397$	0.36	0.23	1.00	0.51	0.576	0.567
[SII]	$\lambda 6717 + 31$	6.01	...	1.67	1.74	1.705	3.167
[SIII]	$\lambda 9532 + 9069$	0.61	...	0.46	0.54	0.501	0.575
[FeI]	$\lambda 2382$	...	...	...	...	1.056	...
[FeI]	$\lambda 2600$	...	...	...	...	0.691	...
[FeI]	$\lambda 8617$	...	...	...	...	0.107	...
[FeI]	1.257μ	...	...	1.40	1.36	0.147	...
[FeI]	1.644μ	...	...	1.40	1.36	0.109	...
[FeI]	26μ	...	...	1.40	1.36	0.023	...
[FeI]	Total	...	...	...	...	4.606	...

Model identifications: see table 2.8

^a. Bold values indicate lines from model NS130, with no FeII cooling, where those values vary greatly from model MS130

2.6 Summary

In summary, the test models presented indicate that the methods developed here are satisfactory, and the resulting photoionization and shock model structures are broadly correct. They are in general agreement with the structures calculated in previous works, once differences in the atomic data and the detailed photoionization/cooling treatments are taken into account.

The main result to come out to the testing procedure is the importance of the rôle of iron, particularly the FeII ion, in the shock models. This ion is shown to be very important to the low temperature regions of the shock structures. A depletion factor of ~ 100 for Fe is required to bring the emission spectrum in line with the general observations. The sensitivity of the shock spectrum and the shock structures to the abundance of the FeII ion should provide a sensitive means of directly measuring gas phase depletion of this heavy atom, using radiative shock spectra. The observations of Russell (1989) may immediately indicate that, in the SNR shocks studied there, the depletion of Fe is generally a factor of 100 or more, despite the possibility of grain destruction by the shock itself. Detailed analysis of this aspect of shock structures is outside the scope of this thesis, and work in this area is deferred to future studies.

The following chapter is based on the paper:

‘Cooling Functions
for
Low Density Astrophysical Plasmas’.

by Ralph S. Sutherland and M. A. Dopita.

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Chapter 3

Cooling Functions

3.1 Introduction

The rate at which a plasma cools is a fundamental parameter in many astrophysical problems. The phase structure of a multi-phase interstellar medium is determined by the temperature dependence of the cooling rate (McKee & Ostriker 1977). Our ability to perform hydrodynamic modeling of systems that include a gas component, such as galaxy collisions (*i.e.* Müller *et al.* 1989), relies on cooling functions for the gaseous component. Even comparatively recent work, such as Müller *et al.* (1989) & Mair *et al.* (1988), has used simple cooling functions from Aller (1961) and methods of Cox & Tucker (1969) and Tucker & Gould (1966). The aim of this work is to provide a full and self-consistent grid of cooling functions for both the collisional ionization equilibrium (CIE) and some non-equilibrium cases, and to investigate the metallicity dependence of these. A secondary aim is to demonstrate the magnitude of the deviations in non-equilibrium models, compared to the equilibrium case, so that the adequacy of the commonly used equilibrium case can be assessed.

In the past, calculations of cooling functions have been fairly limited in their scope, concentrating on simple, optically thin, CIE models (Cox & Tucker 1969; Cox 1972). Since then, both the atomic data and computing power available, have improved. Improved treatment of many atomic processes is now possible. Important improvements have been made in the following areas: photoionization edge calculations (Gould 1978, Gould & Jung 1991), collisional ionization rates (Younger 1981, 1982, 1983), dielectronic recombination rates (Nussbaumer & Storey 1984, 1986, 1987), and rates for charge transfer reactions (Butler *et al.* 1980a,b; Dalgarno *et al.* 1981). The cooling function derived by Gaetz & Salpeter

(1983), which used the simpler equilibrium calculations of Shull & van Steenberg (1982), came a little too early to take full advantage of these treatments.

The CIE calculations of Shull & van Steenberg (1982) and Arnaud and Rothenflug (1985) (hereafter A&R) have been coupled to EUV-XUV spectral synthesis calculations by both Gaetz & Salpeter (1983) and Mewe *et al.* (1985, 1986). Böhringer & Hensler (1989) and Landini & Monsignori Fosse (1990) (hereafter L&M) used their own equilibrium calculations based on the A&R and Shull methods respectively. The emission processes used to derive these cooling functions typically cover only a limited spectral range. For example Gaetz & Salpeter (1983) have included only line radiation with $\lambda \leq 3000 \text{ \AA}$, L&M were restricted to $\lambda \leq 2000 \text{ \AA}$, while some work by Mewe *et al.* (1985) was limited to $\lambda \leq 270 \text{ \AA}$. These works consider largely emission line transitions, and the continuum emission processes are calculated only for some species such as hydrogen and sometimes helium.

Non-equilibrium calculations of cooling functions, apart from those applying in shock models, have not been well covered in the literature. Shapiro & Moore (1976) represents perhaps the last published investigation into non-equilibrium effects in isochoric plasma cooling models, and this was restricted to warm and cool regimes ($\log(T) < 6.0$; T being the temperature in K). So, at the time of writing, apart from Böhringer & Hensler (1989) and L&M, there are no cooling function calculations in the literature that include the most recent atomic physics. Very recent work, still in press, by Schmutzler & Tscharnuter (1992) does look at non-equilibrium cooling without the coupling of the internal diffuse field permitted in our self-consistent flow model. Their plasmas constitute a subset of the ions and radiative transitions used here. Some additional work on non-equilibrium cooling has been done in terms of the prediction of column densities of the observed galactic halo absorption line species (Edgar & Chevalier 1986) but this was not directly to do with the cooling functions *per se*.

In this paper a grid of models covering CIE models of various metallicities are presented along with non-equilibrium isobaric (NEQ) cooling models covering a range of density, temperature and metallicity. The effect of the internal diffuse field on the plasma is also examined, relaxing the optical thinness requirement of previous studies. For the NEQ models, two limiting cases are considered, the case in which the diffuse radiation field is zero (the zero-field, or optically thin case), and the case in which the full diffuse field generated by the cooling plasma is re-absorbed downstream (the full-field case). The model is one of an approximately isobarically cooling flow, with the flow variables obeying the Rankine-Hugoniot

conditions. Deviations from strictly isobaric conditions arise from additional ram pressure terms. The model structure is discussed in detail in section 3.5.3.

In section 3.5 we will show that non-equilibrium cooling produces significantly different cooling functions and ionization balances to the standard CIE models. This has important implications. The cooling efficiency of the cooling plasma is significantly reduced, by as much as a factor of three, and this will directly affect any hydrodynamic modeling that uses gas cooling by increasing the corresponding cooling timescales. The change in ionization balance which brings about this decreased cooling will also affect any diagnostic line interpretation. In particular the hot galactic halo absorption line observations of CIV, NV, OVI, and Si II,III and IV, should not use CIE calculations to estimate plasma temperatures. If the gas is cooling, then the NEQ calculations here indicate that the peak ionization temperatures of C and Si are greatly affected by the non-equilibrium conditions. Any temperature estimates based on these species using CIE assumptions will be in error.

Our primary aim is to provide a useful grid of cooling functions over a wide range of temperature and metallicity that may be used in other areas of astrophysics such as galaxy formation, merger, and cooling flows. We have the secondary purpose of presenting the new code: MAPPINGS II, which is being used in new work by the authors. The discussion will be limited strongly to a description of the methodology and data sources being used, along with the most immediate implications of the cooling curves and the non-equilibrium models. The original MAPPINGS code was described by Binette *et al.* (1985) and here we present the major changes that have extended the performance of the code by several orders of magnitude in temperature, density range and spectral coverage.

3.2 The Modeling Code

Until recently it has not been possible to create self-consistent models of astrophysical plasmas covering a wide range of physical conditions, since the large amounts of atomic data required were simply unavailable. The pioneering shock modeling efforts of Cox (1972) and later Dopita (1976,1977a), Raymond & Smith (1979) and Shull & McKee (1979), suffered from this lack of atomic data and the lack of some processes, particularly the older codes, which were later shown to be important. The photoionization cross-sections were very poorly determined, and collisional ionization rates were modeled in a very simple manner (*i.e.* Lotz 1967). The code of Dopita concentrated on the detailed treatment of the low

temperature regime ($\log(T) < 5.2$), while Raymond extended to higher temperature plasmas. These codes have evolved since then, as new processes have been included such as dielectronic recombination, secondary ionizations, Auger processes, autoionization, and charge transfer reactions.

As far as CIE models are concerned a major improvement in their calculation was made possible by Younger (1981,1982,1983) with his work on collisional ionization. Based on his methods, A&R compiled data and applied them to equilibrium ionization calculations in the optically thin limit. The recent work of Böhrringer & Hensler (1989) used the A&R methodology and data, whereas the L&M work still used the Shull and van Steenberg (1982) rates. These recent works on optically thin CIE cooling functions fall some considerable way short of providing a physically realisable cooling function suitable for many calculations. In particular it should be noted that even the simple calculations of Shapiro & Moore (1976) showed significant non-equilibrium effects on the cooling functions.

In this paper the results were calculated with a new code: MAPPINGS II, developed in an attempt to treat a wide range of plasma conditions in a consistent way. The initial framework for this code is the older code MAPPINGS (Binette 1982, Binette *et al.* 1985), which gives basic model structures for photoionization nebulae and low-velocity shockwaves. In the new code, which operates under the UNIX system on Sun workstations, MAPPINGS was extended and merged with the XUV spectrum methods of Mewe, Gronenschild & various co-workers (1978,1981,1985,1986) and L&M (1990). In addition, the collisional ionization data of A&R (1985) have been combined with more robust methods to allow the use of Younger's collisional ionization methods far from equilibrium. Improved photoionization threshold values from Gould (1978) and Gould & Jung (1991) were included where available. Finally, we have included more accurate methods of handling hydrogenic ions.

Thus, MAPPINGS II is intended as a detailed modeling code for low *and* high temperatures, including both collisional shock and photoionization models in one, consistent, framework. The loss rates generated come from a wide range of processes including fine-structure, intersystem and forbidden emission, as well as resonance transitions and full continuum calculations on an ion by ion basis. Emission line intensities in the spectral range from the [NII] 205μ fine structure transition up to a NiXXVIII λ 1.24 Å resonance line are computed.

Considerable reorganization of the code was required to allow the expansion from 66 ions to 225 ions with all their attendant data and updated treatments, without slowing the code down to an unusable level. MAPPINGS II now includes

calculations for up to 16 atoms (H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Cl, Ar, Ca, Fe & Ni), and all stages of ionization. This extends the useful temperature range up from $\log(T) \approx 5.0$ up to $\log(T) \approx 8.5$ (above which relativistic effects become important). Radiative processes now calculated include 1683 transitions, including some 940 resonance lines (compared to ~ 60 in the older MAPPINGS code). The continuum emission processes and their spectral distributions are now calculated in detail, to include contributions from all species present, for free-free and free-bound emission on an ion by ion basis, and all H and He like ions for two-photon processes. The treatment of coronal diagnostic He ion lines allows for collisional coupling effects between the triplet levels of the ions. Non-relativistic Compton heating has been added. The ionizing radiation field is computed over a range of 5 eV to 11 keV in a total of 360 energy bins.

The atomic physics required to calculate the energy balance in the photoionization and shock modeling of MAPPINGS II may be conveniently divided into three parts. Firstly, there are those atomic processes which directly affect the ionization balance. These processes include: photoionization, collisional ionization, charge transfer reactions and various forms of recombination. These are covered in § 3.3.1 to § 3.3.4. The second general area includes radiative emission processes, covered in § 3.3.5 and § 3.3.6. Finally, various processes operate to heat and cool the plasma, and these are discussed in § 3.3.7, where the cooling functions are also defined.

In the following section, only those processes that have changed from the treatment in the older MAPPINGS code will be presented in detail, whereas others will be simply stated and references to previous works used. Further, the emphasis in this section is on describing the actual calculations used in the MAPPINGS II code. In choosing the expressions that are used, the aim was to obtain useful expressions that are valid over as large as possible range. This often means not using the most refined, elegant, approximations but reverting to more 'brute force' solutions that are more suited to computer application. The underlying physics is not always very clear in some of these lower level approximations. However, the cited references contain ample discussions about the processes involved. In particular, the classic work on hydrogenic recombination by Seaton (1959) involves several stages of approximation before the final, commonly used, expressions are derived. In this work, the approximations are taken back to intermediate stages to give rather unwieldy, but more robust expressions which are easily handled nowadays with numerical computer methods.

Unless otherwise noted, all expressions given here use cgs units.

3.3 Atomic Physics

The ionization balance of a plasma is determined by its temperature, ionization history, and by the atomic processes operating in the plasma. In this section the methods used to calculate various atomic processes are described.

3.3.1 Photoionization

In its treatment of photoionization, MAPPINGS II is similar to MAPPINGS, except that it includes more edges and the photoionizing radiation vectors have been extended. The fit used for the photoionization cross-section, as a function of photon frequency above the threshold frequency is (Seaton 1958):

$$\sigma_{photo} = \sigma_{thr} \left(\beta(\nu/\nu_{thr})^{-s} + (1 - \beta(\nu/\nu_{thr})^{-s-1}) \right) \text{ cm}^{-2} \quad (3.1)$$

Where data are available, multiple edges have been included for each ion. The data for β , s and ν_{thr} are from: Raymond (1976,1979); Osterbrock (1989); Gould (1978), and Gould & Jung (1991). Two electron Auger processes are also calculated for those ions where data are available (Weisheit 1974). Secondary ionizations resulting from photoionization processes are accounted for as described in Shull (1979) and rates for heavier atoms are derived as described in Binette (1982).

For the 225 ions considered 305 photoionization edges occur in the range 5 eV to 11 keV. The ionizing radiation field is calculated in a vector of 360 frequency bins with the 305 photoionization edges defining the majority of the bin energy ranges. Extra bins are included where photoionization edges are widely spaced to give an even coverage of bins over any given energy interval.

This simple definition then allows the very sharp edges to be accounted for because the $(n - 1)^{th}$ bin is everywhere below the edge in question, the n^{th} bin starts at the edge, and the intensity of the bin is taken as the intensity at the center of the bin interval. When calculating photon absorption, the continuum bin intervals are interpolated using a power law fit over the interval, and the result is integrated over the cross-section expression for each ion to give a total cross-section for the bin.

3.3.2 Electron Collision Ionization

Provided that the electrons have a thermal Maxwell distribution, the rates of electron collision ionization may be calculated using the methods of Younger

(1981,1982,1983). This is based upon a five parameter fit to each component of a collision cross-section, and the rate can be calculated using the same five fitting parameters and two exponential integrals. The advantage of this method is that the parameters can be derived directly from collision cross-section experiments, or from theoretical calculations. The fits are made on a shell-by-shell basis so the parameter values can be related back to the electronic structure and the contribution to the cross-section of each shell can be separated. The reversibility implicit in this method provides a means for an internal cross check of the consistency of the data. The atomic data have been taken from A&R and references therein.

In order to handle non-equilibrium cases an improved method of calculation is required, so in the computations presented here the following methodology has been developed.

Following Younger (1983), the cross-section (Q) for each electron shell can be expressed as:

$$uI^2Q = A \left(1 - \frac{1}{u}\right) + B \left(1 + \frac{1}{u}\right) + C \ln u + \frac{D}{u} \ln u \text{ cm}^2 \text{ eV}^2 \quad (3.2)$$

where: $u = \varepsilon/I$, ε = electron energy, I = shell ionization potential and A, B, C and D are fit coefficients for a given ion.

Integrating this expression over a Maxwell distribution we have:

$$I^{3/2}S = 6.69 \times 10^{-7} x^{3/2} \int_1^\infty uI^2Q e^{-ux} du \quad (3.3)$$

where $x = (I/kT)$.

This integral can be expressed in terms of the ionization potential and the fitting coefficients as:

$$F(x) = [A + B(1+x)] f_1 - [A - B(2-x)] f_2 + C f_3 + D f_4 \quad (3.4)$$

where $f_1 = (1/x)e^{-x}$, $f_2 = E_1x$, $f_3 = (1/x)f_2$ and $f_4 = E_2(x)$.

Finally the collisional ionization rate for a given ion of a given atom is derived here as:

$$S_{coll.}(T) = \frac{6.69 \times 10^{-7}}{kT^{3/2}} \sum_{i=1}^{\#shells} \frac{e^{-x_i}}{x_i} \Phi(x_i) \text{ cm}^3 \text{ s}^{-1} \quad (3.5)$$

where F has been rewritten as Φ , to collect exponential integral terms together, from (3.4):

$$\Phi(x) = [A + B(1+x)] - [C + Ax - B(2x - x^2)] e^x E_1(x) + D e^x E_2(x) \quad (3.6)$$

The expressions given by A&R for evaluating the exponential integrals (E_1 and E_2) suffered both from typographical errors in E_1 , limited accuracy, and a

limited useful range of application for E_2 . Here expressions are based on the polynomial ratios given in Abramowitz & Stegun (1964:Equations 5.1.53,56) are used to evaluate E_1 . When reorganized, these expressions can be evaluated quite efficiently. These expressions are considerably more accurate than the A&R expressions, and use only one matching point at $x = 1$. The second exponential integral E_2 may be obtained from the first by a recurrence relation also given by Abramowitz & Stegun (1964:Equation 5.1.14).

The MAPPINGS II code uses the Coefficients A, B, C, D and I for each shell of each ion, evaluates the sum of equation (3.5) using equation (3.6)

Collisional autoionization is treated in Li-like, Na-like, and in the heavier Mg through S isoelectronic sequences. Particular attention is given to CaI, CaII, FeIV and FeV, as described in A&R, Appendix A, the refinement here being the use of these robust expressions for evaluating the exponential integrals.

The data for the collisional cross-section coefficients are based on experimental results where possible, on theoretical calculations in other cases, and on isoelectronic interpolation as a last resort. For Chlorine the values used for I, A, B, C and D were interpolated and the values used are given in table A.1.

3.3.3 Charge Transfer Reactions

Our treatment of charge transfer reactions includes 61 reactions for H and He interacting with C, N, O, Ne, Si, S and Ar. The rates are taken from A&R, Butler (1980), Butler & Dalgarno (1980) Butler & Raymond (1980) , Dalgarno *et al.* (1981) and Field & Steigman (1971), with the exception of the OIII-OII reaction:

Based on work by Che & Köppen (1983) and Dopita & Metheringham (1991), a revised rate for this reaction is used, which is smaller than the Butler rate by a factor of 10.

3.3.4 Radiative and Dielectronic Recombination

As in MAPPINGS, radiative and dielectronic recombination rates have been calculated to the first order using power law fits (Aldrovandi & Pequignot 1973, 1976). Although marginally better methods and data are known for a small range of ions (*i.e.* Gould 1978), the benefits of a consistent set of data and the simplicity of the calculations involved support the continued use this method, at least

until a greater range of atomic data is available for use in the more sophisticated methods. The accuracy of the experimental data is not very good in any case so the benefits of a more complex treatment is not clear. The low-temperature corrections given by Nussbaumer & Storey (1984,1986,1987) for dielectronic recombination are used for C, N, O, Ne, Mg, and Al.

The rates for dielectronic recombination, in particular, are subject to considerable uncertainty. Along with the charge exchange rates above, these represent the least certain of the atomic data that relate directly to the ionization balance.

The rate coefficients used here are from the recent L&M and Nussbaumer & Storey references.

Hydrogenic Radiative Recombination

For most ions the accuracy of the available data makes any further refinement in the rate calculation method meaningless, however the treatment for hydrogenic ions must be much more accurate because in astrophysical plasmas hydrogen is often the overwhelmingly abundant species, and many properties of the plasmas depend critically on the hydrogen ionization balance. Fortunately this problem is amenable to accurate theoretical calculation. The entire hydrogen iso-electronic sequence can be treated in the same manner.

When calculating the recombination rates of hydrogenic ions, many codes have used the simple power law fits for low temperatures. However, recent codes (MAPPINGS and A&R) now use more detailed fits to rates from the classic works of Seaton (1958,1959) and Burgess (1958).

The fits used then, to make analytical calculation easier, need no longer be used, and more accurate results can be obtained by taking the approximations back to lower levels and higher complexity. In MAPPINGS and A&R the total recombination rate is given by a fit to an asymptotic expansion of a series fit to the original g_{II} (free-bound) Kramers-Gaunt factor from Seaton (1959):

$$\alpha_{total}(Z, T) = 5.197 \times 10^{-14} Z \lambda^{1/2} (0.4288 + \ln(\lambda)/2 + 0.469 \lambda^{1/3}) \quad (3.7)$$

where: $\lambda = h R c \frac{Z^2}{k T} = 157890 \frac{Z^2}{T}$.

Equation (3.7) gives good accuracy in the low (Z scaled) temperature range $\log(T/Z^2) < 6.0$, but diverges strongly from the true value above this range, in such a way as to increase the calculated recombination rates to extremely high values. This would erroneously predict that H would recombine above $\log(T) = 8.0$. By going back to the expressions from which this high level approximation

was made, an expression may be obtained that remains accurate to much higher temperature regimes ($6.5 \leq \log(T/Z^2) \leq 7.5$), and when it finally diverges, it diverges in the sense that the rates tend rapidly to zero, giving the expected fully ionized state. This is illustrated in figure (3.2). Following Seaton (1959) we have an expression for the azimuthally averaged recombination rate to quantum level n in a hydrogenic ion:

$$\alpha_n(Z, T) = DZ\lambda^{1/2} \left(\frac{x_n}{n} \right) S_n(\lambda) \quad (3.8)$$

where: $D = \frac{2^6}{3} \left(\frac{\pi}{3} \right) \alpha^4 c a_o^2$, $x_n = \frac{\lambda}{n^2}$

If we consider D to represent a 'classical' cross-section based on α , the fine structure constant, and a_o , the first Bohr radius, the $S_n(\lambda)$ term then represents the 'quantum correction', first derived by Gaunt (1930), and expanded on by Menzel and Perkeris (1935).

$$S_n(\lambda) = \int_0^\infty \frac{g_{II}(n, \varepsilon) e^{-x_n u}}{(1+u)} du \quad (3.9)$$

where: g_{II} is the free-bound Kramers-Gaunt factor (Kramers 1923; Gaunt 1930), $u = n^2 \varepsilon$, ε is the electron energy in Rydberg units and n is the principal quantum number.

Seaton's asymptotic expansion of g_{II} was:

$$g_{II}(n, \varepsilon) \approx 1 + 0.1728n^{-2/3}(u+1)^{-2/3} + 0.0496n^{-4/3}(u+1)^{-4/3}(u^2 + 4/3u + 1) \dots \quad (3.10)$$

With this expansion the integral in equation (3.9) can be written:

$$S_n = S^{(0)} + S^{(1)}\lambda^{-1/3} + S^{(2)}\lambda^{-2/3} \dots \quad (3.11)$$

where:

$$S^{(0)} = e^x E_1(x) \quad (3.12)$$

$$S^{(1)} = 0.1728x^{1/3} X_1(x) \quad (3.13)$$

$$S^{(2)} = -0.0496x^{2/3} X_2(x) \quad (3.14)$$

Where $E_1(x)$ is the first exponential integral $E_1(x)$ and the integrals X_1 and X_2 may be expressed using hypergeometric functions (see Seaton equations 20-24).

Summing equation (3.8) and equation (3.11) over n terms, Seaton gives:

$$\sum_{n'=n}^{\infty} \alpha_{n'} \approx 1/2D\lambda^{1/2} \left\{ \frac{x_n}{n} S_n(\lambda) + \sigma_n(\lambda) \right\} \quad (3.15)$$

where

$$\sigma_n(\lambda) = \int_0^{x_n} S_{n'}(\lambda) dx_{n'} \quad (3.16)$$

Using equation (3.11) and the expansion:

$$\sigma_n = \sigma^{(0)} + \sigma^{(1)}\lambda^{-1/3} + \sigma^{(2)}\lambda^{-2/3} \dots \quad (3.17)$$

equation (3.16) can be evaluated.

Thus from (3.11) and (3.17):

$$\sigma^{(0)} = E_1(x) + \ln x + \gamma \quad (3.18)$$

For $x < 0.02$ Seaton's expressions for the higher S and σ terms can be simplified to:

$$S^{(1)} = \frac{1}{2} \left\{ 0.4629(1 + 4x) - 1.0368x^{1/3} \left(1 + \frac{15}{8}x \right) \right\} \quad (3.19)$$

$$S^{(2)} = \left\{ -0.0672(1 + 3x) + 0.1488x^{2/3} \left(1 + \frac{9}{5}x \right) \right\} \quad (3.20)$$

$$\sigma^{(1)} = \frac{x}{2} \left\{ 0.4629(1 + 2x) - 0.7776x^{1/3} \left(1 + \frac{15}{14}x \right) \right\} \quad (3.21)$$

$$\sigma^{(2)} = x \left\{ -0.0672 \left(1 + \frac{3}{2}x \right) - 0.0893x^{2/3} \left(1 + \frac{9}{8}x \right) \right\} \quad (3.22)$$

For larger x , Seaton's tables I and II, giving numerical integration results, are used to evaluate S and σ terms using linear interpolation. These tables are reproduced in table A.2, up to $x = 0.17$ for convenience. Above $x \approx 0.15$, equation (3.7) is used, so none of the large x approximations of Seaton are required.

At this point in the development of the computational algorithms, an error in Seaton's fits and/or tabulated data became apparent. Seaton's expression for $S^{(1)}$ and $\sigma^{(1)}$, for small x in equations (3.19 and 3.21) did not match up with the last few data points given in his table I and II. The effect on the recombination rate was to produce a discontinuity when the methods change over from tabular data to polynomial expressions. By dividing the polynomial fits by a factor of 2, reasonable continuity was achieved. The tabular data matched well with equation (3.7) at $\log(T/Z^2) = 6.0$. This is shown in figure 3.1. The equations given above include these corrections in equations (3.19 and 3.21).

We have used equation (3.7) when $\log(T/Z^2) \leq 6.0$, and table A.2, and equation (3.15) with equations (3.12, 3.18 and 3.19-3.22) for higher temperatures, to calculate the recombination rates for hydrogenic ions. By calculating the total rate and subtracting the $n = 1$ rate using equation (3.8), we can derive the rates for the 'on-the-spot' approximation if required.

FIGURE 3.1: Hydrogenic recombination rate discontinuity. Seaton's (1959) rate terms $S(1)$ and $\sigma(1)$, when evaluated using Seaton's expressions and tables, do not behave in a continuous manner. When the total rate is evaluated using; equation (3.7) for $x > 0.15$, Seaton's table I for $0.02 < x < 0.15$, and Seaton's version of equation (3.19) for $x < 0.02$, a gross discontinuity is observed at $x = 0.02$ (gray line). Empirically this can be remedied by reducing the polynomial fits of Seaton for $S(1)$ and $\sigma(1)$ by a factor of 2. This produces the relatively smooth curve (solid line). These corrections are included in equations (3.19 and 3.21).

A comparison between these various methods of calculation is shown in figure 3.2.

3.3.5 Line Radiation Processes

Strictly speaking, the radiation field and the ionization balance are coupled. In the limiting case of an optically thin, or zero-field, plasma this coupling condition can be relaxed, so that a purely local ionization balance computation can be used to calculate the emission spectrum of the plasma. When the radiation field is strongly coupled to the ionization balance, iterative methods must be used to find a fully self-consistent solution.

It should be kept in mind that as the new data coming out of the Opacity Project work becomes more complete, the area of collisional line excitation may be significantly affected. The new data will alleviate the need for the Gaunt factor methods used here to derive collision strengths (Ω_{gj}) from the oscillator strengths (equation (3.25)). The explicit temperature dependences of the collision strengths may also be included. In the case of resonance lines in particular this may have the potential to affect the cooling function significantly. So, with the proviso that the calculation of collisional excitation rates may be subject to future changes, this work proceeds with more the conventional methods and data currently in wide use.

The principal radiative processes considered will be discussed in the following sections.

Resonance Lines

For the resonance line calculations, it is assumed that collisional excitation is dominant, and that the ions are excited from their ground states. Assuming a Maxwellian velocity distribution for the electrons, the power emitted in a transition from level j to k , excited from ground level g (where g and k may be the same) is given by equation(3.23): (Kato 1976;Mewe & Gronenschild 1981; L&M)

$$P_{jk} = n_e n_H A_{el} X_i S_{gj} E_{jk} B_{jk} \text{ ergs cm}^{-3} \text{ s}^{-2} \quad (3.23)$$

Where n_e is the number density of electrons, n_H the number density of hydrogen, A_{el} the abundance of the element el relative to hydrogen, X_i the fraction of ion i , S_{gj} the collisional excitation rate between level g and j , E_{jk} the transition energy, and B_{jk} is the radiative branching ratio for the transition.

FIGURE 3.2: Comparison of various hydrogenic recombination rate calculations. In turn: Low temperature power law fit, curve I, Seaton's high order approximation used by A&R and MAPPINGS I (equation (3.7)) curve II, and the corrected version of Seaton's more detailed methods used here (equation (3.15)), curve III. The useful range is extended by an order of magnitude.

Using the excitation rate given by:

$$S_{gj}(T) = \left(\frac{h^2}{(2\pi m_e)^{3/2} k^{1/2}} \right) \frac{\exp[-E_{gj}/kT]}{T^{1/2}} \left(\frac{\Omega_{gj}}{\omega_g} \right) \text{ cm}^3 \text{ s}^{-1} \quad (3.24)$$

where: Ω_{gj} is the collision strength and ω_g is the statistical weight of the ground level. Collisional de-excitation is not considered for the resonance lines in this work, limiting the validity of the cooling functions to the low density regime, $\log(n_0) < \sim 8$.

Estimating Ω_{gj} from the absorption oscillator strength (following Seaton 1958):

$$\Omega_{gj} = \frac{8\pi}{\sqrt{3}} \frac{\omega_g f_{gj}}{E_{gj}} \bar{g}(T) \quad (3.25)$$

and then using:

$$f'_{gj} = f_{gj} B_{jk} C / a \quad (3.26)$$

where $a = E_{gj}/E_{jk}$, B_{jk} is the radiative branching ratio, and C is a cascade correction (Mewe & Gronenschild 1981), we obtain:

$$P_{jk} = 8.63 \times 10^{-6} (n_e n_H A_{el} X_i E_{jk}) \frac{\exp[-E_{gj}/kT]}{T^{1/2}} \frac{8\pi}{\sqrt{3}} f'_{gj} \bar{g}(T) \quad (3.27)$$

The averaged Gaunt factors are evaluated, using the first exponential integral E_1 , by:

$$\bar{g}(x) = A + e^x (Bx - Cx^2 + Dx^3 + E) E_1(x) + (C + D)x - Dx^2 \quad (3.28)$$

The values for the Gaunt coefficients: A , B , C , D and E , as well as effective oscillator strength (f') values were taken from L&M and references therein. There appears to be an error in the expression for f' in L&M. By inspection, the f' values listed for the transitions in L&M do not include the $8\pi/\sqrt{3}$ factor as implied by their equation. Here it is assumed that the expression (24) from Mewe & Gronenschild (1981) was intended as described in equation (3.25) here. The problem of the radiative transfer of resonance line radiation is treated using an escape probability formalism developed by Capriotti (1965), implemented by Binette *et al.* (1985). The thermal width and velocity gradients across slab elements are included. The resonance lines therefore see a greater effective path length in a given model step than other frequencies.

Forbidden Lines

The low-lying fine structure energy levels of the p^2 , p^3 and p^4 ions of N, O, Ne, Mg, Si, S, Cl, Ar and Fe can be treated as five-level atoms. Complete data for

collisional and radiative transition probabilities between these levels are available. These are used to solve for the level populations and transition rates. Once the populations are known the emitted radiation is calculated. The methods and data are from Pradhan (1976), Zeippen (1982), Mendoza & Zeippen (1982) and Osterbrock (1989) as described in Binette (1982).

The plasma is assumed to be always optically thin in the forbidden lines. These lines calculations naturally include collisional de-excitation and should be valid in the density regime defined by the resonance line treatment above.

MAPPINGS II uses this five-level atom treatment for 29 ions for 290 transitions.

Inter-system Lines and Fine-Structure Lines

These lines are treated on a two-level approximation, similar to the resonance lines. The radiative and collisional rates are used to derive the temperature and density dependence of the line emissivity. The methods used are described by Binette (1982), and have not changed from MAPPINGS. Additional data are from L&M.

He-like Ion Lines

The coronal diagnostic XUV He Triplet systems are treated as three-level atoms with collisional coupling of the forbidden and intersystem transitions, to give a density sensitivity at high T in the $n_e = 10^9 - 10^{12} \text{ cm}^{-3}$ range. The data and calculation methods used here are based on the work of Mewe & Gronenschild (1981). The population rates (S_f and S_i) for the 2^3S and 2^3P levels are coupled using the branching ratios B_f and B_i :

$$S_{f,\text{coupled}} = [S_f + (1 - B_i)S_i] B_f \quad (3.29)$$

$$S_{i,\text{coupled}} = S_i B_i + [S_f + (1 - B_i)S_i] (1 - B_f) \quad (3.30)$$

where the intersystem radiative branching ratio is:

$$B_i = \frac{A_{2^3\text{P}-1^1\text{S}}}{(A_{2^3\text{P}-1^1\text{S}} + A_{2^3\text{P}-2^3\text{S}})} \quad (3.31)$$

The forbidden branching ratio is related to B_i by the critical density β_c

$$B_f = (1 + \beta_c n_e B_i)^{-1} \quad (3.32)$$

and β_c is calculated using the empirical fit of Mewe:

$$\beta_c(T) \approx 330Z^{-14.57} \left(\frac{T_5}{Z^2} \right)^{-0.73Z^{-0.415}} \quad (3.33)$$

where $T_5 = T/10^5 \text{K}$. Mewe & Gronenschild (1981) give data for B_i and β_c for the He like ions of carbon through nickel.

The FeII System.

A 14-term, multi-level atom model is employed for the specific case of the FeII ion. Data for the IR transitions between the ground a^6D , a^4F , a^4D and a^4P terms (115 transitions) are from Nussbaumer & Storey (1980,1988). Additional data for allowed and E2 forbidden transitions between the a^6S , a^4G , b^4P , b^4F , z^6P_0 , z^6D_0 , z^6F_0 , z^4P_0 , z^4D_0 and z^4F_0 terms were derived the transition data of Fuhr *et al.* (1988). A total of 357 transitions from $\lambda 2300 \text{ \AA}$ down to 90μ are calculated.

Hydrogen and Helium Recombination Lines.

The recombination component of the optical hydrogen and helium resonance line spectra are calculated in detail using an intermediate, linear combination, of case A and B calculations based on the methods of Brocklehurst (1971) and Johnson (1972). These take into account the azimuthal distribution of recombinations to a given n level. The radiative transfer effects noted by Clegg & Harrington (1989) on the optical helium spectrum, particularly $\text{HeI} \lambda 10830$ are not as yet fully accounted for in MAPPINGS II. However this detail will have no effect on the total energy balance.

3.3.6 Continuum Radiation

The continuum calculations hinge on the calculation of the appropriate Gaunt factors. Using the convenient formulation of Mewe *et al.* (1986), the Gaunt factors for each of the three processes can be evaluated and the added to get a total power of the continuum emission as a function of photon energy and plasma temperature.

Using the expression:

$$P_c(\lambda, T) = \frac{64\pi}{3} \left(\frac{\pi}{6} \right)^{1/2} \frac{e^6 10^8}{c^2 m_e^{3/2} k^{1/2}} n_e^2 G_c \lambda^{-2} T^{-1/2} \exp[-E/kT] \text{ ergs cm}^{-3} \text{ s}^{-1} \text{ \AA}^{-1} \quad (3.34)$$

with e the electron charge in e.s.u, and λ in Angströms, we obtain:

$$P_c(E, T) = 4.268 \times 10^{-26} n_e^2 G_c E^{-1} T^{-1/2} \exp[-E/kT] \text{ ergs cm}^{-3} \text{ s}^{-1} \text{ Hz}^{-1} \quad (3.35)$$

with E in eV. The continuum Gaunt factors for free-free, free-bound and two-photon processes are combined as the sum.

Free-Free Radiation

To compute the temperature averaged free-free Gaunt factor we have used the fit by Gronenschild & Mewe (1978) to the original work of Karzas & Latter (1961):

$$G_{ff} = \frac{N_H}{n_e} \sum_{el,i} A_{el} X_i z^2 \varphi_{ff} \quad (3.36)$$

$$\varphi_{ff} = \left\{ \left[\frac{\sqrt{3}}{\pi} e^x K_0(x)^2 \right] + [A - B \log(u)] \right\}^{1/2} \quad (3.37)$$

where:

- A_{el} = element abundance relative to hydrogen,
- X_i = ionization fraction of ion considered,
- z = effective nuclear charge, including screening effects,
- $K_0(x)$ = the modified Bessel function of the second kind.,
- $u = \frac{E}{kT}$ the scaled photon energy,
- $x = u/2(1 + \sqrt{10}\gamma)$
- $\gamma^2 = \left(\frac{I_{el,i}}{kT} \right)$
- $I_{el,i}$ = ionization potential of the i^{th} ionization stage of element el

Also:

$$A = 1.2 \exp \left[- \left((\log \gamma^2 - 1)/3.7 \right)^2 \right] \quad (3.38)$$

$$B = 0.37 \exp \left[- \left((\log \gamma^2 + 1)/2.0 \right)^2 \right] \quad (3.39)$$

The modified Bessel function may be readily evaluated using polynomials from Abramowitz & Stegun (1964) equations (9.8.1), (9.8.5) and (9.8.6).

Values for z are given in table A.3.

Free-Bound Radiation

The free-bound Gaunt factor is calculated by considering recombinations to the ground term in addition to a sum of recombinations to excited terms using a hydrogenic approximation for these higher terms, based on Mewe *et al.* (1986).

$$G_{fb} = \left(\frac{N_H}{n_e}\right) \left(\frac{I_H}{kT}\right) \sum_{el, i, n, (\nu > \nu_{n_0+1})} A_{el} X_i \varphi_{fb} \quad (3.40)$$

where I_H is the ionization potential of hydrogen, and:

$$\varphi_{fb} = \xi(el, i, n) g_{fb} z^4 n^{-5} \exp[E_n/kT] \quad (3.41)$$

where E_n = energy of the n^{th} energy level and $\xi(el, i, n)$ is the number of vacancies in the n^{th} level of the i^{th} ionizations stage of the atom el .

We separate the sum over all levels into two terms, the first to account for recombinations to the ground term and a second to account for recombinations to excited states:

$$\sum_n \varphi_{fb} = \varphi_{fb}(el, i, n_0) + \Delta\varphi_{fb}(el, i, n_0) \quad (3.42)$$

with

$$\Delta\varphi_{fb} \cong 2z^4 f(n_0) \exp\left[\frac{(\gamma z)^2}{(nz_0)^2}\right] \quad (3.43)$$

and f is evaluated using:

$$f(n_0) = \sum_1^\infty n^{-3} - \sum_1^{n_0} n^{-3} = \zeta(3) - \sum_1^{n_0} n^{-3} \quad (3.44)$$

where $\zeta(3) \approx 1.202 \dots$ is the Reimann function of argument 3.

Mewe *et al.* (1986) give data for $\xi(el, i, n)$, based on straight-forward theoretical calculations. These values are given in table A.3.

Mewe *et al.* go on to simplify the free-bound expression (in their equation 16), but we explicitly evaluate equations (3.40-3.44), taking g_{fb} to be 0.9 for the ground term and 1.0 for higher terms. The continuum calculations of L&M appear to neglect excited term recombinations.

Two-Photon Emission

Two-photon emission is calculated using the method from Gronenschild & Mewe (1978). This is best expressed in terms of wavelength:

$$G_{2\gamma} = \frac{N_H}{n_e} \sum_{el, i, \lambda < \lambda_0} A_{el} X_i \lambda_o \Lambda O \varphi_{2\gamma} \quad (3.45)$$

where $\Lambda = \frac{\lambda_0}{\lambda}$ and λ_0 is the threshold wavelength,

$$\varphi_{2\gamma} = \left\{ \cos \left(\pi \left[\Lambda - \frac{1}{2} \right] \right) \right\}^{1/2} \exp \left[u - \frac{u}{\Lambda} \right] \quad (3.46)$$

and:

$$\begin{aligned} O &= 3.488 \times 10^4 f\bar{g} \\ f\bar{g} &= 0.0229 \text{ (for H ions)} \\ f\bar{g} &= 0.0374 \left(1 - 1.34Z^{-1} \right) \text{ (for He ions)} \end{aligned} \quad (3.47)$$

This Gaunt factor is calculated at a particular wavelength, but the flux density is still calculated by equation (3.35) in frequency units.

Values for λ_0 are based on the Grotian diagram data of Bashkin & Stoner (1975,78,81) and Lide (1991). These are given in table A.3 in terms of the $1s$ - $2s$ energy gaps. These energies define additional bin values for the ionizing radiation vector described in section 3.3.1.

3.3.7 Plasma Heating and Cooling Processes

The net cooling function of a plasma can be defined in terms of the collisional line radiation, free-free and two-photon continuum, recombination processes, photoionization heating, collisional ionization and Compton heating:

$$\Lambda_{net}(T, A) = \Lambda_{lines} + \Lambda_{cont.} \pm \Lambda_{rec} - \Lambda_{photo} + \Lambda_{coll} \pm \Lambda_{Compton} \quad (3.48)$$

where T is the electron temperature(K), and A is the metallicity or composition.

The processes that lead to the Λ_{photo} , Λ_{lines} , Λ_{coll} and $\Lambda_{cont.}$ terms have been described in sections 3.3.1 to 3.3.6. The Λ_{photo} arises from the photoionization rate of equation (3.1) and the energy of the absorbed photons. The Λ_{coll} term is the product of the collisional ionization rate (equation 3.5) and the ionization potential of the ion being ionized summed over all ions and represents the energy lost by the colliding electrons. The Λ_{lines} and $\Lambda_{cont.}$ terms also come from the energy lost by the exciting electron collision and equals the total emitted flux. Note that the $\Lambda_{cont.}$ term only includes contributions from free-free and two-photon emission. The free-bound emission comes under the Λ_{rec} term described below in section 3.3.7.

Additional plasma heating processes are considered in MAPPINGS II. These are treated as energy terms, integrated over the electron thermal distribution and/or the photon spectral energy distribution. These are the Λ_{rec} and $\Lambda_{Compton}$ terms representing the net recombination heating or cooling and the heating due to Compton processes.

Recombination Heating

It is important to treat the radiation from recombination processes separately. Recombination may be a heating or cooling effect, depending on the electron energy distribution that the recombining electrons are being removed from. The recombination cross-sections are a strong function of energy, and are largest near the threshold. If the electron energy distribution peak is higher than the threshold for instance, then relatively cold electrons will be preferentially *removed from the system*. This results in a net heating due to recombination. The total internal energy is reduced, but the energy per particle increases. This heating is approximated by determining the mean energy of the recombining electrons, and comparing this with the mean electron energy, kT , as described by Binette *et al.* (1985). This is the reason that the continuum free-bound emission is not included directly in the cooling function sum.

Compton Heating

The net Compton heating is calculated with a non-relativistic expression based on the Thomson cross-section from Krolik *et al.* (1981) after work by Levich & Sunyaev (1970).

$$\Lambda_{Compton} = \frac{\Phi \sigma_T n_e}{m_e c^2 n_t^2} (4kT \langle \varepsilon_\gamma \rangle) \quad (3.49)$$

where Φ is the total flux, σ_T is the Thomson cross-section and the mean photon energy is derived from an integral over the spectrum ϕ_γ :

$$\langle \varepsilon_\gamma \rangle = \Phi^{-1} \int \phi_\gamma \varepsilon_\gamma d\varepsilon \quad (3.50)$$

3.4 Collisional Ionization Equilibrium

In the absence of any significant radiation field the ionization balance can be calculated using only the recombination, collisional ionization and charge transfer rates. We have therefore computed the collisional ionization equilibrium balance for the elements: H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Cl, Ar, Ca, Fe & Ni as a function of temperature. As a comparison to the published results of A&R and Shull & van Steenberg (1982), figures (3.3 - 3.5) show the ionization balances for C, Ne, and Fe. The complete CIE balance calculated for the range $\log(T) = 4.0$ to 8.5 is presented in table A.5.

Our results agree well with A&R. There are small differences due to variations in the charge transfer rates used, and several corrections to the recombination

FIGURE 3.3: CIE balance for carbon. The results of Shull & van Steenburg (1982) in the upper panel, Arnaud & Rothenflug (1985), center, and MAPPINGS II results in the lower panel curves. The extended hydrogenic recombination treatment allows the temperature range to be increased. The slight bump at (a) occurs at the change over to equations (3.19 to 3.22).

FIGURE 3.4: CIE balance for neon. The results of Shull & van Steenberg (1982) in the upper panel, Arnaud & Rothenflug (1985), center, and MAPPINGS II results in the lower panel curves. The differences in the region $\log(T) = 5.5$ to 6.0 may be attributed to variations in the coefficients for radiative recombination given by Landini & Monsignori Fossi (1990). The effect of low temperature dielectronic recombination corrections do not appear to be significant.

FIGURE 3.5: CIE balance for iron. The mid--range temperature balance for iron is greatly affected by the Younger collisional ionization rate methods. The ionization curves show distinct asymmetries. The coronal diagnostic Fe XIV ion, that produces the $\lambda 5303 \text{ \AA}$ optical line, is affected. The temperature of peak ionization, and the degree of that ionization change from the older Shull & van Steenberg work (line a). The present results agree well with the results of Arnaud & Rothenflug (line b), indicating that the collisional ionization rate changes are the most important.

rates as noted by L&M have been included. The work of A&R was published before the Nussbaumer and Storey (1987) work which provides additional corrections for neon. We expect that our results for hydrogenic ions are more accurate, and the balance for hydrogen is given over a wider temperature range than in previous works. We note that MAPPINGS II does not use matrix inversion in the balance calculations, but relies instead on the slower, but more stable, vector normalization method of Pullman (1976) as implemented by Binette (1982) and described in Binette *et al.* (1985). This method has a greater dynamic range and provides higher accuracy in the case of minor species. This method is time-dependent, so that equilibrium balance calculations are made by taking a time span much greater than any of the atomic process timescales.

The CIE balance calculated for Chlorine should be regarded as approximate, particularly under low temperature regimes. This is because the ionization and recombination rates for Cl I are based on an extrapolation from similar ions, whereas the higher ion data were interpolated. In any case Chlorine is a minor constituent in the plasmas considered here, and it was not included in the reduced abundance calculations. (see table A.4) The continuum Gaunt factors calculated for a CIE plasma, with solar abundances according to Anders & Grevesse (1989), are shown in figure(3.6) for $\log(T) = 6.5$. Once the minor differences in abundances are taken into account, the agreement with Mewe *et al.* (1986) is very good.

Finally, the ionizing radiation fields calculated by these methods are shown for a range of temperatures and under CIE conditions in figure(3.7), for comparison with L&M. The absence of the Helium two-photon processes in the L&M work implies a particularly deep drop in the continuum level around $\lambda 1000\text{\AA}$, reaching down to a free-free continuum for the $\log(T) = 4.5$ spectrum (L&M figure 2). In this paper, the Helium two photon contribution reduces the depth of this region, and the free-free continuum never dominates in the ionizing spectrum at this temperature (see figure 3.7, spectra 2).

3.5 Cooling Function Calculations

The cooling functions presented in this paper then represent a total cooling function, in that transitions from [NII] 205μ up to NiXXVIII $\lambda 1.24\text{\AA}$ are summed, and the continuum processes are summed over all frequencies. This should be taken into account when comparing the curves here with those given by Gaetz & Salpeter (1983), Böhringer & Hensler (1989), and L&M which only summed over

FIGURE 3.6: Continuum Gaunt factors for free-free, free-bound and two-photon processes, calculated at a temperature of $\log(T) = 6.5$. The abundances are solar, from Anders & Grevesse (1989). The abundances vary slightly from the Allen (1973) values used in Mewe (1986). In particular, the neon levels are higher. Principal contributions to the processes are indicated. The heavy line indicates the total continuum Gaunt factor. The smooth gray line is the free-free curve. The rectilinear striped line represents the free-bound curve and the thin dark line is the two-photon contribution.

CIE : Ionizing Radiation

FIGURE 3.7: CIE ionizing photon spectra, in the interval 5 eV to 11 keV. Solar abundances are from Anders & Grevesse (1989), used for solar values throughout subsequent sections of this paper. Temperatures of $\log(T) = 4.0$ to 8.5 in 0.5 dex steps are presented. Note the continuum in the $\log(T) = 4.5$ model, compared with Landini & Monsignori Fosse (1990). Also the observed cluster '7 keV iron line' (*cf.* Sarazin 1988) is apparent in the $\log(T) = 7.5$ and 8.0 spectra.

restricted wavelength ranges.

In this section we present only the models and the results. Detailed discussion of these is deferred until section 3.6.

3.5.1 Abundances

The abundances used in all the cooling function calculations are given in table A.4. The solar values from Anders & Grevesse (1989). The primordial ratios are based on Wheeler *et al.* (1989) for most atoms, Bessell *et al.* (1991) for oxygen and on Silk (1991, private communication) for helium in particular. The most significant feature of the primordial abundance ratios is the value of +0.5 for [O/Fe] based on the Bessell work. The enhanced oxygen abundances is important as oxygen is perhaps the most important coolant in all the calculations due to both high abundances and efficient resonance line cooling properties.

The Abundance series used were $[\text{Fe}/\text{H}] = +0.5$, solar, -0.5 , -1.0 , -1.5 , -2.0 , -3.0 and zero metals (H and He only). Models having a metallicity, $[\text{Fe}/\text{H}] \leq -1.0$ used the primordial ratios. The $[\text{Fe}/\text{H}] = -0.5$ model used ratios interpolated between solar and primordial ratios. The super-solar model used solar ratios.

3.5.2 Standard Collisional Ionization Equilibrium (CIE) Cooling Function

Under CIE conditions the photoionization heating ($-\Lambda_{\text{photo}}$ in equation (3.48)) is insignificant, leaving only collisional line radiation, continuum radiation and recombination heating as significant terms. These terms are all functions of temperature and abundance in CIE. We have computed a grid of models covering a temperature range of $4.0 \leq \log(T) \leq 8.5$ and using the abundance series of section 3.5.1. This yields eight curves that are closely enough spaced in T and A (in equation 3.48) to allow interpolation with a reasonable level of accuracy.

The models consist of a series of independent, isochoric and stationary, plane-parallel slab models. The hydrogen density was nominally 1.0 cm^{-3} , independent of temperature. For each slab the CIE was calculated, and the various plasma properties were derived. The radiation field was calculated, but photoionization effects of this field were suppressed. The normalization factor for the cooling function Λ_N (equation (3.57)) is taken as $n_i n_e$ where n_i is the total number density of ions and n_e is the total number density of electrons. This definition is generally valid, and independent of composition. It differs from the commonly used factor

$n_H n_e$ or even n_e^2 commonly used in hydrogen rich plasmas (L&M; Gaetz & Salpeter, 1983; and Böhringer & Hensler, 1989). The curves were calculated for a fixed ion density, and the electron density is given as a function of temperature to allow the volume emissivity to be derived. Additional parameters such as the density, pressure, isothermal sound speed, mean molecular weight and cooling time-scale are also given in the tables.

These quantities were calculated as follows:

Taking:

$$n_e, n_t = \sum_i^{ions} n_i, \text{ and } N = (n_t + n_e) \quad (3.51)$$

to represent the number densities of electrons, the sum of ion number densities, and the total number density of all species, then we have:

Mean particle mass:

$$\bar{\mu} = \sum_i^{species} \frac{n_i m_i}{N} \quad (3.52)$$

Mass density:

$$\rho = N \bar{\mu} \quad (3.53)$$

Gas pressure:

$$P = \frac{\rho k T}{\bar{\mu}} = N k T \quad (3.54)$$

Internal energy:

$$U = \frac{3}{2} N k T \quad (3.55)$$

Cooling timescale:

$$\tau_{cool} = \frac{U}{\Lambda_{net}} \quad (3.56)$$

Normalized cooling rate:

$$\Lambda_N = \frac{\Lambda_{net}}{n_t n_e} \quad (3.57)$$

Isothermal sound speed:

$$C_i = \left(\gamma \frac{P}{\rho} \right)^{1/2}, \quad \gamma = 5/3 \quad (3.58)$$

The units used in tables A.6 - A.10 are: μ : grams, ρ : g cm⁻³, P : ergs cm⁻³, U : ergs cm⁻³, τ_{cool} : seconds, Λ_{net} : ergs cm⁻³ s⁻¹, Λ_N ergs cm³ s⁻¹, and finally C_i : km s⁻¹. The resulting cooling functions are given in table A.6 and shown in figure (3.8)

FIGURE 3.8: CIE Normalized cooling functions as a function of metallicity. The upper gray curve represents the $[\text{Fe}/\text{H}] = +0.5$ super solar model, followed by the heavy solid curve representing solar metallicities. Below this, decreasing metallicities of -0.5 , -1.0 , -1.5 , -2.0 , -3.0 are shown, and the bottom curve represents the primordial zero metal case with hydrogen and helium with an abundance ratio of $[\text{He}] = -0.1928$ relative to hydrogen. The normalization factor used here is display in the lower panel. Apart from the low temperature drop due to hydrogen recombination the number densities remain constant. Variation due to composition changes are indistinguishable on this scale.

The plasma cooling timescale is shown in figure (3.9). In this plot a reduced timescale is used, with a normalization factor of $(n_e n_t)/(n_e + n_t)$, so that the curves from the variable density, non-equilibrium models can be compared more easily. The tables use the unnormalized, physical cooling timescale as defined in equation (3.56).

Shapiro and Moore (1976) showed that the equilibrium case can only possibly apply to temperatures above $\log(T) = 6.0$, since below this temperature the cooling time-scales become very rapid compared to any recombination and collisional ionization rates that determine the equilibrium time-scales.

3.5.3 Non Equilibrium (NEQ) Cooling Functions

In general, the ionization state of an astrophysical plasmas cooling in non-equilibrium conditions is determined by both the composition and the thermal history of the plasma. As a consequence a wide range of initial conditions is possible. The choice of the initial remains somewhat arbitrary. In order to limit the choices of initial conditions a set of physically realisable parameters must be imposed. In this way, the effect of a number of parameters can be explored in a reasonable number of models. The most important of these parameters; abundance, temperature and density are somewhat constrained by observations and the effect of each of these is discussed in the following sections.

The model structure is that of a cooling slab of plasma, starting from the CIE at the initial temperature, which is followed during its (approximately) isobaric cooling,. A Lagrangian model is used to follow a 'parcel' of gas through the cooling flow. Rankine-Hugoniot equations are used to mediate the flow. The equations used to follow the parcel flow, in the absence of magnetic fields, are:

Conservation of mass:

$$\rho v = \rho_0 v_0 \quad (3.59)$$

Conservation of momentum:

$$\rho h v^2 + p = \rho_0^2 v_0^2 + p_0 \quad (3.60)$$

Energy balance:

$$N dH/dt = -n_e n_t \Lambda_{net} \quad (3.61)$$

where the enthalpy per particle is:

$$H = 1/2 m v^2 + 5/2 k T / m \quad (3.62)$$

FIGURE 3.9: Cooling timescales calculated for the CIE models, using equations (3.55 and 3.56). The resulting timescale is then normalized by a reduced factor: $(ne \ nt)/(ne + nt)$ so later comparison with variable density non-equilibrium models may be made. The normalization factor is shown in the lower panel. The solar metallicity model is the heavy solid curve second from the bottom, the other metallicity levels are indicated with the same lines styles as in figure 3.8, with the primordial curve being the uppermost curve.

Momentum transfer is therefore properly accounted for, and the hot gas is moving at the correct infall speeds relative to the cooled, condensed regions. Deviations from isobaric conditions then arise from ram pressure ρv^2 terms. No magnetic fields are considered in these models, although MAPPINGS II may include magnetic pressure terms if desired. In the models, as discussed earlier, the local diffuse field is calculated in detail. Velocity gradients across each step of the model will determine the transfer of resonance lines. This effect is accounted for by an escape probability formalism (Capriotti 1965). The diffuse field was allowed to couple through the photoionization mechanisms with the local ionization and energy balance of the models, in an iterative, self-consistent manner. The geometry is that of an infinite plane parallel sheet and therefore the locally produced radiation field is divided into upstream and downstream components in equal parts. Since, for the upstream field, $h\nu < kT$ at any point in the flow, its effect on the ionization balance is less important than the downstream field. We have therefore computed the ionization balance in the downstream-only approximation for the diffuse field. In this geometry the radiation field is a maximum so we call this the full-field case. The coupling between the diffuse field and the local ionization balance can be switched off, to simulate the optically thin, or zero-field case. The implications of these two limiting cases are discussed in later sections.

We calculated the same plasma properties as in the CIE models using equations (3.51-3.58) and are given in tables (A.7-A.10). The cooling function calculations were terminated at a temperature of $\log(T) = 4.0$, or earlier if photoionization heating ever came to dominate the models, resulting in negative values for Λ_N .

Density Effects

We have generated three models to explore the effects of pressure. The first model is appropriate to the pressure domain encountered in disk galaxy galactic fountain models (Shapiro & Field, 1976; and Bregman, 1980,1988); $\log(p/k) \sim 4$ (p/k in units of $\text{cm}^{-3} \text{ K}$). The second model was scaled to the pressures appropriate for cluster cooling flows (*i.e.* Fabian, 1988; Sarazin, 1986), $\log(p/k) \sim 6$. Finally, a model with $\log(p/k) \sim 8$ was considered in order to determine the behavior under conditions when collisional de-excitation effects have become important. The models were calculated for a starting temperature of $\log(T_0) = 6.5$. The cooling curves are given in figure (3.10).

The lack of any pressure dependence for $4 \leq \log(p/k) \leq 6$ indicates that collisional de-excitation never becomes important in this range. As expected,

FIGURE 3.10: NEQ normalized cooling functions as a function of pressure. The solid curve (II) represents the $\log(p/k) \approx 6$ models in the zero-field case. Broken curves (I & III) represent the $\log(p/k) \approx 4$ and ≈ 8 curves respectively. Only the $\log(p/k) \approx 8$ curve shows significant depression due to collisional de-excitation, principally of forbidden lines. The normalization factors used here are displayed in the lower panel. The three pressure domains clearly separate on this plot, and the number densities are not constant.

the $\log(p/k) \sim 8$ model shows the de-excitation of the forbidden line emission is important in the range $\log(T) < 4.5$ resulting in a depressed cooling rate. A default value for $\log(p/k) \sim 6$ is used for the remaining calculations and this low density limiting case is implied for all further results.

Temperature Effects

In order to investigate the effect of the initial temperature on the cooling function we have run a series of zero and full-field models with starting temperatures over the range: $5.5 \leq \log(T_0) \leq 8.5$. The initial ionization state was that of CIE for the initial temperature. The resulting curves are shown in figures (3.11 and 3.12) and tables A.7 and A.8. The full-field case produced only a slight difference in the total cooling function, due to the local diffuse field maintaining a higher state of ionization as a given temperature.

The zero-field models very closely follow the CIE cooling function above $\log(T) = 6.5$, in agreement with the results of Shapiro & Moore (1976). Below $\log(T) = 6.0$ the curves progressively deviate and the characteristic 'twin peaks' associated with oxygen and carbon cooling respectively, are suppressed by a factor of 3 to 10. The NEQ cooling function is relatively featureless in this range.

Abundance Effects

The relatively minor effects of both pressure and initial temperature reduces the range of important free parameters, leaving chemical composition of the plasma as the key variable. An NEQ abundance series which can be applied to a wide range of astrophysical problems can be calculated taking a pressure of $\log(p/k) \sim 6$ and an initial temperature of $\log(T_0) = 7.5$. These conditions are typical of those observed for coronal gas in large cluster (*c.f.* Sarazin 1988, and references therein) equivalent to the virial temperature associated with a mass of order $10^{15} M_\odot$ inside a 1 Mpc radius. In CIE at this temperature, all the atoms except Fe and Ni are fully ionized. The ionization state of Fe and Ni is dominated by the hydrogen and helium like ions. These initial conditions start the cooling curve at the end of the free-free radiation dominated region, above which CIE and NEQ models converge. Both zero-field and full-field cases were calculated for the abundance series of section 3.5.1. The cooling functions and cooling timescales are shown in figures (3.13 and 3.14) and are tabulated in tables A.9 and A.10.

FIGURE 3.11: Full-Field NEQ normalized cooling functions as a function of initial temperature. The solid curves represent curve for different starting temperatures at CIE: $\log(T_0) = 5.5 - 8.5$ in 1.0 dex steps using the full-field case models and solar metallicity. There is only a slight initial temperature dependence and the variation from the NEQ zero-field models is generally a suppression of the order of ~ 0.1 dex in the cooling rates. The normalized solar CIE curve is overlayed in light gray. The normalization factors used are displayed in the lower panel.

FIGURE 3.12: Zero-Field NEQ normalized cooling functions as a function of initial temperature. The solid curves represent curve for different starting temperatures at CIE: $\log(T_0) = 5.5$ to 8.5 in 1.0 dex steps, using the zero-field models and solar metallicity. As in figure 3.11, the normalized solar CIE curve is overlayed in light gray. The $\log(T_0) = 6.5, 7.5$ and 8.5 curves overlay almost exactly, and only the $\log(T_0) = 5.5$ curve differs from these in its initial stages. The curves also agree very well with the CIE curve above $\log(T_0) = 6.5$. The normalization factors used here are displayed in the lower panel. Slight curvature due to ram pressure terms are apparent, but in general the pressure domain is constant at $\log(p/k) \approx 6$.

FIGURE 3.13: NEQ full-field and zero-field normalized cooling functions as a function of plasma metallicity. The solid curves represent curves for different metallicities; Solar (heavy solid curve), $[\text{Fe}/\text{H}] = -0.5$ (gray), -1.0 , -1.5 (gray), -2.0 , -3.0 , and the lowest curve represents the primordial zero metal case with $[\text{He}] = -1.1928$ compared to hydrogen. The zero and full-field models form pairs of curves, with the zero-field curves being the upper curve in each case. The normalized solar CIE curve is overlayed in light gray for comparison. The normalization factors used are displayed in the lower panel as in earlier figures.

FIGURE 3.14: NEQ full-field and zero-field normalized cooling timescales as a function of plasma metallicity. The solid curves represent curve for different metallicities; Solar (lowest solid curve), $[\text{Fe}/\text{H}] = -0.5, -1.0, -2.0, -3.0$, and the lowest curve represents the primordial zero metal case with $[\text{He}] = -1.1928$ compared to hydrogen. The zero and full-field models form pairs of curves, with the zero field curves being the lower curve in each case. The normalized solar CIE curve is overlaid in light gray for comparison. The normalization factors used are displayed in the lower panel as in earlier figures.

3.6 Discussion

Here we will discuss the results of the standard CIE calculations, and then go on to compare the NEQ results with the CIE results. We hope determine the extent of the differences and the significance of these differences.

3.6.1 Collisional Ionization Equilibrium Models

The results given here for optically thin collisional ionization equilibrium agree with those of Gaetz & Salpeter (1983), Böhringer & Hensler (1989) and L&M. The CIE curve has proven to provide an upper limit to the cooling rate of the plasmas, since all the time-dependent effects have resulted in reduced cooling efficiency in the temperature range considered. Therefore cooling time-scales given by such calculations should be considered to be lower limits for any astrophysical plasmas. The CIE and NEQ models all converge in the hot regime of $\log(T) > 7.5$ where all plasmas are totally ionized and electron free-free emission is the dominant cooling process. The free-free power law can be used to extrapolate the cooling function up to higher temperatures with a fair degree of accuracy until relativistic effects may become important above $\log(T) = 9.0$.

At High temperature, the Fe group line emission processes largely determine the cooling function, whereas at low temperatures the lighter atoms such as C, O, & Ne dominate the cooling.

The effect of the primordial ratios is only clearly seen in the oxygen contribution at $\log(T) \sim 5.3$ (figure 3.8). The enhanced cooling rate, relative to the $\log(T) = 4.9$ carbon peak, is apparent in the $[\text{Fe}/\text{H}] = -0.5$ and -1.0 models, due to the $[\text{O}/\text{Fe}] = +0.25$ and $+0.5$ ratio used for oxygen in these models. The oxygen contribution is still apparent at $[\text{Fe}/\text{H}] = -3.0$ levels, where it may not otherwise have been important.

The cooling timescales for the models form a smoothly varying family of curves. Attempts to fit power series polynomials to these curves would be quite inefficient, would not accurately reproduce the smaller scale variations, found in the curved region between $\log(T) = 5.0$ and 6.0 . The values for these curves are given in table (A.6) so that interpolation methods may be used instead.

3.6.2 Non-Equilibrium Models.

Plasmas cooling under NEQ conditions generally have lower cooling efficiencies. This is a consequence of the suppression of the strong contributions of the lighter elements such as C, O and Ne. Features in the cooling curve due to the much heavier iron atoms are only marginally affected. In particular, the normally dominant carbon and oxygen peaks at $\log(T) \sim 5.0$ are greatly reduced or absent, while the iron peaks at $\log(T) \sim 6.0$ and ~ 7.0 are relatively unaffected.

Non-Equilibrium Ionization Balance

The differences between the CIE curves and the NEQ curves are most easily described in terms of the limiting rates, and the critical species involved. The collision strengths for permitted lines of the beryllium and lithium like ions are very large. As a consequence the resonance line emission of these ions can dominate the cooling rate. The combined factors of high cosmic abundance, and ionization potentials that match temperatures suited to excite their strong transitions, make CIII and OIV crucial ions in determining the cooling functions.

In the NEQ models the ionization balance generally lags behind the CIE case. The main reason for this is the very slow rates associated with recombination of hydrogenic and helium like ions, and in light elements in general. This effect is clearly demonstrated in figure 3.15 in which the cooling timescale for a CIE plasma of solar abundances is compared to the collisional equilibration timescale of carbon and iron ions. This equilibration timescale is approximated by:

$$\tau_{cie} = 1/(\alpha_{rec.} + S_{coll.}) \quad (3.63)$$

where $\alpha_{rec.}$ is the total recombination rate, and $S_{coll.}$ is the total collisional ionization rate. The temperature range over which the ions have a fraction greater than 1 part in 10^3 are indicated, along with the temperature of maximum ionization fraction.

A common feature of the τ_{cie} values from equation(3.63) for the two different atoms is the very long timescales that occur when the electron configuration form a closed shell electron structure. Ions such as the helium-like CV, and both the neon-like FeXVII and helium-like FeXXV have longer equilibration timescales. Nevertheless, in the case of iron above $\log(T) = 6.0$, all the ions equilibrate much more quickly, throughout their dominant temperature ranges than any cooling timescale. The long timescales associated with closed electron shells are not sufficient to change the ionization balance far from CIE. In the case of carbon

FIGURE 3.15: CIE timescales for individual ions vs CIE cooling timescale. In this figure, the cooling timescale for the solar CIE model is plotted in the dashed curve. Collisional equilibration timescales are plotted for carbon and iron ions using the solid curves. The extent of these curves represents the temperature range over which the ion fraction is greater than 1 part in 1,000 under CIE conditions. The diamond symbols mark the temperature where the ion is most abundant, except for the stripped ions, where the symbol indicates the last 1 part in 1,000 change in fraction before the ionization levels out at 1.0. The equilibration timescales for most iron ions is much more rapid than the cooling timescale, whereas the carbon ions are close to or exceed the cooling timescale. This implies that CIE is a poor approximation for these light ions, particularly the helium like CV ion.

matters are somewhat different. In particular, the long collisional ionization equilibration timescales for C V and C VI may exceed the cooling timescale. As the plasma cools, the cooling and equilibration timescales diverge even further. As a result in the overall ionization balance of carbon is governed by the slowly recombining CV ion. This may be seen in figure 3.16. This means that the CIII and IV ions will achieve their maximum ionic fractions at lower temperatures than in the CIE case, although their equilibration timescale are at least comparable to the cooling timescales. The result is that a significant ionic fraction of CV remains down to temperatures below $\log(T) = 4.5$.

Using the $\log(T) = 6.5$ solar abundance models, these effects are nicely demonstrated by comparing the carbon ionization balance calculated for the CIE, zero-field and full-field cases (see figure 3.16) In the NEQ models, the population of the strong coolant CIII ion at $\log(T) = 5.0$ can be down by a factor of 10 to 100 compared to the CIE model. Eventually, when the fraction of CIII reaches a maximum, the temperature is so low that the electrons are simply not energetic enough to excite the strong resonant lines of this species, and the strong cooling function peak is absent.

Any radiation field will retard recombination, hence the full-field models always show the highest degree of ionization at any given temperature.

The non-equilibrium ionization balance strongly affects the peak ionization temperature for some ions. In particular, the lighter ions and lower ionization species will tend to have peak ionization fractions at lower temperatures than expected with simple CIE calculations. In figure 3.17 the temperature at which a given ion reaches its peak ionization is plotted for the NEQ zero-field case vs the CIE models. There are significant differences which appear as deviations from the diagonal. We have plotted the species that are observed as absorption line species in our galactic halo (*c.f.* Savage & de Boer 1981; Savage and Massa 1987). The important C IV, and Si II, Si III and Si IV ions show large deviations from the CIE peak temperatures, while the N V and OVI species are not so strongly affected. We conclude that temperature estimates based on CIE assumptions in early works such as Savage & de Boer (1981) may be grossly in error even if the absorption line gas is simply cooling, without any other source of heating such as photoionization. The ionization balance for the zero-field and full-field cases differ as well, as shown in figure 3.16 so if thermal instabilities arise, as seems likely to be the case (see §3.6.2), then any alteration of the radiative transfer caused by 'clumping' will have an additional effect of the ionization balance and hence the observed columns densities. This is in contrast to the work of Edgar

FIGURE 3.16: Carbon Ionization Balance for CIE and NEQ cases. The three different cases of CIE, zero-field NEQ and full-field NEQ are plotted from a temperature of $\log(T) \approx 8.5$ down to 4.0. The Heavy lines represents the ionization fraction of the odd ion stages CI, CIII, CV, CVII. The dashed line (a,b,c) marks the peak emission of C III in the CIE model. The levels of C III are reduced in the NEQ models by a factor of 10 or more, due to lagging recombination of higher ions. In the full field case the fully stripped CVII is still at 1 % levels at temperatures as low as $\log(T) \approx 5.0$.

& Chevalier (1986) who assumed that thermal instabilities will not affect the column densities.

In this work we are restricting ourselves to the consideration of the cooling functions and we therefore defer detailed modeling of the ionization balance and column densities in the context of cooling flows and the halo absorption line medium to future work.

Non-Equilibrium Cooling Functions

The cooling functions are composed of the terms described in equation (3.48). The significance of these terms is best described by figure 3.18. Here we compare the cooling functions for the CIE and the NEQ zero-field solar abundance curves. The contributions have been sorted by process in the upper panels so that the Λ terms can be identified, and by element in the lower panels to show the most important species. (The lower panels show only select cooling species for clarity)

As can be seen, the cooling due to resonance lines is the overwhelmingly dominant contribution in the range $4.5 \leq \log(T) \leq 7.0$. Below this, collisional excitation of hydrogen, forbidden lines and cooling from FeII are most important. In the NEQ case the forbidden line radiation is relatively more important than in the CIE case below $\log(T) = 4.5$. Above $\log(T) = 5.7$ there is little to distinguish the CIE and NEQ models, with the resonance lines dominating until the free-free emission dominates above $\log(T) = 7.0$.

As foreshadowed in §3.6.2, the species contribution plot reflects to some extent the changes in the ionization balance between the CIE and NEQ models. The low ionization species are suppressed, in particular carbon and silicon (see also figure 3.17) and their emission is correspondingly weaker.

Using the resonance losses equation (3.23) it can be seen that the ionization balance affects the losses directly through the X_i term. The emission is further reduced however since the ions persist to lower temperatures and the $\exp[-E_{gj}/kT]$ term in equation (3.24) begins to dominate as less energetic electrons become available. The other line and continuum processes have similar terms. These effects therefore combine to greatly affect the low temperature regions of the NEQ cooling functions so that even the strong oxygen cooling peak is affected although the oxygen ions are not so affected by lagging ionization as the carbon ions as indicated in figure 3.17.

FIGURE 3.17: Halo absorption line ions. The peak ionization temperature for the ions of carbon, nitrogen, oxygen and silicon are plotted for the NEQ zero-field model as a function of the corresponding CIE peak temperature. Some of these ions are observed as absorption line species in our galactic halo (*c.f.* Savage and de Boer 1981). The carbon and silicon ions in the range II - V are strongly affected by non-equilibrium cooling effects, causing peak ionization to occur at lower temperatures.

FIGURE 3.18: Cooling function contributions. In the upper panels the contributions from the processes described in § 3.3 are shown. The resonance radiation dominates over most of the temperature range. In the non-equilibrium case, the forbidden line emission is relatively more important at low temperatures than in the CIE case where hydrogen and FeII emission dominate. The lower panels show the emission by species, selecting only the dominant species for clarity. The silicon emission does not change in the highly ionized silicon emission between the models, whereas the low ionization silicon emission is greatly affected. (see § 3.6.2)

Thermal Instabilities

Thermal instabilities are not specifically modeled in this work, but it should be noted that even in the NEQ models presented here, the isobaric thermal stability criteria of Schwartz *et al.* (1972):

$$\frac{d \ln(\Lambda_N)}{d \ln(T)} > 2 \quad (3.64)$$

is generally not satisfied above $\log(T) = 5.0$. Therefore NEQ cooling does not serve to stabilize the plasma against thermal instabilities.

Thus under both CIE and NEQ cooling thermal instabilities will give rise to clumps of cooled plasma embedded in a hot medium. The cooled gas in this case would intercept less of the diffuse ionizing radiation field than in the full-field approximation. In this sense, then, the zero-field series of NEQ cooling functions presented here may well be the most appropriate for simple calculations which imply the presence of thermally unstable cooling. As noted above, the differences in the total cooling function between the zero-field and the full-field cases is not significant, however individual ion balances may be greatly affected and therefore the presence of thermal cooling instabilities should have an effect on the observed column densities of ions such as carbon and silicon in a cooling flow.

Primordial Abundances

A comparison of the CIE and NEQ zero-field functions can be made for primordial abundances, which may be appropriate to galaxy and cluster formation simulations. In this roughly spherical situation, dilution factors due to the global geometry as well as more local instabilities should result in a low or nearly zero-field case. In figure 3.19 the CIE and NEQ zero field cooling functions are compared. The ultimate result of the non equilibrium effects is to reduce the cooling rates at the emission peaks of helium and hydrogen. It is interesting that the peaks are no broader in the NEQ model. This is due to fact that the fully stripped HII and HeIII, remain ionized longer, preventing the HI and HeII populations from building up by the time the peak emission temperature is reached. The emission on the low temperature side of the peaks is limited by the availability of electrons energetic enough to excite the resonance lines.

FIGURE 3.19: Primordial cooling functions for CIE and zero-field NEQ models. In both these models the free-free cooling dominates down to below $\log(T) = 6.5$. The upper curve (I) is the CIE model, the lower (II) represents the zero-field NEQ case. The NEQ peaks due to helium and hydrogen are reduced due to lagging ionization, and prevented from spreading to lower temperature by limiting electron energies.

3.7 Conclusions

The main conclusion that may be drawn from the calculations presented here is that the cooling of a slab of plasma depends on both the thermal history of the plasma and any geometric factors that will affect the degree of radiation coupling in the ionization balance calculations. The abundance of the elements has a strong effect in all models, but abundance levels of $[\text{Fe}/\text{H}] < 3.0$ become virtually indistinguishable from the zero metal, primordial, hydrogen and helium case.

The CIE case produced an upper limit to the cooling rates in these calculations, and so any cooling timescales derived from CIE calculation should be treated as lower limits for strictly cooling plasmas. The slow recombination rates for the inefficient coolants of the helium isoelectronic sequence result in longer cooling timescales in all the cooling NEQ models investigated here. An inverse effect should be observed in shock heated plasmas due to different ionization rates, so that low ionization species remain present in the high temperature plasma, and one would expect a high cooling rate relative to CIE rates at high temperatures in such heating models, at least over a collisional ionization timescale. This was noted in the work of Dopita *et al.* (1982) in modeling work on Herbig-Haro objects. This has not been modeled in this work, but will be part of future work on shock heating. This then represents a basic hysteresis effect in heating and cooling plasmas, ruling out any general cooling function for plasmas that are cooling and heating as a function of time. Simulations that explicitly include the thermal and ionization history of the plasma would appear to be necessary. In the cases where the local radiation field is zero, the cooling rate can become independent of the initial temperature, in the NEQ cases this is only true above $\log(T) = 6.5$.

In circumstances where thermal instabilities can be expected, less of the diffuse field from hot plasma will be intercepted by any condensed, cool, clumps. This argument suggests that a low diffuse field case may be most appropriate for many calculations. This will be closest to the NEQ zero-field models presented here, however for more accurate results the degree of geometric dilution would have to be modeled using two or three spatial dimensions in the modeling code.

Therefore, when choosing the cooling functions to use in other calculations, consideration of the degree of radiation field coupling must be taken, and if the radiation field is likely to remain low then the NEQ zero-field case may be sufficiently accurate. If the radiation field could build up to significant levels then the full-field models may provide a useful limiting case.

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Special Note

To aid computer implementation of the cooling curves presented here, data files containing the cooling data will be made available in electronic form on request to the author. This may be then transmitted over the electronic network as required. Physical mail should be addressed to the address given at the beginning of this paper, while electronic mail may be posted to: mad@merlin.anu.edu.au on the internet.

The following chapter is based on the paper:

“Shock Excitation
of the
Emission Line Filaments in Centaurus A.”

by Ralph S. Sutherland, G. V. Bicknell
and
M. A. Dopita.

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Chapter 4

The Centaurus A Filaments

4.1 Introduction

The emission line filaments of Centaurus A were discovered independently by Blanco *et al.* (1975) and Peterson *et al.* (1975) and since that time, their interpretation has presented a interesting challenge to observers and theoreticians. Graham and Price (1981) obtained spectra of a number of the filaments and showed that the filaments exhibit a large velocity dispersion - a fact which is fundamental to a correct interpretation if the theory presented in this paper contains an element of truth. All of these workers also showed that the spectra display unusually high [OIII] emission, beyond the range observed in normal HII regions and slow fully radiative shocks and this is one of the key observational characteristics which a successful theory is required to explain.

More recent and more detailed observations, in the form of narrow band imaging, and high and low dispersion spectra, of the “inner” and “outer” filaments in Centaurus A have been obtained by Morganti *et al.* These workers recovered the result of Graham and Price, that the filaments have a high velocity dispersion and to some extent, mapped this out, finding sharp changes in velocities ranging from $200 - 400 \text{ km s}^{-1}$ as well as line-splitting of the same order of magnitude in some regions. They also showed that the spectra contained a significant flux in low excitation lines such as [OI] $\lambda 6300$ and the [SII] $\lambda\lambda 6717 + 31$ in addition to the high excitation lines previously mentioned. On the basis of their data Morganti *et al.* (1991) have argued that the filaments are photoionized by an EUV-X-Ray continuum which is beamed from the galaxy core, thereby suggesting that Centaurus A is a blazar viewed at such an angle that we do not directly see the highly beamed continuum emission. Morganti *et al.* show that the beaming

in their model is not brought about by obscuration of the core by, say a dusty torus, since the obscured radiation would be reradiated in the infrared and the required infrared flux is not observed. Thus the required beaming presumably corresponds to relativistic beaming of an UV/X-Ray continuum. In a subsequent paper Morganti *et al.* (1992) show that there is an ionization gradient in the “inner filaments” and argue that the direction of the ionization gradient supports their model.

The images obtained by Morganti and co-workers of both the inner and outer filaments show that the two sets of filaments are quite different morphologically. The inner filaments are fairly linear whereas the outer filaments are laterally extended and show several interesting arc-like features. The morphological features of the outer filaments prompted simulations by Bicknell (1991) of transverse supersonic streams interacting with stationary dense material. Arc-like features strikingly similar to some of the regions in the outer filaments were reproduced in these simulations. Since interactions of a dense gas with a transonic stream seem to be implicated in at least some of the morphological features of the filaments Bicknell (1991) argued that the excitation of the filaments is also due to such an interaction. Binette *et al.* (1985) have, in the context of AGN emission, suggested that high velocity shocks could produce a sufficient flux of ionizing radiation to ionize precursor material. Bicknell(1991) adapted this idea in a model for the Centaurus A filaments which showed that autoionizing shocks are feasible on energy grounds and which also estimated the correct Balmer-line flux for the observed velocity dispersion for the most prominent knots.

Thus, there are two qualitatively quite different ideas for these filaments, and the major purpose of this paper is develop further and in detail the autoionizing shock model. However, we should also emphasize that the correct interpretation of the Centaurus A data has ramifications well beyond this particular case. First, the concept of beaming plays a significant rôle in various *Unification Schemes* and it is important to ascertain the usefulness and limits of the unified approach. Second, as Morganti *et al.* have noted, the line ratios of the filaments are typical of the line ratios in many radio galaxy extended emission line regions, possibly indicating a common excitation mechanism. Third, there are other important examples of apparent jet - emission line region interactions in radio galaxies such as Coma A (van Bruegel *et al.* 1985) and Seyfert galaxies (Whittle 1989). The physical processes may well be similar to the those occurring in Centaurus A.

The plan of this paper is as follows: In § 2 we elaborate upon the calculations presented in Bicknell (1991) and show that the production of the emission line

luminosity of the inner filaments is energetically consistent with the interaction of dense clouds with a jet whose parameters (Mach number and density ratio) are consistent with our knowledge of the parameters of jets in Fanaroff-Riley Class I radio sources. We also demonstrate that the turbulent velocities observed in the filaments are consistent with their production by the Kelvin-Helmholtz instability acting at the jet-cloud interface. Order of magnitude estimates for the luminosity of the brightest knots in the inner Centaurus A filaments are derived and consistency between the observed velocity dispersion and the $H\beta$ luminosity of the knots is demonstrated. In §§ 3 and 4 we present detailed model calculations of UV and X-ray emitting shocks using the latest, extended, version of the MAPPINGS photoionization and shock code (*c.f.* Chapters 2 & 3). In these sections we work through a succession of models ultimately presenting what we believe to be the most successful model for the emission line regions - that of the collision of two unequal density clouds with relative velocities of the order of 300 km s^{-1} . Such a collision gives rise to a fast shock and a slow shock. The former produces the flux of UV and soft X-ray radiation which photoionizes the surrounding gas producing the high excitation component of the spectrum and the latter is primarily responsible for the low excitation lines. Our best model provides good estimates for all of the optically observed lines, including the temperature-sensitive line $[\text{OIII}]\lambda 4363$ as well as making useful predictions for the fluxes of various UV lines. The UV fluxes are quite distinct from those predicted by the beaming model. The sizes of the line-emitting regions are correctly estimated.

4.2 Basic Physics and Magnitude Estimates

4.2.1 Outline of Model

In outline, our model for the emission line luminosity is as follows: Interaction of dense molecular clouds with the outflowing plasma in the radio source (velocity $\sim 1,000 - 10,000 \text{ km s}^{-1}$) produces, through the Kelvin-Helmholtz instability, a turbulent supersonic velocity field in the gas which is being ablated from the dense cloud. Clumps of supersonically moving material collide with each other and produce strong shocks which radiate a large fraction of their internal energy in a flux of UV - soft X-ray photons. These photons irradiate the precursor gas producing a high excitation photoionized spectrum. The low excitation part of the spectrum arises from shock waves in the dense gas.

This model is motivated by two important observed properties of the filaments.

First, they are located near the so-called “middle-lobe” of Centaurus A. The Morganti *et al.* outer filaments are located in the southern part of this lobe, whereas the inner filaments are located between the “middle lobe” and “inner lobe” along the direction of the inner northern jet. The unpublished radio images which form the basis of these comments (Burns, 1991) are of low dynamic range and there is no jet visible at the location of the inner filaments. However, the second major property of the filaments, their high internal velocity dispersion ($\gtrsim 200 \text{ km s}^{-1}$), first remarked upon by Graham and Price (1981) and studied in detail by Morganti *et al.* (1991) and Morganti *et al.* (1992) suggests that the filaments are interacting strongly with rapidly moving plasma. An additional feature of the more recent data is the line splitting $\sim 200 - 400 \text{ km s}^{-1}$ in some regions.

In any case, the existence of a jet at the location of the inner filaments is an important qualitative prediction of this model. Furthermore, the different locations of the inner and outer filaments (with respect to lobe and jet) qualitatively explains their different morphology: Clouds interacting with a supersonic/transonic collimated jet will be more elongated by the flow than clouds interacting with the flow in a subsonic lobe.

4.2.2 The Energy Budget

In this subsection we consider the energy budget of our model and show that the energy flux incident upon the filaments is capable of powering the emission lines.

Here and in the following sections we concentrate on the inner filaments since it is for those that the highest quality data are available.

It is generally accepted that the velocities of non-thermal plasma in class I extragalactic radio sources such as Centaurus A are at most mildly supersonic (*i.e.* Bicknell 1990). It is also reasonable to assume that regions such as the inner lobes contain material which is still in motion at approximately transonic speeds (*c.f.* the simulations of Norman *et al.* (1988)). Thus the jet energy flux intercepted by the each of the knots in the inner filaments is:

$$\begin{aligned}
 F_E &= \frac{\gamma}{\gamma - 1} P_{\text{jet}} A_{\text{knot}} v_{\text{jet}} \left(1 + \frac{\gamma - 1}{2} M_{\text{jet}}^2 \right) \\
 &= 1.0 \times 10^{37} \frac{\gamma_{\text{jet}}^{3/2}}{\gamma_{\text{jet}} - 1} \eta^{-1/2} \left(\frac{n_{\text{ism}}}{10^{-3}} \right) \left(\frac{T_{\text{ism}}}{10^7} \right)^{3/2} \eta^{-1/2} \left(\frac{A}{10^4 \text{ pc}^2} \right) \\
 &\quad M_{\text{jet}} \left(1 + \frac{\gamma_{\text{jet}} - 1}{2} M_{\text{jet}}^2 \right) \text{ ergs s}^{-1}
 \end{aligned} \tag{4.1}$$

where M_{jet} is the jet Mach number and η is the ratio of the lobe density to the

density of the hot interstellar medium. (See, for example, Bicknell (1986) for the source of expressions for the jet energy flux.) Some of the fiducial parameters in the above expression are obtained from Burns, Feigelson and Schreier (1983) who estimate a number density $n_{\text{ism}} \approx 3 \times 10^{-3} \text{ cm}^{-3}$ in the region $3' < r < 6'$ from the galaxy center. Using their density profile $n(r) \propto r^{-1.8}$, and assuming that the gas density is $\approx 3 \times 10^{-3}$ at $r = 4.5'$ implies that the gas density at the radius of the inner filaments is $\sim 10^{-3} \text{ cm}^{-3}$. Fabian *et al.* (1986) estimate $T_{\text{ism}} \approx 1.4 \times 10^7 \text{ K}$ using a derived temperature-luminosity relation for elliptical galaxies. The [OIII] images of Morganti *et al.* (1991) show that the projected cross-sections of the clouds are $\approx 4 \times 10^4 \text{ pc}^2$. If the jet is not substantially mixed with the ISM then, most likely $\gamma \approx 4/3$ and $\eta < 1$. If substantial mixing has occurred, then $\gamma \approx 5/3$ and $\eta \approx 1$.

With our proposed mechanism virtually all of the incident energy flux is dissipated by the shocks produced by cloud-cloud collisions. As we show below most of the post-shock internal energy is radiated and for optical depths $\gtrsim 1$ most of the above energy flux is reradiated in line emission. For a normally photoionized HII region the total line flux is about 50 times the $H\beta$ flux. In the photoionization scenario we are discussing here, this factor may exceed 100 (see following section). Since the $H\beta$ flux is approximately $\sim 10^{37} \text{ ergs s}^{-1}$ for each of the bright knots A, B and C, approximately $10^{39} \text{ ergs s}^{-1}$ of incident energy are required. In table 4.1 we show the incident energy fluxes calculated for a plausible range jet parameters and for $n_{\text{ism}} = 10^{-3} \text{ cm}^{-3}$ and $A_{\text{knot}} = 4 \times 10^4 \text{ pc}^2$. (The energy flux scales directly with these parameters.)

One can see from this table that the energy requirements are met by quite reasonable jet parameters, generally Mach numbers in the range of 1 – 2 and density ratios in the range of 0.1 – 1.0. The energy requirements are slightly easier to meet when $T_{\text{ism}} > 10^7$. However, we regard the fact that we can easily get to within an order of magnitude of the required value to be a compelling argument in favor of the basic model. The velocities implied by these jet parameters are also given in table 4.1. The velocities most consistent with the energy budget are in the range of 2,000 – 10,000 km s^{-1} and are in accordance with what we normally expect for jet velocities in class I sources.

TABLE 4.1: JET VELOCITIES AND ENERGY BUDGET

γ	$T_{\text{ism}}/10^7 K$	$\mathcal{M}$	η	V_{jet} (10^3 km s^{-1})	F_E ($10^{38} \text{ ergs s}^{-1}$)
5/3	1.0	1.0	1.0	0.5	1.7
5/3	1.0	2.0	1.0	1.0	3.4
4/3	1.0	1.0	0.1	4.3	6.8
4/3	1.0	1.5	0.1	6.5	10.2
4/3	1.0	2.0	0.1	8.6	13.6
4/3	1.0	2.0	0.2	4.3	9.6
4/3	1.0	2.0	0.5	1.7	6.1
5/3	2.0	1.0	1.0	0.7	4.9
5/3	2.0	2.0	1.0	1.4	9.7
4/3	2.0	1.0	0.1	6.1	19.3
4/3	2.0	1.5	0.1	9.2	28.9
4/3	2.0	2.0	0.1	12.2	38.6
4/3	2.0	2.0	0.2	6.1	27.3
4/3	2.0	2.0	0.5	2.4	17.2
5/3	3.0	1.0	1.0	0.8	8.9
5/3	3.0	2.0	1.0	1.7	17.9
4/3	3.0	1.0	0.1	7.5	35.4
4/3	3.0	1.5	0.1	11.2	53.1
4/3	3.0	2.0	0.1	15.0	70.8
4/3	3.0	2.0	0.2	7.5	50.1
4/3	3.0	2.0	0.5	3.0	31.7

4.2.3 Development of a Supersonic Turbulent Region

Magnitude of the Induced Velocity

As we stated above, we suggest that the Kelvin-Helmholtz instability is most likely involved in the production of supersonic turbulence within the dense cloud. The contour maps of the [OIII] images support this idea. The morphology they reveal (which are not dominated by the brightest regions of emission as are the grayscale images), is reminiscent of the late stages of development of the Kelvin-Helmholtz instability (see for example Bicknell *et al.* 1990). It is therefore of interest to examine the relationship between the Kelvin-Helmholtz instability, the range of jet parameters which are required by the energy budget and the velocities which are induced in the dense gas through the action of this instability. Since the jet flow envisaged is not highly supersonic, we are justified, for order of magnitude purposes, in using growth rates derived from the incompressible Kelvin-Helmholtz instability (Chandrasekhar, 1961, p481 ff). The growth rate estimated here is faster than the compressible growth rate but the values used are indicative.

For a perturbation $\propto \exp i\omega t$, ω is given by

$$\omega = k_x V_{\text{jet}} \left(-\frac{\eta_{\text{jc}}}{1 + \eta_{\text{jc}}} \pm i \frac{\eta_{\text{jc}}^{1/2}}{1 + \eta_{\text{jc}}} \right) \quad (4.2)$$

where k_x is the x -component of the wavenumber, η_{jc} is the ratio of the jet density to the cloud density (as distinct from the ratio of the jet density to the hot ISM density used above). The velocity induced at the surface of the dense material by the instability is $w = \omega \delta z_s$ where δz_s is the deformation of the surface. The other components of velocity add another factor of $\sqrt{2}$ so that the amplitude of the total perturbation to the surface velocity is

$$\delta v = 2\pi \sqrt{2} \frac{\eta_{\text{jc}}^{1/2}}{1 + \eta_{\text{jc}}} \frac{\delta z_s}{\lambda} V_{\text{jet}} \quad (4.3)$$

$$\approx 890 \text{ km s}^{-1} \left(\frac{\eta_{\text{jc}}}{10^{-4}} \right)^{1/2} \frac{|\delta z_s|}{\lambda} \left(\frac{V_{\text{jet}}}{10^4 \text{ km s}^{-1}} \right) \quad (4.4)$$

where λ is the wavelength of the perturbation. Extrapolating this relation to large amplitudes shows that when the instability saturates (when $|\delta z_s| \approx \lambda/2$) the amplitude of the velocity perturbation induced in the dense layer is:

$$\delta v \approx 450 \text{ km s}^{-1} (\eta_{\text{jc}}/10^{-4})^{1/2} (V_{\text{jet}}/10^4 \text{ km s}^{-1}) \quad (4.5)$$

If the value of the ratio of jet density to hot ISM density (η) is of the order of unity and the density of the dense cloud is $\sim 10 \text{ cm}^{-3}$ (see § 4.4) then η_{jc} is

$\sim 10^{-4}$, giving an induced velocity amplitude of order 450 km s^{-1} . If $\eta \sim 0.1$ then $\Delta v \sim 140 \text{ km s}^{-1}$. Thus when the instability develops (on the order of a few growth timescales) regions of the interface collide with a relative velocity $\sim 2\delta v$ and these numerical estimates of δv are consistent with the observed changes of velocity in the knot region of order $200 - 400 \text{ km s}^{-1}$ (Morganti *et al.* 1991).

The Instability Timescale and the Cloud Destruction Timescale

The timescale for growth of the instability implied by equation (4.2) is

$$t_g \approx 3.1 \times 10^5 \text{ yr} \left(\frac{\lambda}{200 \text{ pc}} \right) \left(\frac{V_{\text{jet}}}{10^4 \text{ km s}^{-1}} \right)^{-1} \left(\frac{\eta_{\text{jc}}}{10^{-4}} \right)^{-1/2} \quad (4.6)$$

where the fiducial value of λ is given by the actual sizes of the knots. This timescale determines the time over which the velocity perturbations will grow to saturation and develop into shocks. The clouds are destroyed by the shocks on a destruction timescale $t_d \approx \lambda V_{\text{sh}}^{-1} \approx \lambda (\Delta v)^{-1}$ which is almost identical to the growth time scale. Unless these time scales are an appreciable fraction of the radio source age their appearance is transitory and unlikely to be observed. Now Centaurus A *in toto* is an extremely large source and likely to be quite old. However, the structure of the inner regions of Cen A is quite likely due to a more recent outburst. A rudimentary indication of the relevant timescale for the outburst may be derived from the spectral index variations in the inner northern lobe (Clarke *et al.* 1992). These indicate ages for the plasma in that lobe of the order of a few $\times 10^6 \text{ yr}$. For the above instability timescale to be of order this age one requires jet velocities to be lower than our fiducial value of 10^4 km s^{-1} and/or a value of η_{jc} say $\sim 10^{-5}$. In this way growth and destruction timescales of the order of the estimated age of the inner VLA source can be comfortably achieved and are also consistent with the energy budget.

Of necessity these estimates are only approximate but they do achieve a measure of consistency with several aspects of the source dynamics. In essence the physical picture is of the development over $\gtrsim 10^6 \text{ yr}$ of supersonic turbulent velocities $\sim 200 \text{ km s}^{-1}$ through interaction of a dense ($n \sim 10 \text{ cm}^{-3}$) cloud with a moderate speed ($V \sim 5,000 \text{ km s}^{-1}$) jet. It will be interesting to perform simulations of this envisaged situation. This should confirm some of the physics outlined here and provide more robust estimates of the relevant timescales and velocities.

4.2.4 The $H\beta$ Luminosity

Equal density clouds

The flow of energy, from kinetic energy of the dense gas to thermal energy in the shocked gas to ionizing radiation to Balmer emission is relatively straightforward so that order of magnitude estimates for the Balmer line intensities are readily derived.

In order to estimate the $H\beta$ luminosity, we consider the collision of two equal density clouds with number density $n \sim 1\text{cm}^{-3}$ (Morganti *et al.* 1991) and relative velocity $\Delta v \sim 200\text{km s}^{-1}$. This is most easily contemplated in the frame in which both clouds have a velocity $0.5\Delta v$ towards each other. In this frame the end result of the collision is two shock waves traveling with approximately equal velocities into the unshocked plasma. Ideally one could imagine the shocks propagating initially with a speed $2/3 \times \Delta v$ with respect to the unshocked material and then decelerating as cooling becomes more important and the shocks lose pressure support. However, the actual situation is more complex. Innes, Giddings and Falle (1987a,b) and Innes (1992) have shown that if one makes the restriction to one dimension, the shock takes on a pulsating character due to alternating post-shock cooling and restoration of pressure support behind the shock. In more than one dimension however, transverse collapse of the thermally unstable post-shock plasma is also likely to be important. Therefore, the end result of such a shock is likely to be some variation in shock velocity (of which the Innes *et al.* and Innes calculations represent an extreme case) accompanied by the formation of numerous filaments and condensations of dense material in the vicinity of the shock. These instabilities all take place on a cooling time scale which (as is shown below) is quite short in the post-shock plasma. This structure is pertinent when we consider detailed emission line modeling in the following sections. For order of magnitude purposes, in this section, we therefore assume that the shock velocity is approximately $0.5\Delta v$

The temperature behind the shocks produced by the collision is

$$\begin{aligned} T_{\text{sh}} &\approx \frac{3}{64} \frac{\mu m_p}{k} (\Delta v)^2 \\ &= 1.3 \times 10^5 \left(\frac{\Delta v}{200 \text{ km s}^{-1}} \right)^2 \end{aligned} \quad (4.7)$$

and for $\Delta v \sim 300 - 400\text{km s}^{-1}$ a flux of UV-soft X-ray radiation is produced. Gas yet to enter the shock is photoionized and the following calculation for an optically thick photoionized region establishes order of magnitude estimates for the emerging $H\beta$ flux as well as scaling relationships for its dependence upon Δv .

The cooling time of the plasma, $t_{\text{cool}} = 3 k T n_{\text{sh}}^{-1} \Lambda^{-1} \approx 4.2 \times 10^{12} T_6 \Lambda_{-22}^{-1} n_{\text{sh}}^{-1}$ where $\Lambda \sim 10^{-22} \text{ ergs cm}^{-6} \text{ s}^{-1}$ is the usual cooling function. The shocked plasma will expand sideways at approximately the post shock sound speed giving a cooling length $l_{\text{cool}} \approx c_s \times t_{\text{cool}} \approx 20 T_6^{3/2} \Lambda_{-22}^{-1} n_{\text{sh}}^{-1} \text{ pc}$. This is considerably less than the dimensions of the knots so that we are justified in assuming that all of the post-shock internal energy is radiated as EUV - soft X-ray radiation with a luminosity,

$$\begin{aligned} L &= \frac{9}{128} n_0 m_p (\Delta v)^3 A_{\text{sh}} \\ &= n_{\text{e,sh}} n_{\text{p,sh}} V_{\text{sh}} \int_0^\infty \Lambda_\nu d\nu \end{aligned} \quad (4.8)$$

where n_0 is the number density of the unshocked (precursor) region and the subscript sh refers to the shocked region. The monochromatic emissivity of the plasma is represented in the usual way as $n_e n_p \Lambda_\nu(T)$. The number of ionizing photons per second emitted by the shocked material,

$$\mathcal{N} = n_{\text{e,sh}} n_{\text{p,sh}} V_{\text{sh}} \int_{\nu_0}^\infty \frac{\Lambda_\nu}{h\nu} d\nu \quad (4.9)$$

Combining, equations (4.8) and (4.9),

$$\mathcal{N} = \frac{9}{128 h \nu_0} f n_0 m_p (\Delta v)^3 A_{\text{sh}} \quad (4.10)$$

where the dimensionless parameter,

$$f = \frac{\int_{\nu_0}^\infty (\nu_0/\nu) \Lambda_\nu d\nu}{\int_0^\infty \Lambda_\nu d\nu} \quad (4.11)$$

The parameter f depends upon the details of the cooling in the post-shock plasma. If one assumes equilibrium cooling (as in Bicknell 1991), the Raymond-Smith (1977) code can be used to give $f \approx 0.3$ over the range of interest. However, the post-shock cooling is a non-equilibrium cooling process, where highly ionized species persist longer than in the equilibrium case to give more efficient UV radiation production. The highly ionized species of carbon and oxygen in particular give an enhanced percentage of UV emission in the cooling process as described in Sutherland and Dopita (1992). In the shock models of the following section a value of $f \approx 0.8$ was achieved.

Standard case B recombination theory (*c.f.* Osterbrock 1989, Chapter 4) then implies

$$\begin{aligned} L_{H\beta} &= \frac{9}{128} f \left(\frac{\alpha_{H\beta}}{\alpha_B} \right) \left(\frac{h\nu_{H\beta}}{h\nu_0} \right) \left(\frac{\Delta\Omega}{4\pi} \right) n_0 m_p (\Delta v)^3 A_{\text{sh}} \\ &= 1.5 \times 10^{36} \text{ ergs s}^{-1} f n_0 \left(\frac{\Delta v}{200 \text{ km s}^{-1}} \right)^3 \left(\frac{A_{\text{sh}}}{10^4 \text{ pc}^2} \right) \end{aligned} \quad (4.12)$$

This luminosity has a strong dependence upon Δv . However, $\Delta v = 300 \text{ km s}^{-1}$, $f \approx 0.8$, $n_0 \sim 1$ and $A \approx 4 \times 10^4 \text{ pc}^2$ gives a value of $L_{H\beta} \approx 2 \times 10^{37} \text{ ergs s}^{-1}$. *This luminosity is consistent within a factor of 2 of the luminosities of knots A, B and C as determined by Morganti et al. .* Moreover, the required velocity is within the observed range over a large part of the knot region.

The above calculation implicitly assumes an optically thick pure hydrogen plasma. Naturally, the emission line luminosity is smaller if the region is optically thin (as we argue in the following section that it is). However, if the optical depth is not too small, equation (4.12) is still a reasonable order of magnitude approximation. The presence of other ions in the photoionized plasma has a more important effect especially when the ionizing radiation hardens with increasing shock velocity. The fraction of the total field absorbed by the hydrogen cross-section is reduced in comparison to other ions which then become more important in the ionization-recombination balance. This has the effect of diminishing the efficiency of $H\beta$ production and the power of Δv in the above equation is reduced. At the same time the *bolometric* luminosity should maintain an approximate $(\Delta v)^3$ dependence as the input energy emerges in other lines.

In detail, the emission from a given line from a complex species such a oxygen is complicated by the ionization balance. The HeII ion, with it's larger energy range cross-section, is more sensitive to the energies of the radiation produced in the $\sim 200 - 400 \text{ km s}^{-1}$ range, without complex ionization balance effects. The HeII λ 4686 line should therefore display a better $(\Delta v)^3$ dependence than other visible emission lines. To test this, a set of simple single shock models with self-consistent preionization and optically thick equilibrium precursor zones were computed for velocities of 150 to 500 km s^{-1} . The power-law velocity dependence of some for some relevant optical lines was determined. The $H\beta$ line varied as $v^{2.45}$, while the HeII λ 4686 displayed a $v^{3.5}$ dependence over this range of velocities. Other lines showed similar behavior: [OIII] λ 5007 $\propto v^{4.1}$, [NII] λ 6584 $\propto v^{3.0}$ and [OII] λ λ 7320+30 $\propto v^{3.2}$. The total luminosity showed the expected v^3 dependence. The deviations from the v^3 relation for individual lines reflects both the changing excitation due to variations in the ionizing spectral shape, and simple ionization balance effects. In practice, these luminosities follow curves on a log-log plot and the power-laws quoted here are generally overestimates at both the highest and lowest velocities.

When the model line ratios are presened in §4.4 the actual $H\beta$ luminosity for each model is also given. The variations in model structures, such as optical depth and other radiative transfer effects discussed later, result in further devia-

tions from the power-laws given above. For the time being we note that despite its shortcomings equation (4.12) is a useful indicative estimate of the $H\beta$ luminosity to be expected from a given shock velocity and the following discussion uses the approximate $(\Delta v)^3$ relationship for simplicity. The errors resulting from the various effects can be generally compensated for by small variations in the velocities to achieve the desired luminosity.

In anycase, the substantial increase in emission line luminosity with higher velocities is consistent with the Morganti *et al.* observations (1991; 1992) and is a characteristic of these types of shock induced ionization models. The striking fact about the above calculation is that it gives the correct order of magnitude of the emission line luminosity relying upon essentially simple physics and observational data.

Unequal density clouds

As we shall show in the development of this model it is attractive to consider the collision of unequal density clouds. How can these arise in from the surface instability of the interface between the jet and the cloud? One way may simply be to appeal to density variations induced by the hydrodynamic development of the surface instability. Another way which may be more attractive, is for parts of the surface of the cloud to be heated by the radiation in the shocks to $\sim 10^4 K$. These regions of the surface expand to form low density clouds and these collide with the denser parts of the interface. Expansion of gas takes place at a velocity $v_{\text{exp}} = [2/(\gamma - 1)]^{1/2} c_s \approx 26 \text{ km s}^{-1} (T/10^4 K)^{1/2}$ and the time to expand a distance D is given by $t_{\text{exp}} \approx 3.7 \times 10^6 \text{ yr } (D/100 \text{ pc}) (T/10^4)^{-1/2}$. As we show in in § 4.4 the size of the low density region is possibly less than 100 pc so that this expansion time scale is close to the growth timescale for the instability. Thus the formation of diffuse high velocity clouds in close proximity to a denser region is quite plausible.

If the colliding clouds are of unequal density, the reflected shocks produced by their collision are of unequal velocities. Following the adiabatic treatment of Landau and Lifshitz (1987) the collision of two clouds produces a contact discontinuity on either side of which there are regions of unequal density but equal pressure. (In the nonadiabatic case considered in §§ 4.3 and 4.4, this internal region is divided into further zones. However, the general principle discussed here remains the same.) The velocities of the reflected shocks are $v_{\text{sh}} = ((\gamma + 1)p_{\text{sh}}/\rho_{\text{ext}})^{1/2}$ where p_{sh} is the pressure in the shocked region and ρ_{ext} is the density of gas external to each shock. Clearly then, a density ratio of 10 leads to a shock velocity ratio

~ 3 . Thus a shock proceeding at $\sim 200 \text{ km s}^{-1}$ into the less dense gas would be accompanied by a shock traveling at $\sim 60 \text{ km s}^{-1}$ in the opposite direction. In this case it is only the fast shock which produces the ionizing radiation which is therefore reduced by a factor of 2. In order to produce the same $H\beta$ luminosity, the product of $n_0 (\Delta v)^3$ needs to be increased by approximately a factor of 2 and is therefore not a cause for great concern. Thus within the constraints implied by the data a single autoionizing shock is adequate. Note that in this case, there are equally important contributions to the $H\beta$ flux from both the low and high density region.

Recently, van Gorkom (1992) has discovered HI gas in the vicinity of the outer filaments with a surface density $\approx 5 \times 10^{20} \text{ atoms cm}^{-2}$. This generally supports the notion that the filaments are in fact due to the interaction of dense gas with the radio plasma.

4.2.5 Estimate of the Ionization Parameter

As mentioned earlier, the high excitation of the filaments, as indicated by the value of $O[\text{III}]/H\beta \sim 10$ is an important feature of the observations. The main parameter which determines $O[\text{III}]/H\beta$ is the ionization parameter

$$Q = \frac{(\text{No. of ionizing photons}) \text{ cm}^{-2} \text{ s}^{-1}}{\text{Atomic Number Density}} \quad (4.13)$$

The physical meaning of Q is that it represents the velocity of an ionization front produced by the field. The contribution to the ionization parameter per fast shock is given by

$$Q_0 = \frac{\mathcal{N}}{n_{\text{ph}} A_{\text{sh}}} \quad (4.14)$$

$$\begin{aligned} &= \frac{9}{256} (h\nu_0)^{-1} f m_p \frac{n_0}{n_{\text{ph}}} (\Delta v)^3 \\ &= 2.8 \times 10^6 \text{ cm s}^{-1} f \frac{n_0}{n_{\text{ph}}} \left(\frac{\Delta v}{100 \text{ km s}^{-1}} \right)^3 \end{aligned} \quad (4.15)$$

where n_0 is the density in the diffuse region and n_{ph} is the density in the photoionized region (which may or may not be equal to n_0). For equal (or nearly equal density) shocks the total ionization parameter $Q = 2Q_0$; for shocks of greatly differing density $Q \approx Q_0$. Generally, a value of $Q \sim 10^8 \text{ cm s}^{-1}$ is required to give a value of $O[\text{III}]/H\beta \sim 10$. It can readily be seen from this expression for Q_0 that, in the equal density case with $f \approx 0.8$, $\Delta v \approx 300 \text{ km s}^{-1}$ and $n_0 = n_{\text{ph}}$

that Q is indeed of this magnitude. A slight increase in Δv in the unequal density case achieves the same result in the diffuse region. Furthermore, when the photoionized region is, say, an order of magnitude more dense than the diffuse high velocity region, then the ionization parameter has a more moderate value and the corresponding emission is of lower excitation.

4.3 Parameters and Structure of the Emission Line Models

4.3.1 Preamble

In order to justify our ideas for the excitation of these filaments it is necessary to calculate spectra and to show that these are at least approximately consistent with the observations. There are four major features of the observations that we need to address:

1. The $H\beta$ luminosity. (This has been addressed in an order of magnitude manner in the previous section. However, it is incumbent upon detailed models to reproduce this.)
2. The linear dimensions of the prominent knots of emission.
3. The high $[\text{OIII}]/H\beta$ ratio observed throughout the filaments. It is well known that this is inconsistent with other modes of excitation, *i.e.* slow radiative shocks or excitation by massive O or OB stars.
4. The relatively high fluxes in a number of low excitation lines such as $[\text{OI}]\lambda 6300$ and $[\text{SII}]\lambda\lambda 6716 + 31$
5. The temperature sensitive ratio, $I_{4363} / (I_{5007} + I_{4959})$

The observed spectra (Morganti *et al.* 1991) of the brightest knots from the inner filaments are summarized here in table 4.2. This table gives the mean intensities and indicates the ranges over which they vary for the observed optical lines. The data are derived from the published spectra by taking the most complete spectra from the bright knots A, B & C. These spectra are the only ones with reasonably reliable $[\text{OIII}]\lambda 4363$ fluxes.

Before embarking on a description of the results of our modeling, we describe in this section, the basic structure of the models and the parameters which we employ. The model results are described in the following section.

TABLE 4.2: OBSERVED LINE RATIOS
 $H\beta = 1.0$

		Slit 1 ^a .			Slit 2 ^b .		
Transition		Max	Avge	Min	Max	Avge	Min
[SII]	$\lambda 6717 + 31$	2.490	1.968	1.110	1.820	1.470	1.100
[NII]	$\lambda 6584$	2.680	1.905	1.300	1.900	1.548	1.160
H α	$\lambda 6563$	4.920	4.348	3.950	3.900	3.777	3.640
[OI]	$\lambda 6300$	1.430	0.977	0.630	1.170	0.815	0.510
[OIII]	$\lambda 5007$	9.010	7.780	6.100	11.490	10.523	8.600
HeII	$\lambda 4686$	0.320	0.267	0.210	0.400	0.353	0.280
[OIII]	$\lambda 4363$	0.190	0.150	0.110	0.200	0.140	0.050
[NeIII]	$\lambda 3868$	1.520	1.185	1.010	1.660	1.410	1.210
[OII]	$\lambda\lambda 3727$	7.700	6.312	5.610	6.430	5.102	3.980
Ratios							
	$I_{6725} / H\alpha$	0.560	0.450	0.281	0.474	0.389	0.296
	$I_{6584} / H\alpha$	0.615	0.437	0.329	0.501	0.409	0.305
	$I_{6300} / H\alpha$	0.291	0.222	0.159	0.305	0.215	0.137
	$I_{4363} / (I_{5007} + I_{4959})$	0.017	0.013	0.010	0.013	0.008	0.004
	I_{5007} / I_{3727}	1.463	1.239	1.000	2.721	1.736	1.337

^a. Slit position towards the center of the knots.

^b. Slit position on edge towards radio jet and nucleus.

Based on the arguments of the previous section, we discuss a logical sequence of models of increasing complexity, each of which has its own appealing features. We believe that the physical situation envisaged in the third model is probably the most realistic for reasons we describe below. Our model sequence is as follows:

1. The collision of two equal density clouds with either optically thick or thin precursors.
2. The collision of two unequal density clouds with an optically thin precursor on the low density side. This is modeled using infinite plane parallel geometry.
3. The collision of two unequal density clouds, as above, with allowance for interface instabilities.

(The term “precursor” refers to gas which has not entered the shock.s)

4.3.2 Models

Densities and Velocities

We consider a number of different models involving collisions between clouds of different density ratios (1:1 and 10:1) and with a range of velocities of the primary shock from 150 to 450 km s⁻¹. As pointed out earlier the velocity field throughout the filaments is highly turbulent with spatially rapid changes in velocity of the order of 150 – 400 km s⁻¹ and this range of shock velocities effectively brackets the observations.

Using simple recombination (Case B) theory and assuming a volume implied by the knots having a similar depth to their observed breadth the observed luminosity of $\sim 10^{37}$ ergs s⁻¹ over a (200pc)³ volume requires a hydrogen number density of order unity. Accordingly we use a fiducial value of $n_1 = 1.0\text{cm}^{-3}$.

Figure 4.1 illustrates our generic collision model. The double shock structure in the middle produces UV and X-ray radiation from at least one of the shocks and this photoionizes the two clouds. The resulting spectrum in our model, is composed of a contribution from the hot shocked material and the cooler photoionized plasma zones.

In all of the models discussed here we use an infinite plane parallel approximation with some modifications to be discussed later.

FIGURE 4.1: The Generic cloud-cloud collision model structure. In the collision, a double shock structure forms in the middle, with shocks travelling out from the central contact discontinuity.

TABLE 4.3: ABUNDANCES
LOG NUMBERS RELATIVE TO H = 0.00

H	0.00	C	-3.44	Ne	-3.91	Si	-4.45	Ca	-6.64
He	-1.01	N	-3.95	Mg	-4.42	S	-4.79	Fe	-6.33
		O	-3.07	Al	-5.53	Ar	-5.44	Ni	-7.75

Abundances

In the absence of contrary evidence we assume solar abundance levels for all of the models. Solar abundances are used (Anders and Grevesse 1989) . The elements included in these calculations and the abundances levels are given in table A.4

In addition to the normal abundance ratios, the heavy elements Ca, Fe and Ni were depleted by factors of 10-100 in order to prevent emission from these species from becoming too strong. In particular the newly implemented FeII ion calculations in MAPPINGS II, which involve some 357 UV/optical and IR transitions in a 14 term atom model, predict stronger [FeII] emission than observed unless the iron levels are reduced by a factor of 100 or so. We don't draw any strong conclusions based on these depletions, except to say that they could be consistent with the presence of local dust in the filaments, if the observed steep $H\alpha : H\beta$ ratio of 3.5 - 4.5 is due to local reddening. There then remains the question of whether actual depletion by grain adsorption has occurred but we do not address this problem.

Cross-checks show that the depletions have negligible effect on other lines in the final spectra.

Allowance for Instabilities

As we outlined in the previous section, shocks with the velocities which appear to be relevant here are subject to various instabilities whose investigation has only begun in the previously cited papers by Innes and colleagues. Since we do not have a three dimensional radiation hydrodynamics code we need to make a number of approximations. In order to appreciate the nature of these approximations it is best to describe the perfect plane parallel case first following which we describe our modifications.

The cooling instabilities discussed by Innes (1992) and Innes *et al.* (1987a,b), in their one dimensional investigations, produced regions subject to pulsations initiated by the cooling of post-shock plasma. In our view, cooling of the post-shock

gas will, in higher dimensions, lead to clumping and geometrical effects will reduce the amount of photoionizing radiation absorbed in the cooling stream (see figure 4.2). In reality, determining the degree to which the radiative transfer is affected is a function of the hydrodynamic evolution of the flow. In order to approximate the process within the framework of our 1 dimensional treatment we identify two limiting cases: (1) The flow remains perfectly planar and a one-dimensional treatment for the radiative transfer is adequate. (2) The flow fragments to such an extent that the covering factor of the fragments is quite small and we neglect the absorption of the downstream radiation whilst still following the cooling from this gas.

In the following sections these cases are referred to as the smooth and fragmented cases respectively.

4.3.3 Cloud–Cloud Collision Models

For the the reasons stated above we use a fiducial number density of $n_1 = 1.0\text{cm}^{-3}$ for the precursor region. As can be seen from equation 4.15, in the previous section, the ionization parameter does not depend on density since the energy flux that passes through the shock front is proportional to the density.

Referring to figure 4.3 and table 4.4 a perfect plane parallel collision between two variable density clouds has the following structure.

For the equal density case, we have zones **A** and **B** only, in a mirror symmetric configuration (case 1 in figure 4.3). The radiation from each shock contributes to both the precursor zones when the central shocked region is optically thin.

The collision of two unequal density clouds is a more complex interaction (case 2 in figure 4.3). A high velocity shock forms zone **B**. This high temperature, collisionally ionized plasma emits strong UV/soft X-ray radiation both upstream of the shock and downstream. The lower density precursor material (zone **A**) is is photoionized by the radiation before it enters the shock. The downstream radiation may form another photoionized zone in the denser cloud (zone **C**). A secondary shock, with a velocity determined by the primary shock velocity and the cloud-cloud density contrast, is driven into the denser cloud producing zones **D**, **E** and **F**. The observed spectrum depends on the contributions from these various zones with their different ionization and density structures. The results section describes the detailed treatment of the zones and the assumptions that have gone into the final computed spectra.

Thermal Instabilities

FIGURE 4.2: A Schematic diagram of thermal instabilities in a 2 dimensional shocked flow. When the flow fragments, due to unstable cooling, the dense cloudlets **A**, **B**, **C** and **D** intercept only a small fraction of the downstream radition field. The amount intercepted by the clouds will produce a range of geometric dilutions of the field.

TABLE 4.4: QUALITATIVE MODEL STRUCTURE.

Zone	Temperature (K)	Length (pc)	Density (cm^{-3})	Emission Lines	Notes
A	max 16000	50-1000	$n = 1.0$ isochoric	H β $\lambda 5007$ $\lambda 1909$	The main resolved structure. Consists of photoionized low density gas that has not yet entered the main shock.
B	$1 - 3 \times 10^6$	1-10	$n = 4$ at max T isobaric	$\lambda 4363$ $\lambda \lambda 3737$ $\lambda 3426$ $\lambda 1550$ $\lambda 1240$	The hot gas which has passed through the primary shock. Source of the main ionizing radiation field.
C	max 10,000	0.5-50	$n = 10$ isochoric	$\lambda 9532$ $\lambda 5007$ $\lambda 3869$	The part of the denser cloud which is ionized by radiation from the primary shock.
D	$1 - 5 \times 10^5$	0.001	$n = 40$ at max T isobaric	$\lambda 6717$ $\lambda 6584$ $\lambda 6300$ $\lambda 4363$ $\lambda \lambda 3727$ $\lambda 1548$	The slower secondary shock wave which travels into the preionized denser cloud.
E	cold	Variable $\sim (\Delta t \times 10^6)$ cm	$n > 10^3$ isobaric with B, D and F	Infrared?	Dense gas which cools after having passed through the secondary shock. Not detectable.
F	max 8000	0.001	$n \approx 1000$ isobaric	H β $\lambda 6717$ $\lambda 6584$ $\lambda 6300$ $\lambda \lambda 3727$ $\lambda 2799$	Dense gas which absorbs the radiation field from the primary shock. Extremely bright in a pure planar model. Broken up in a 3D model.

Cloud-Cloud Collision Double Shock Structures

Schematic Thermal Structure

FIGURE 4.3: Thermal structure of the cloud-cloud collision models. Case 1 represents the case where the two clouds are of equal density and a symmetric structure forms. In case 2 the density contrast between cloud 1 and cloud 2 results in the two shocks having differing velocities and hence different emission properties. See the main text for more details.

The Modeling Code, MAPPINGS II

The modeling carried out here uses a new version of the MAPPINGS code (*c.f.* Chapter 2 and 3) which extends the previous version of MAPPINGS (Binette *et al.* 1985). MAPPINGS II includes atomic data for up to 16 atoms: H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Cl, Ar, Ca, Fe and Ni. Provision is made for all stages of ionization up to Ni XXIX. However, in the present modeling only the first ten or fifteen stages are required. Improvements in MAPPINGSII include more rigorous treatment of continuum radiation processes, collisional ionization, hydrogenic recombination and charge exchange reactions. The new code calculates over 1,600 resonance, inter-combination and forbidden transitions in the spectral range of NiXXVIII $\lambda 1.24$ down to [NII] $205\ \mu$

The increased ionization range permits the modeling of plasmas up to $\log(T) \sim 8$ compared to the $\log(T) \sim 5.5$ of the previous version of MAPPINGS, and far exceeds the old 6 ionization stage limit. This allows us to use one code in a self-consistent way to model collisionally ionized plasma produced by a high velocity shock together with the detailed interaction of the emitted radiation with the low temperature photoionization zones associated with the shock.

4.4 Results

4.4.1 Equal Density Cloud Collisions

We have computed equal density ratio cloud-collision models with the following parameters (see figure 4.3, case 1):

- Density of precursor (zone A), $n_1 = n_2 = 1\ \text{cm}^{-3}$
- $v_{\text{shock}} = 150, 200, 250\ \text{km s}^{-1}$.
- Optical depths (at $911\ \text{\AA}$) of precursor region , $\tau_H = 1$ and ∞
- Smooth and fragmented shocks.

Two distinct spectra may be formed from the models for each velocity. Both contain the contribution from the photoionized precursor zone A. Where they differ is in the post-shock zone. In the *fragmented case* the shocked flow is completely unstable, breaking up into small condensations. In this case the downstream material absorbs none of the downstream radiation field. The dense cooling material radiates a purely cooling spectrum which is not very luminous in $\text{H}\beta$ and the low

ionization species are relatively weak in emission. In the *smooth case* the shocked flow is completely stable and all of the downstream radiation is reabsorbed by the dense downstream material and the center of the shocked structure is optically thick. This produces both very strong low ionization species and reduces the ionization in the shock precursor zones since the radiation from a given shock can not reach the opposite shock front.

The results of the equal density models are summarized in tables 4.5a and 4.5b.

Table 4.5a shows the simplest case where the precursor zone A is optically thick (that is radiation bounded). This model implies that the visible knots are just a small fraction of the low density gas present in the filaments. The spectra produced by the smooth and fragmented cases of this model fail to reproduce the observed spectra. In particular the [OIII] λ 5007 line is too weak in all of the smooth models and is only strong in the high velocity fragmented case. When the [OIII] emission is strong in the fragmented model, the low ionization species are too weak (*i.e.* [OII] λ 3727). The smooth models produce stronger low ionization species emission such as the [SII] lines but fail to produce adequate flux in the high excitation lines. Thus it is not possible to simultaneously reproduce both the high and low ionization species emission with this model.

The optically thin (density bounded) precursor variants of the equal density models, given in table 4.5b, efficiently produce spectra whose high excitation component is consistent with the observations when the shock velocities are $\sim 200 \text{ km s}^{-1}$ or more, and the shocked flow is fragmented. These models imply that the visible knots constitute all of the low density gas in the filaments.

In the fragmented flow models of table 4.5b, strong [OIII], [NeIII] and He II lines are produced. The differences from the optically thick model are mainly due to the relatively weaker H β emission from the precursor zone. The smooth flow models continue to fail to produce strong [OIII] emission even with the relative increase in [OIII] emission from the optically thin precursor. This is due to the center of the shock structure becoming optically thick in this case reducing the flux of ionizing radiation into the low density zone A and enhancing the Balmer and low ionization emission.

The important temperature sensitive $I_{4363} / (I_{5007} + I_{4959})$ ratio is only in the observed range when the [OIII] emission is strong in the 200 km s^{-1} fragmented flow model. At higher velocities this ratio drops off below the observed value of $\gtrsim 0.01$ as the contribution from the cooler photoionized zone A increases, and it is too strong when [OIII] λ 5007 is weak and the contribution from the hot shocked

TABLE 4.5A: EQUAL DENSITY MODELS, PRECURSOR $\tau_H = \infty$
 $n_1 = n_2 = 1.0 \text{ cm}^{-3}$, $H\beta = 1.0$

		150 km s ⁻¹		200 km s ⁻¹		250 km s ⁻¹	
Transition		Smooth	Frag.	Smooth	Frag.	Smooth	Frag.
[SIII]	$\lambda 9532$	0.467	0.806	0.824	0.997	0.990	0.748
[SII]	$\lambda 6717+31$	1.473	0.643	1.982	0.315	2.390	0.208
[NII]	$\lambda 6584$	1.167	1.235	1.169	0.556	1.392	0.416
H α	$\lambda 6563$	3.008	2.979	2.961	2.943	2.927	2.904
[OI]	$\lambda 6300$	0.234	0.061	0.513	0.061	0.809	0.048
[OIII]	$\lambda 5007$	1.225	1.780	2.758	5.714	5.726	12.121
HeII	$\lambda 4686$	0.033	0.043	0.045	0.072	0.053	0.088
[OIII]	$\lambda 4363$	0.065	0.063	0.044	0.051	0.050	0.083
[NeIII]	$\lambda 3869$	0.135	0.146	0.203	0.320	0.333	0.626
[OII]	$\lambda \lambda 3727$	3.730	4.000	3.236	2.475	3.098	1.639
[NeV]	$\lambda 3426$	0.028	0.028	0.142	0.142	0.095	0.109
Ratios							
	$I_{6725} / H\alpha$	0.490	0.216	0.669	0.107	0.817	0.072
	$I_{6584} / H\alpha$	0.388	0.415	0.395	0.189	0.476	0.143
	$I_{6300} / H\alpha$	0.078	0.020	0.173	0.021	0.276	0.017
	$I_{4363} / (I_{5007} + I_{4959})$	0.035	0.023	0.010	0.006	0.006	0.004
	I_{5007} / I_{3727}	0.328	0.445	0.852	2.309	1.848	7.395
	H β Luminosity ^a	0.42	0.43	0.80	0.81	1.49	1.49

^a. $\times 10^{37} \text{ ergs s}^{-1} \text{ per } (100pc)^2$

TABLE 4.5B: EQUAL DENSITY MODELS, PRECURSOR $\tau_H = 1.0$.
 $n_1 = n_2 = 1.0 \text{ cm}^{-3}$, $H\beta = 1.0$

Transition		150 km s ⁻¹		200 km s ⁻¹		250 km s ⁻¹	
		Smooth	Frag.	Smooth	Frag.	Smooth	Frag.
[SIII]	$\lambda 9532$	0.336	0.681	0.582	0.734	0.798	0.339
[SII]	$\lambda 6717+31$	1.783	0.855	2.825	0.702	3.645	0.563
[NII]	$\lambda 6584$	1.011	0.908	1.282	0.593	1.781	0.460
H α	$\lambda 6563$	3.027	3.002	2.971	2.944	2.937	2.894
[OI]	$\lambda 6300$	0.320	0.125	0.728	0.114	1.222	0.097
[OIII]	$\lambda 5007$	1.500	3.309	2.122	7.531	3.462	15.379
He II	$\lambda 4686$	0.046	0.108	0.063	0.206	0.074	0.286
[OIII]	$\lambda 4363$	0.093	0.155	0.062	0.135	0.060	0.201
[NeIII]	$\lambda 3869$	0.185	0.333	0.217	0.576	0.270	0.967
[OII]	$\lambda \lambda 3727$	4.312	6.481	3.849	4.950	4.113	3.846
[NeV]	$\lambda 3426$	0.040	0.069	0.211	0.420	0.148	0.378
Ratios							
	$I_{6725} / H\alpha$	0.589	0.285	0.951	0.238	1.241	0.195
	$I_{6584} / H\alpha$	0.334	0.302	0.432	0.201	0.606	0.159
	$I_{6300} / H\alpha$	0.106	0.042	0.703	0.039	0.416	0.034
	$I_{4363} / (I_{5007} + I_{4959})$	0.040	0.031	0.053	0.012	0.011	0.009
	I_{5007} / I_{3727}	0.348	0.511	0.198	1.521	0.842	3.999
	H β Luminosity ^a	0.30	0.17	0.54	0.27	0.96	0.43

^a. $\times 10^{37} \text{ ergs s}^{-1} \text{ per } (100pc)^2$

zones become important.

Unfortunately then, for the equal density models, there is only a restricted range of velocities and precursor optical depths possible if both the high excitation [OIII] and [NeIII] lines are to be produced simultaneously with the medium excitation [OII] lines and a high value of the [OIII] $\lambda 4363$ ratio. Allowing an optically thick center to the colliding clouds increases the low ionization species at the expense of the high ionization species since the precursor ionization parameter decreases. In all cases the [OI] lines are too weak.

Thus we may summarize the equal density modeling by stating that these models are attractive in that they correctly reproduce the high excitation part of the spectrum but indicate that denser co-spatial material is required for the low excitation component. Furthermore, if the equal density cloud model is to successfully explain the majority of the emission using $\sim 200 \text{ km s}^{-1}$ models then thermal instabilities and hence fragmented flows are necessary.

The problems encountered by the equal density model are largely overcome by the unequal density collision models presented in the following subsections which combine the high radiation fluxes from faster shocks with the efficient production of medium ionization lines like [OII] $\lambda\lambda 3727$ from slower shocks produced in the denser material.

4.4.2 Unequal Density Cloud Collisions.

We have already, in the previous section, presented an argument as to how different density clouds may arise in the Centaurus A filaments. In this subsection we present models of unequal density cloud collisions with both fragmented and smooth primary shocks (see figure 4.3 and table 4.4). In the case of unequal densities, the secondary shock progresses more slowly into the dense material at $v_2 \approx v_1 (n_1/n_2)^{1/2}$ where v_1 is the speed of the fast, primary shock and n_1 and n_2 are the corresponding densities (see figure 4.3, case 2).

When we considered the equal density case above, we were able to appeal to instabilities in order to make the central regions optically thin. This is not possible here, for although the tail of the primary shock can be rendered optically thin by fragmentation, zones **E** and **F** of the secondary shocked region are always optically thick in pure plane parallel models. In either case (that is, smooth or fragmented primary shock) the downstream radiation from the primary shock is always absorbed in a very dense ($n \sim 10^3 \text{ cm}^{-3}$) isobaric zone **F**. The spectra from these two cases are very similar.

In considering the density contrast used in our models we should note the neutral hydrogen observations of van Gorkom (1992) who detected a HI column density of $\sim 5 \times 10^{20} \text{cm}^{-2}$. If the associated cloud were composed completely of HI and were as deep as it is broad, then the hydrogen number density would be approximately 1cm^{-3} . However, this column density is typical of that for neutral hydrogen with approximately a magnitude of extinction to UV radiation ($A_V \sim 1$) (c.f. Kulkarni and Heiles 1988). Therefore, it is more likely that the observed HI represents a surface layer on a more extensive molecular cloud with a density $> 1 \text{cm}^{-3}$. This layer would be dissociated by the ambient radiation field (presumably starlight and/or X-rays from the ISM). We therefore use a fiducial value of $n_2 = 10 \text{cm}^{-3}$ for the dense material in our unequal density collisions. This density is somewhat arbitrary but is large enough to produce qualitatively different spectra from the equal density case. Higher densities present modeling difficulties at present.

Obviously, such a large dense molecular cloud would be the original source of gas which is being ablated by the radio jet to form the observed filaments.

In the light of this discussion we have therefore computed unequal density ratio models which assume plane parallel homogeneous media, with the following parameters:

- Density of precursor, $n_1 = 1 \text{cm}^{-3}$
- Density of secondary cloud, $n_2 = 10 \text{cm}^{-3}$
- $v_1 = 300, 400, \text{ and } 450 \text{ km s}^{-1}$.
- Optical depth (at $911\text{\AA}$) of primary precursor region, $\tau_H = 1$
- Smooth and fragmented primary shocks.

The computed spectra are composed of a weighted combination of the spectrum from the optically thin main shock precursor (zone A), the main shock itself (zone B), and the secondary shock (zone D). Depending on whether the main shock is smooth or fragmented there is a contribution from a low ionization parameter zone in the main shock or the secondary shock tail respectively (zone F).

When calculating the emission from zone D we can make some further modeling simplifications. The recombination timescale in the unshocked dense cloud is $\sim 10^{13}/n^2 \approx 10^{11} \text{ s}$ and the cloud destruction timescale (which essentially determines the lifetime of the observed structures) for the primary shock is $\sim 10^{13} \text{ s}$. The secondary shock becomes optically thick in $\sim 10^{10} \text{ s}$. Thus any region of the

dense cloud which is promptly preionized by the primary shock is quickly cut off and any preionization of this region is completely due to the much weaker field of the secondary shock. This means that we can use an independent, self-consistent model for the secondary shock and calculate its spectral contribution independently. The spectra obtained in this way are summarized in table 4.6.

As expected from the results of the equal density models, the optically thick zone in the center of the shocked structure (zone **F**) produces very strong emission from the low ionization species such as [SII]. In these models the secondary shocks do produce the required strength of [OII] $\lambda\lambda 3727$ emission but the emission from [OIII] is too weak.

The most encouraging feature of these spectra is the apparent lack of velocity dependence of the line ratios. This is mostly due to the fact that zone **F** is in a similar density and ionization state for all velocities and is an intrinsically bright component.

In summary, these models produce fairly constant spectra which are of too low excitation. The resolution of this problem lies in accounting for the formation and possible destruction of the low excitation zone **F** and is discussed in the following subsection.

4.4.3 Unequal Density with Interface Instabilities.

In our final model refinement, we modify the model described in the previous section by relaxing the plane parallel assumption in the region of the contact discontinuity. (This is in addition to the relaxation of this assumption in the primary shock flow.) This is in an attempt to give better account for thermal/hydrodynamic processes expected to arise in this type of situation as well as to obtain a closer fit to the observed spectra.

In the pure plane parallel model, zone **F** intercepts *all* of the downstream radiation from zone **B**, regardless of the smooth or fragmented nature of **B**. If zone **A** is optically thin ($\tau_H < 1.0$) then zone **F** is the brightest optical component of the model. The extremely strong emission of [SII] $\lambda\lambda 6717 + 31$ and [NII] $\lambda 6584$ from this zone overwhelms the red part of the spectrum, and these lines may even exceed the $H\alpha$ intensity (see table 4.6).

In zone **F** we cannot appeal to thermal instabilities since the secondary shock plasma is not thermally unstable. Nevertheless, additional instabilities at the contact discontinuity can be expected. If the collision is even slightly oblique, shear instabilities will occur. We should also emphasize that in the pure plane

TABLE 4.6: UNEQUAL DENSITY MODELS, PRECURSOR $\tau_H = 1.0$
 $n_2 = 10n_1 = 10.0\text{cm}^{-3}$, $H\beta = 1.0$

		300 km s ⁻¹		400 km s ⁻¹		450 km s ⁻¹	
Transition		Smooth	Frag.	Smooth	Frag.	Smooth	Frag.
[SIII]	$\lambda 9532$	0.773	0.803	1.178	1.324	1.132	1.267
[SII]	$\lambda 6717+31$	3.337	3.403	4.163	3.600	4.002	3.335
[NII]	$\lambda 6584$	1.817	1.889	2.478	2.839	2.480	2.801
H α	$\lambda 6563$	2.961	2.962	2.931	2.929	2.930	2.930
[OI]	$\lambda 6300$	1.173	1.231	1.877	1.643	1.830	1.523
[OIII]	$\lambda 5007$	3.604	3.608	3.953	4.033	3.236	3.449
HeII	$\lambda 4686$	0.066	0.065	0.101	0.104	0.098	0.107
[OIII]	$\lambda 4363$	0.086	0.085	0.099	0.098	0.099	0.103
[NeIII]	$\lambda 3869$	0.306	0.312	0.374	0.427	0.333	0.408
[OII]	$\lambda \lambda 3727$	5.052	5.316	5.345	6.424	5.235	6.368
[NeV]	$\lambda 3426$	0.080	0.081	0.118	0.120	0.176	0.186
Ratios							
	$I_{6725} / H\alpha$	1.127	1.149	1.420	1.229	1.366	1.138
	$I_{6584} / H\alpha$	0.614	0.638	0.846	0.969	0.846	0.956
	$I_{6300} / H\alpha$	0.396	0.416	0.641	0.561	0.625	0.520
	$I_{4363} / (I_{5007} + I_{4959})$	0.018	0.017	0.018	0.018	0.023	0.022
	I_{5007} / I_{3727}	0.713	0.679	0.740	0.628	0.618	0.542
	H β Luminosity ^a	2.02	2.09	3.72	3.90	4.95	5.19
^a . $\times 10^{37}$ ergs s ⁻¹ per (100pc) ²							

parallel model zones **D**, **E** and **F** are extremely thin, of the order of 0.01% the thickness of the entire region. Thus, in the pure plane parallel approximation we have the somewhat absurd situation of a thin but extremely dense “skin” absorbing most of the radiation from the primary shock. This skin will obviously be broken up by the shear instabilities just mentioned and any turbulent velocity across the interface. Disruption of the thin layers representing zones **D**, **E** and **F** results in the diminished luminosity of **F**. The luminosity of **F** is derived from the reprocessing of the ionizing radiation field and if it breaks up then its emission line spectrum fades rapidly. This is due to both the smaller fraction of intercepted radiation and to the resulting lower temperatures. The lower temperature leads to higher densities and a shift towards lower energy, infrared fine-structure transitions as the main cooling. Line quenching at higher densities will eventually limit even these mechanisms. Zone **D** on the other hand is a shock structure and is self-luminous. It is not greatly affected by breaking up on scales greater than a cooling length, only 10^{16} cm so.

In contrast to the zone **D** calculations in table 4.6 an effect that follows from the breakup of the dense thin layers in the interface region, needs to be taken into account. The main radiation field from the primary shock flows past the secondary shock and preionizes the dense material into which the secondary shock is traveling. This results in a more highly ionized precursor zones for the secondary shocks than is produced in the simple self-consistent shock models used in the previous model. In this model we use the radiation from the primary shock to preionize the dense cloud forming zone **C** (see figure 4.3 case(2)).

This extra preionization occurs when the speed of the ionization front from the primary field exceeds the secondary shock speed, that is when the ionization parameter $Q_2 > v_2$. Using the estimate of Q from the previous section and the above estimate for v_2 shows that when:

$$\beta = n_2/n_1 \lesssim 25 \left(\frac{v_1}{200 \text{ km s}^{-1}} \right)^4$$

preionization of the dense cloud by the radiation from the main shock will occur. Our value of $\beta = 10$, together with the velocities used here, implies that preionization of **D** by the primary shock field always occur.

The final computed spectra are therefore composed of some of the components from the straight-forward unequal density models described above in § 4.4.2. We further assume that interface instabilities break up the thin layers **D**, **E** and **F** reducing the spectral component of **F** and it is removed from the integrated spectrum. There is a new contribution from zone **C** that is of moderately high

ionization, and the secondary shock zone **D** has a different preionization state. These spectra are combined to give table 4.7.

These spectra give a very satisfactory fit to the observations. The ratios do not display a particularly strong velocity dependence within the modeling range of 300 - 450 km s⁻¹. We also present the spectra as they would appear with some local reddening. Adopting a reddening constant $c = 0.5$ and employing the standard reddening function of Kaler (1976) reproduces the observed H α to H β ratio. This generally improves the spectral fit, strengthening the red [SII], [NII] and [OI] lines and not affecting the [OIII] lines significantly. The [OII] $\lambda\lambda 3727$ emission is slightly weaker than the published values of Morganti *et al.* (1991), but as this line was on the very edge of their detector these line intensities are subject to the greatest calibration uncertainties.

Any remaining weakness in [OI] $\lambda 6300$ may possibly be accounted for by zone **F** persisting to some degree as a very low ionization parameter zone. We have chosen to take a limiting case by simply removing zone **F** from the spectra, but some spectra with an arbitrarily low ionization parameter could be included to produce strong [OI] $\lambda 6300$ and very little other optical forbidden line emission.

Overall the global properties of high excitation lines such as [OIII], [NeIII] and He II are reproduced. In particular the [OIII] $I_{4363} / (I_{5007} + I_{4959})$ ratio is in the observed range. The correct modeling of this ratio has been an outstanding problem with the pure photoionization models, as emphasized by Robinson (1989) and Tadhunter *et al.* (1989). The low excitation lines arise naturally (and strongly) from high density shocked zones, without our having to invoke a wholly arbitrary density distribution *a priori*.

The Ionization Gradient.

Projection effects arise since the precursor zone is spatially resolved in the Centaurus A filaments, whereas the shocked structure remains unresolved. A given line of sight might pass through more or less of the precursor zone before reaching the shocked structure. Since the precursor is a strong contributor to the [OIII] $\lambda 5007$ radiation, an [OIII]:H β gradient could arise with the simple geometry shown in figure 4.4. In table 4.8 a number of weighings for the spatially resolved and unresolved components are given and these may be compared to the observations of Morganti *et al.* (1991) (see table 4.2) for their slit 1 and slit 2 which are near the knot centers and the edges respectively.

In the [OIII] $\lambda 5007$:H α ionization gradient map images made by Morganti *et al.*

TABLE 4.7: BEST MODELS SPECTRA.
 $n_2 = 10n_1 = 10.0\text{cm}^{-3}, H\beta = 1.0$

Transition		Raw Spectra: Velocity (km s^{-1})				Reddened Spectra: $c = 0.5$ Velocity (km s^{-1})			
		300	350	400	450	300	350	400	450
[SIII]	$\lambda 9532$	0.663	0.615	0.514	0.374	1.377	1.278	1.069	0.777
[SII]	$\lambda 6717+31$	1.324	1.539	1.935	2.296	1.994	2.318	2.916	3.460
[NII]	$\lambda 6584$	1.083	1.080	1.122	1.209	1.592	1.589	1.649	1.777
H α	$\lambda 6562$	2.962	2.931	2.922	2.915	4.342	4.295	4.283	4.272
[OI]	$\lambda 6300$	0.233	0.311	0.459	0.614	0.321	0.430	0.634	0.849
[OIII]	$\lambda 5007$	8.837	11.499	10.796	9.561	9.169	11.930	11.201	9.920
He II	$\lambda 4686$	0.170	0.248	0.290	0.270	0.170	0.248	0.290	0.270
[OIII]	$\lambda 4363$	0.178	0.226	0.243	0.247	0.154	0.195	0.210	0.213
[NeIII]	$\lambda 3869$	0.678	0.830	0.779	0.681	0.504	0.617	0.578	0.506
[OII]	$\lambda \lambda 3727$	5.889	5.718	5.490	5.101	4.178	4.057	3.895	3.620
[NeV]	$\lambda 3426$	0.156	0.198	0.279	0.434	0.101	0.128	0.181	0.281
Ratios									
	$I_{6725} / H\alpha$	0.447	0.525	0.662	0.788	0.459	0.540	0.681	0.810
	$I_{6584} / H\alpha$	0.366	0.369	0.384	0.415	0.367	0.370	0.385	0.416
	$I_{6300} / H\alpha$	0.078	0.106	0.157	0.211	0.074	0.100	0.148	0.199
	$I_{4363} / (I_{5007} + I_{4959})$	0.015	0.015	0.017	0.019	0.012	0.012	0.014	0.016
	I_{5007} / I_{3727}	1.501	2.011	1.967	1.874	2.194	2.941	2.875	2.741
	H β Luminosity ^a	1.21	1.46	1.96	2.86				

^a. $\times 10^{37} \text{ ergs s}^{-1} \text{ per } (100pc)^2$

TABLE 4.8: APPARENT IONIZATION GRADIENT.

Transition		Unresolved:Resolved		
		25:75	50:50	75:25
[SIII]	$\lambda 9532$	0.387	0.514	0.587
[SII]	$\lambda 6717+31$	1.446	1.935	2.212
[NII]	$\lambda 6584$	0.840	1.122	1.280
H α	$\lambda 6563$	2.891	2.922	2.940
[OI]	$\lambda 6300$	0.343	0.459	0.524
[OIII]	$\lambda 5007$	16.043	10.796	7.834
HeII	$\lambda 4686$	0.410	0.290	0.223
[OIII]	$\lambda 4363$	0.320	0.243	0.200
[NeIII]	$\lambda 3869$	1.027	0.779	0.638
[OII]	$\lambda \lambda 3727$	4.137	5.490	6.253
[NeV]	$\lambda 3426$	0.439	0.279	0.189

FIGURE 4.4: The formation of an apparent ionization gradient due to projection effects. [OIII] emission will be strongest when the line of sight passes through more or the precursor zone.

(1992) it should be noted that the gradients do *not* slope along the line towards the nucleus, rather, in most cases, they point to approximately $\sim 30 - 40$ degrees anti-clockwise to the beam direction in most cases, and in filament A the ionization gradient is almost perpendicular to the nuclear direction. In our model the projection does not have to lie along the line of sight to the nucleus, merely that the general plane of the collision(s) is oblique to our line of sight. In our model we predict that the denser material is generally to the south of the knots, while the jet is passing north of the knots and the general plane of interaction is sloping away from us to the north.

In our interaction model we may further expect a generally higher level of ionization in regions of higher velocity dispersion due to stronger excitation of [OIII] by the faster shocks. If a velocity distribution is set up in the cloud-jet interaction with higher velocities nearer to the interaction then a genuine ionization gradient could also arise. This is especially in the case of thin equal density cloud collisions which have a stronger [OIII] $\lambda 5007$ velocity dependence (see table 4.5b). Indeed the velocity field observations (Morganti *et al.* 1991; Evans *et al.* 1992) do show more velocity dispersion along the edges of filaments where the [OIII] radiation is strongest.

This leads us to the conclusion that the ionization gradient observation does not strongly distinguish between either the beamed nuclear radiation models or the shock, autoionization models. However our shock ionization model does predict the velocity-excitation correlation and allows a more general orientation of the ionization gradient component due to projection effects.

Predicted UV Spectra.

We present the Ultraviolet spectra predicted by the best models, described earlier, in table 4.9a. For comparison we also give UV fluxes predicted by Robinson (1992) using a *single slab* photoionization model with a similar power-law photoionizing field to the field used in the Morganti *et al.* work. (see Table 4.9b). The UV fluxes and line ratios are significantly different in the photoionizations models in comparison with the present shock models. The UV fluxes are relatively weak in the photoionization models. For most of the UV lines this is essentially a result of the lack of hot shocked plasma providing energetic thermal electrons to collisionally excite the various UV transitions. In the case of CIV $\lambda\lambda 1549$ there is an additional strong contribution from the secondary shock in our models (see table 4.4). It is possible that a more complex photoionization model involving a spectrum of cloud densities (as used by Morganti *et al.* ,

TABLE 4.9A: ULTRAVIOLET SPECTRA, BEST MODELS.
 $n_2 = 10n_1 = 10.0\text{cm}^{-3}$, $H\beta = 1.0$

Transition		Velocity (km s^{-1})			
		300	350	400	450
C I]	$\lambda 2967$	0.244	0.259	0.268	0.304
Mg II	$\lambda 2799$	0.546	0.570	0.560	0.537
[Mg V]	$\lambda 2783$	0.038	0.051	0.059	0.066
C II]	$\lambda 2326$	1.083	1.046	0.803	0.535
N II]	$\lambda 2159$	0.104	0.109	0.109	0.089
[Si IX]	$\lambda 2149$	0.068	0.104	0.095	0.073
C III]	$\lambda 1909$	2.363	2.504	2.112	1.442
[Mg VI]	$\lambda \lambda 1806$	0.170	0.164	0.146	0.127
N III]	$\lambda 1750$	0.349	0.374	0.385	0.329
O III]	$\lambda 1666$	0.642	0.722	0.783	0.795
HeII	$\lambda 1640$	1.274	1.860	2.178	2.024
C IV	$\lambda \lambda 1549$	7.027	14.780	17.168	10.436
N IV]	$\lambda 1486$	0.143	0.283	0.439	0.478
[Si VIII]	$\lambda \lambda 1443$	0.304	0.319	0.267	0.205
O IV]	$\lambda 1401$	0.969	1.453	1.983	2.404
Si IV	$\lambda \lambda 1397$	1.415	0.874	0.001	0.221
C II	$\lambda 1335$	4.539	4.323	3.090	1.606
N V	$\lambda \lambda 1240$	1.089	1.281	2.036	3.705
O V]	$\lambda 1218$	0.888	0.893	1.080	1.829

1991) may produce a similar result, however, we feel that it would be difficult for a pure photoionization model to achieve the high temperatures required, as indeed indicated by the low $I_{4363} / (I_{5007} + I_{4959})$ produced by the Morganti *et al.* models.

We conclude that observations in the spectral region between 3000 Å and Lyman α may provide a good discriminant between the beaming model and our cloud-cloud collision model.

Continuum Emission.

The observations do not show any detectable continuum emission. Our modeling is consistent with this. In figure 4.5 we present a $\lambda - F_\lambda$ plot of the combined emission from a 300 km s⁻¹ model. The continuum is obviously weak, and probably unobservable.

The continuum that does exist is dominated by the underlying free-free emission of the fast shock at shorter wavelengths. In the optical the continuum, processes in the photoionization zones make the biggest contribution below the Balmer jump at 3646 Å, but even there the continuum remains very weak compared to the line emission fluxes.

Energetics and Dimensions.

In table 4.10a and 4.10b we give the calculated best model dimensions and H β luminosities. We give ranges over which the emitting regions may vary in both size and luminosity depending on the optical depths of the photoionized zones. The conversion efficiency of the total primary shock emission to the final total H β luminosity was 173:1 in the 350 km s⁻¹ model and similar for the other models. This is quite different to the nominal ratio of 50:1 found in normal HII regions. The conversion efficiency is a complex function of the shock emission spectral energy distribution, the absorbing gas photoionization cross-sections and recombination processes. The final agreement of the H β luminosity and velocity of $\sim 300 - 450$ km s⁻¹ with the observations is a strong feature of these models. The linear dimensions are also in the observed range.

The Ionizing Radiation.

The ionizing radiation produced by these shock model is the integrated emission from plasmas of a wide range of temperature and non-equilibrium ionization

TABLE 4.9B: ULTRAVIOLET SPECTRA,
BEAMED PHOTOIONIZATION MODELS^a.

Transition		Photo 1	Photo 2
Mg II	$\lambda 2799$	2.44	2.84
C II]	$\lambda 2326$	0.76	0.82
C III]	$\lambda 1909$	0.71	1.14
O III]	$\lambda 1666$	0.04	0.08
HeII	$\lambda 1640$	1.76	1.77
C IV	$\lambda\lambda 1549$	0.09	0.49
O IV]	$\lambda 1401$	0.01	0.05
C II	$\lambda 1335$	0.04	0.04

^aRobinson, private communication (1992)

FIGURE 4.5: Optical - Near UV emission for a 300 km/s model. The continuum is very weak compared to the line emission. The upper curve is the total spectrum and the lower curve shows the shock contribution.

TABLE 4.10A: LINEAR DIMENSIONS.

$$n_2 = 10n_1 = 10.0\text{cm}^{-3}, H\beta = 1.0$$

Linear Dimensions : parsecs

	Velocity (km s^{-1})			
	300	350	400	450
Zone A, $\tau_H = \infty$	931.132	1928.931	2366.038	3065.409
Zone A, $\tau_H = 1.0$	60.157	88.302	104.811	128.270
Zone B	1.949	4.157	6.672	9.864
Zone C, $\tau_H = \infty$	19.903	32.736	47.673	68.491
Zone C, $\tau_H = 1.0$	0.501	0.625	0.836	1.000
Zone D	0.001	0.001	0.001	0.001
Zone F	0.001	0.002	0.003	0.003
Expected Range*	60-80	90-125	100-160	130-200

* Varying the optical depth of C.

TABLE 4.10B: $H\beta$ LUMINOSITIES.

$$n_2 = 10n_1 = 10.0\text{cm}^{-3}, H\beta = 1.0$$

 $H\beta$ Luminosities: $\times 10^{37}$ Ergs s^{-1} per $(100pc)^2$

	Velocity (km s^{-1})			
	300	350	400	450
Zone A, $\tau_H = \infty$	1.10	1.62	2.16	2.50
Zone A, $\tau_H = 1.0$	0.24	0.33	0.35	0.44
Zone B	0.11	0.13	0.15	0.17
Zone C, $\tau_H = \infty$	1.14	1.70	2.32	2.77
Zone C, $\tau_H = 1.0$	0.26	0.30	0.39	0.44
Zone D	0.60	0.70	1.08	1.81
Zone F	1.07	1.59	2.14	2.53
Expected Range*	1.21-2.09	1.46-2.86	1.96-3.90	2.86-5.20

* Varying the optical depth of C.

balances. The spectra from the 150, 200, 250, 300, 400 and 450 km s⁻¹ models are shown in figure 4.6.

The pure photoionization models by Robinson (1987) assumed power law ionizing radiation. Here we show the behavior of the ionizing radiation in our models. The ionizing radiation has a strong dependence on the shock velocity, in both shape and integrated intensity. The spectra produce here are not well approximated by either a black body or simple power-law spectrum.

The ionizing spectra are dominated by resonance line emission, especially below $\sim 50\text{eV}$. The underlying continuum is a variable component made up of free-bound and two-photon emission at low velocities and becoming dominated, at higher velocities, by free-free emission from a range of temperatures. This results in a brighter and flatter continuum at higher velocities. This changing spectral energy distribution alters the total energy to $H\beta$ conversion efficiency which in turn affects the actual observed dependence of $H\beta$ on Δv (see § 4.2.4).

The origins of the spectral distributions may be understood in the following terms:

- Below $\sim 60\text{eV}$ the ionizing spectra are all very similar since the major contributions to the spectra are from lower temperature plasmas cooling from a similar ionization state following the initial collisional equilibration of the immediate postshock region. This is demonstrated in figure 4.7 which shows the oxygen ionization balance for the 300 km s⁻¹ fragmented shock model.

After the initial rapid ionization up to oxygen VII (right of **A** in figure 4.7), there is a long hiatus with the helium-like ion dominating. At the other velocities considered a similar ionization structure occurs because of the inherent stability of the helium like ions. Rapid cooling starts at **B** due to the increasing populations of very efficient cooling ions like O IV. This cooling process is triggered by the recombination of the highly stripped ions. Since the ionization state always saturates at virtually 100% He like ions of the abundant species (between **A** and **B**), the cooling onset, and progress is largely independent of the initial temperature.

- Above 60eV differences in the spectra occur due to the influence of temperature dependent continuum processes (such as free-free radiation) in the highest temperature regions of the plasma (*i.e.* at higher temperatures than **B** in figure 4.7).

For all shock velocities the flux of ionizing radiation levels simply increases due to the increasing density of the cooling plasma: Shocks of higher velocity achieve

FIGURE 4.6: The upstream ionizing radiation spectra for fragmented shocks, as a function of velocity.

FIGURE 4.7: Shock model oxygen ionization structure as a function of temperature. Cooling from right to left. The stable OVII ion dominates the oxygen structure of the high temperature zones in all the shock considered here.

higher pressures and this translates to a higher density at a given temperature when the plasma cools (see figure 4.6).

4.5 Discussion and Summary

In this paper we have presented a model for the emission line filaments observed along the radio axis of Centaurus A. As we noted in the introduction, these filaments are of interest not only in their own right but also because of their possible implications for unified schemes of Active Galaxies and the similarity of their line ratios to other Extended and Nuclear Emission Line Regions.

The essence of our model is that shocks, produced through interaction of dense clouds in the environs of Centaurus A with the plasma in the radio jet, emit a sufficient flux of radiation to photoionize the surrounding material. When the shock velocities are more than $\sim 200\text{km s}^{-1}$ this gives rise to a characteristically high excitation spectrum. The observed spectrum is the sum of the high excitation photoionized zones, the emission from the shock regions and any high density compressed zones formed in the shock process.

Essentially our model involves a self-consistent treatment of both the dynamics and the emission line physics of this problem. We have shown that the overall energetics of the knots is consistent with our preconceptions of the densities and velocities of FRI jets. It is also particularly satisfying to see that the turbulent velocities in the knots and their size scale are also consistent with the range of parameters we have assumed for the jet in Centaurus A. Of course, a jet has not yet been detected at the location of the inner filaments and its existence is an important prediction of the model.

The emission line physics of our cloud-cloud interaction model elucidated in §§ 4.3 and 4.4 has only a few free parameters, namely: the initial density, the density contrast and the shock velocity. The initial density is merely a scaling parameter which is in fact determined from the observations and the shock velocity is also strongly constrained by the observed spectrum. Thus, the only *free* parameter is the density ratio of the two clouds. We have considered two values here: 1:1 and 10:1 since these predict qualitatively different spectra. Some of the 1:1 models are good at producing either low or high excitation lines but do not simultaneously produce low medium and high excitation lines in the one model. The 10:1 models discussed in § 4.4.3 satisfactorily reproduce all of the major features of the observed spectra. These include:

1. The $H\beta$ luminosity.
2. The sizes of the emission knots.
3. The temperature sensitive $[OIII] I_{4363} / (I_{5007} + I_{4959})$ ratio.
4. The strengths of the high excitation lines of oxygen, neon and HeII.
5. The strengths of the low excitation lines.

The size and luminosities of the regions do not simply follow from the initial estimate in the recombination rate - volume argument given in § 4.3.2. The sizes are affected by the optical depths determined by spectral modeling and the $H\beta$ luminosities are strongly influenced by the energy conversion efficiency, which is in turn a strong function of the detailed shock cooling/emission process coupled to photoionization and recombination processes in the emitting regions. The fact that the sizes and luminosities are indeed consistent with the observations is an important vindication of this model.

The correct prediction of the temperature sensitive $[OIII]$ ratio is a feature of our model which differentiates it from the alternative beaming model of Morganti and co-workers. Their model requires an additional, unspecified, source of excitation if the $[OIII]\lambda 4363$ intensity is to be explained (Morganti *et al.* 1991). The reason for the higher value of $[OIII]\lambda 4363$ in our models is that the shock precursor region is significantly hotter than it is in a normal photoionization model and there is also a high temperature contribution from the shocked regions (zones **A** and **B** in figure 4.3).

The observed correlation between excitation and velocity dispersion and surface brightness and velocity dispersion is naturally explained by our cloud-cloud interaction model whereas it would have to be an arbitrary co-incidence in the pure beamed photoionization model.

The final picture of the interaction is summarized in figure 4.8. The zone labels described in table 4.4 and figure 4.3 are also used here in this 2 Dimensional representation. The large low density zone **A** is ionized by the radiation from the hot zone **B** produced by the primary shock traveling into **A**. The shocked flow in **B** is fragmented by thermal instabilities and the contact discontinuity zone is disturbed further by other interface instabilities. The radiation from **B** penetrates the dense material in **D**, **E** and **F** to ionize the dense cloud on many ionization fronts **C**. The secondary shock structure probably exists in the form of multiple secondary shocks (zones **D** and **E**). Our final model spectra are a sum of contributions from all these zones.

FIGURE 4.8: Schematic structure of the final model . See text for details.

AGN Implications

Unified theories of Active Galaxies which invoke beamed radiation and orientation effects to explain the observed population of BL-Lac objects for instance are appealing from several points of view. This idea has been extended by optical astronomers in order to explain the deficit of observed ionizing radiation from that required to ionize extended emission line regions. Frequently, the “beaming” is due to optical obscuration. However, Morganti *et al.* (1991) have shown that in the case of Centaurus A a nuclear photoionizing source is necessarily narrowly beamed, presumably due to relativistic aberration. Nevertheless, the model that we have presented here shows that the beamed energy need not be ionizing radiation but rather a mechanical flux carried by an observable jet. This means that other extended emission line phenomena may also be energized by a mechanical rather than a radiation process. In even more general terms our excitation mechanism may apply in any situation where there is bulk turbulent motion of gas with a turbulent velocity $\gtrsim 200 \text{ km s}^{-1}$. This model may be applied to AGN emission, particularly the narrow line regions where current models invoke ensembles of moving clouds. Observations of Whittle (1989) show that while some anomalous Seyferts have [OIII] lines with line widths as high as $500 - 1,000 \text{ km s}^{-1}$ the majority have line widths in the range $200 - 400 \text{ km s}^{-1}$. Our cloud-cloud collision model could be naturally applied to this situation and will again give the characteristic strong forbidden line emission for high and low ionization species.

Similarly, Baum (1990) has observed a large sample of emission line radio galaxies and interestingly the velocity widths range from 150 to 500 km s^{-1} raising the prospect that at least some extended emission line regions are powered by internal shocks. This idea is being currently developed.

Conclusions

We suggest that, for the Centaurus A filaments, our model is to be preferred to the radiation beaming model of Morganti *et al.* for the following reasons:

- As we have stated above, our calculations achieve a high degree of internal consistency in terms of the energy budget, the turbulent velocities observed in the filaments and the emission-line luminosity and we are not required to invoke an invisible ionizing beam with an arbitrary beaming factor to explain the data.
- The very dense material (zones E and F) which is the source of the lowest excitation lines, is a natural consequence of the physics of the shock waves that we have invoked. In the beaming model the very dense material is an *ad hoc* assumption which has to be introduced in order to fit the data.

- The pure beaming model is unable to explain the $[\text{OIII}]I_{4363} / (I_{5007} + I_{4959})$ ratio and Morganti *et al.* (1991) are forced to invoke additional heating processes beyond photoionization in order to explain this ratio.

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Chapter 5

Oxygen–Rich Supernova Remnants

5.1 A Brief Review of Oxygen–Rich Supernova Remnants

The following represents a brief summary of the current understanding of the class of oxygen–rich supernova remnant (OSNRs). The interest in these remnants lies in the unique opportunity that they provide in allowing us to examine directly the internal, nuclear–processed material of massive stars. Historically, this was first realized through the study of Cassiopeia A. There are now seven OSNRs known which display emission from material ejected from the helium–burnt layers of the progenitor star.

5.1.1 Cassiopeia A

Cassiopeia A was an historical supernova which exploded in the late 17th century. It was possibly seen by Flamsteed in 1680 (Ashworth 1980), and was not noted for a very luminous display. Its remnant is now shedding light on the internal structure and evolution of massive stars. This consists of an expanding spherical shell, seen clearly in both the radio (*i.e.* Bell 1977) and X–ray bands (*i.e.* Fabian *et al.* 1980). In the optical it is visible as a rather unspectacular collection of emission line filaments. Observations by Kamper and van den Bergh (1976;1983,1985) classifies the observed optical filaments of this remnant into two groups: the “quasi–stationary flocculi” (QSF) of low velocities, and the fast–moving knots (FMK) with space velocities up to $8,000 \text{ km s}^{-1}$.

The slow-moving knots are assumed to be the remains of material lost by the progenitor star in stellar wind mass-loss phases. These display spectra showing lines of the usual range of element, and strong Hydrogen Balmer lines. The QSF have enhanced nitrogen abundances, and possibly enhanced helium.

The fast-moving knots, on the other hand, display unusual spectra, distinguished by the fact that the normal hydrogen recombination lines are often entirely absent (*c.f.* Chevalier & Kirshner 1978; 1979 and references therein). Individual knots display spectra with both oxygen and neon lines and weaker argon, calcium and sulfur emission. Although quantitative models of the emission mechanism are still being developed, it was apparent very early that the spectra reflect real abundance anomalies.

The correspondence between the pattern of abundant elements seen in the Cassiopeia A remnant, and the nucleosynthetic evolution models of stars massive enough to progress beyond carbon ignition to oxygen-neon and heavier α -burning is very encouraging. Models from various calculations (*i.e.* Weaver *et al.* 1978; Woosley *et al.* 1984; Johnston & Yahil 1984; Woosley & Weaver 1986), consistently predict significant layers of oxygen-neon mixtures in stars more massive than $15 M_{\odot}$. In particular, the well known $25 M_{\odot}$ models display a layer of carbon, oxygen and neon in the inner mass zones between 2 and $8 M_{\odot}$. Deeper layers of the α -processed products of sulfur, argon and calcium occur before the inner iron core is reached. The observed species therefore strongly suggest a massive progenitor for this OSNR. Independent evidence for a massive progenitor for Cassiopeia A comes from X-ray estimates of the hot gas content of the remnant by Fabian *et al.* (1980), which placed a straight-forward lower limit of $\sim 15 M_{\odot}$ on the progenitor star mass.

More light was cast on the nature of this star by recent observations of a new group of filaments, the fast-moving filaments (FMF) (Fesen *et al.* 1987). These show emission of hydrogen lines and a strong overabundance of nitrogen, and have been interpreted as being from a fast Wolf-Rayet (WR) wind in the outer stellar envelope. It is also suggested that the QSF are the remains of an ejected WR ring nebula, commonly seen around early WR WN7-9 stars, consistent with the hypothesis that the star had an initial mass of at least $25 M_{\odot}$.

The long term study of Kamper and van den Bergh (Kamper & van den Bergh 1976; van den Bergh & Kamper 1983, 1985) has revealed other general physical properties of the individual knots. The QSF show e-folding lifetimes of the order of 25 years, over which time they appear and fade. The oxygen-rich knots display similar lifetimes, or even a little shorter. The timescale of around

10^9 seconds is a fundamental property, which any emission mechanism model will have to reproduce. The knot sizes are about 0.01 - 0.05 pc in size and have densities estimated at around $10^3 - 10^4 \text{ cm}^{-3}$. (Chevalier & Kirshner 1978). These parameters will all place constraints on the construction of any physical model of the filament emission process, although the density estimates based on spectral diagnostics are more subject to interpretation.

5.1.2 Other Galactic Remnants

In addition to the well observed Cassiopeia A remnant, two other OSNRs are known in our galaxy. Each display peculiarities of their own, emphasizing the lack of homogeneity in this class of SNR.

SNR G292.0+1.8

The remnant SNR G292.0+1.8 (MSH11-54) is a center-filled radio remnant, and it has been suggested in the past that it may be 'plerionic' or pulsar-powered, similar to the Crab Nebula (Lockhart *et al.* 1977; Goss *et al.* 1979). However, it has a radio spectral index of -0.37, similar to a normal shell SNR and in contrast to the flat spectrum of a synchrotron nebula (Clark *et al.* 1980). It is a strong X-ray source like the rest of the OSNRs, a result which is not unexpected if the hot plasma consists largely of heavy elements. The X-ray data from the *Einstein* SSS instrument shows clear evidence of magnesium, silicon and sulfur emission in the hot phase of the remnant.

The distance to this remnant, which lies very close to the galactic plane, has been estimated at 3.6 kpc by IRAS line of sight dust density (Braun *et al.* 1986). It clearly heavily reddened. However, normal optical emission line methods using Balmer line decrements are useless in this case. A reddening of $E(B-V) = 0.9$ has been quoted by Goss *et al.* (1979), which would be consistent with the estimated distance and position in the galaxy. The true reddening remains very uncertain.

At the estimated distance, the physical size of the centrally emitting region is approximately 2 pc, direct evidence that this is a young supernova remnant. It was probably an historical event, with ages estimated in the range 1,500-2,000 years, but presumably the southerly declination and high reddening prevented it being noticed by northerly civilizations.

The optical spectrum only displays forbidden oxygen and neon lines (Dopita & Tuohy 1984). There is no sign of the heavier elements such as argon or sulfur in the optical spectrum. There has been a suggestion that the X-ray emission

is in fact toroidal in geometry, and there does appear to be growing evidence for the non-spherical nature of the OSNR outbursts, possibly favoring the equatorial plane.

Puppis A

Puppis A is becoming an increasingly well studied remnant (*c.f.* Arendt *et al.* 1991 and references therein). Since the identification by Baade and Minkowski (1954) of some bright nebula condensations with the radio source Puppis A, the remnant was generally held to be a middle aged, fairly normal galactic remnant. The delicate sheets and filaments of other old remnants are not present, rather the optical nebulosity occurs in a collection of individual knots scattered across the 60 - 80 minutes of arc covered by this remnant. These knots display a range of spectra, and some are noted for the particularly strong emission of [NII]. The [NII] λ 6584 emission is between 10 to 20 times $H\alpha$ in some cases (Dopita *et al.* 1977b; Danzinger 1983).

There is also optical evidence that the remnant contains clumped and diffuse coronal gas with [FeXIV] λ 5303 emission detected by Clark *et al.* (1979) and later imaged by Dopita (1981). The [FeXIV] λ 5303 emission, representing the hot phase, and the brighter emission clumps with [OIII] λ 5007 emission representing cooled gas, appear to be spatially anti-correlated in the bright N-W clumpy region, suggested by Dopita (1981) to be the result of the development of thermal cooling instabilities. Clark *et al.* (1979) prefer a picture where the pattern is due to the thermal evaporation of dense clouds that have been over-run by the SNR blastwave. The [FeXIV] λ 5303 corresponds roughly with the overall diffuse X-ray emission although much of the emission is very weak. Puppis A is typical of OSNRs in being a bright X-ray source. It has been observed extensively in X-rays, including spectrally by Winkler *et al.* (1981) and imaging by Petre *et al.* (1982). The X-ray observations have been used to place constraints on the density and temperature of the hot medium in the SNR, and hence the pressure domain of the remnant including any embedded knots.

The status of this remnant was re-evaluated with the discovery by Winkler & Kirshner (1985) of rapidly moving knots of oxygen-rich material. The bright 'Omega' filament displays the typical OSNR forbidden oxygen and neon emission spectrum. Other fainter rapidly moving knots were also detected. By 1988, using plates taken in 1978 and 1986, proper motions were measured for individual knots giving space velocities around 1,500-3,000 km s⁻¹ (Winkler *et al.* 1988). This is somewhat slower than the Cassiopeia A knots, suggesting that deceleration has

occurred. The expansion age they derived, $3,700 \pm 300$ years, makes Puppis A the oldest of the known OSNRs. Arendt *et al.* (1991) favor an even greater age, about 6,000 years. The distance has been estimated between 2 and 4 kpc, although the work by Arendt *et al.* supports the shorter distances. The reddening is again uncertain, and has been estimated at $A_v = 1.5$ by Winkler *et al.* (1988).

The oxygen-rich knots contain the usual oxygen-neon mixture. Other filaments show signs of [SII] $\lambda\lambda 6717+31$ emission, but the same knots also display strong [NII] emission, making the possibility of a deep stellar origin for the observed sulfur unlikely, unless extensive mixing of the deep layers and the outer envelope has occurred.

5.1.3 Extra-Galactic Remnants

There are two known OSNRs in the Large Magellanic Cloud (LMC) and one in the Small Magellanic Cloud (SMC). The typical size of the young OSNRs (1 - 30 pc diameter), when placed at the distance of the Magellanic clouds, makes them ideal targets for typical modern detector systems (both imaging and spectral). The apparent diameters range from some ten arc seconds for the center of SNR 0540-69.3, up to two arc minutes for the LMC remnant N132D. These remnants display the characteristic properties of the OSNRs with rapidly moving oxygen-rich material, and in some cases slow-moving QSF analogous to the Cassiopeia A structures. They are typically radio and X-ray bright.

For this discussion, and the following study, the distances to the LMC and SMC have been taken to be 49.4kpc and 57.0kpc respectively. These values are based on the review by Feast & Walker (1987).

N132D

One of the first remnants identified in the LMC (Westerlund & Mathewson 1966), N132D has high surface brightness in both the optical and radio bands. This OSNR is also one of the brightest X-ray sources in the LMC as a whole. As much as 20% of the X-ray luminosity may come from OVIII line emission (Winkler *et al.* 1979). The optical structure of this remnant is one of a series of three roughly circular structures. There is an outer, diffuse, low excitation nebulosity with a diameter of about 80 pc (Lasker 1978). What is commonly regarded as the remnant proper is a roughly circular structure about 32 pc in diameter. Within this shell lies a complex of knots in a region about 6-12 pc across, containing slow-moving material and the fast oxygen-rich knots. The X-ray and optical

morphology of the 32 pc structure are similar, however the radio diameter of Mathewson & Clark (1973) corresponds only to the inner 6 pc region (where the oxygen-rich knots are also observed). More recent Australia Telescope 6 cm radio observations by Dickel & Milne (private communication 1993), does show the 32 pc remnant extent, however, the detailed structure in the radio image does not correlate well with the optical structure. The *Einstein* X-ray spectrum of Clark *et al.* (1982) also shows the presence of the heavier elements Mg, Si and S at mildly super-solar ratios, while the optical spectra of the oxygen-rich knots show only oxygen and neon.

The optical studies carried out by Lasker (1978;1980) used photographic imaging and spectrophotometry. The results were interpreted in terms of an expanding circular ring of fast-moving oxygen knots, with a diameter of ~ 6 pc. The study by Hughes (1987) suggests that the supernova event occurred in an evacuated cavity. The homogeneous Sedov solution to the X-ray data suggests an age of 4,000-7,000 years, compared to the expansion age of the rapidly moving oxygen-rich knots of $\sim 1,300$ years derived by Lasker (1980) for the 6 pc ring. These ages can be somewhat reconciled by assuming that the remnant is expanding into a very low density cavity. Such a cavity may be produced by the wind-blown bubble mechanism commonly seen with WR stars, recalling once more the frequently invoked relationship between OSNRs and WR stars. The ring of diffuse and relatively faint HII emission seen around N132D (Lasker 1978) at a diameter of about 80 pc is a typical size for a WR or O star wind bubble.

The spectra of the fast-moving knots of N132D show lines of forbidden oxygen and neon transitions. The [OII] $\lambda\lambda 7320+30$ lines are relatively weak compared to some knots in Cassiopeia A, which may indicate a lower knot density. No rapidly moving sulfur, argon or calcium emission has been detected to date (including the present work). In a search for rapidly moving knots rich in sulfur, Lasker (1988,1991) could only place upper limits on the sulfur abundances, since sulfur lines were not detected. The implications of this are unclear however, and interpretation is difficult as the layer that contains the heavier elements is relatively small compared to the oxygen-neon layer in the typical $25 M_{\odot}$ models. The physics of the explosion event, especially the Rayleigh-Taylor instabilities, such as are believed to have occurred in SN 1987A (*i.e.* Fryxell *et al.* 1991), may affect the detectability. For instance if the sulfur containing material is particularly dense, or not currently being excited, then it may be present but not detectable. Sulfur is detected in the X-Ray observations (Clark *et al.* 1982) but at levels only marginally enhanced over solar ratios.

If the outer diameter ~ 32 pc represents the position of the primary blastwave after only 1,300 years, then the front is still traveling at around $10,000 \text{ km s}^{-1}$ and it would seem that significant deceleration has not yet occurred. It is therefore uncertain whether a reverse shock from the blastwave-ISM interface has yet built up as the main front begins to 'snow-plow' into the surrounding ISM. Other reflected shocks from the immediate circumstellar medium do presumably exist, however. Such shocks could excite the oxygen-rich material. The shock interaction model is supported by the correlation between the radio emission being strongest in the central 6–12 pc region where the oxygen-rich material is observed, even though the correlation on sub-parsec scales is not good.

This remnant is a major target in the present work.

SNR 0540-69.3

The unusual remnant SNR 0540-69.3 in the LMC was a long-standing candidate for a remnant containing a pulsar. The central region was known to display synchrotron emission (*c.f.* Mills *et al.* 1978; Long *et al.* 1981; Reynolds and Chevalier 1981). This has subsequently been confirmed with the detection of a pulsar with a period of 0.0502 s (Seward & Harnden 1984; Middleditch & Pennypacker 1985), making it one of only five known definite pulsar/SNR associations. Given the OSNR nature of the remnant, this is good evidence that massive stars in particular can produce dense remnants such as neutron stars.

It may or may not be significant that to date none of the other OSNRs show evidence, spectrally or otherwise, of containing a dense core remnant. This remnant naturally displays the high velocity oxygen-rich emission that places it in this small class of objects, but it does not display the forbidden neon lines present in the other remnants. The optical oxygen-rich emission occurs outside the central synchrotron region. The spectrophotometry of Dopita & Tuohy (1984), first revealed the possible emission of $\text{CaI} \lambda 6573$ in the spectrum. Despite some controversy over this identification in the work by Winkler *et al.* (1989), the overall observed emission of SNR 0540-69.3 remains consistent with the hypothesis of a massive progenitor. The X-ray *Einstein* SSS spectra of the remnant shows that the synchrotron emission could also come from oxygen-rich plasma with a composition similar to that observed optically (Clark *et al.* 1982).

Kirshner *et al.* (1989) presented a detailed spectrophotometric study of SNR 0540-69.3, and made the case that this was the penultimate SNR in the LMC prior to the recent 1987A outburst.

SNR E102.2-7219

The second brightest X-ray source in the SMC is SNR E102.2-7219, which is in turn 10 times brighter than the next brightest SNR. This continues the trend of high X-ray luminosity in OSNRs. The remnant is about 25 arc seconds in diameter (about 7 pc) in the optical, and it is surrounded by a faint halo about 3.5 arc minutes in diameter, which has a high excitation but otherwise normal HII region spectrum (Dopita *et al.* 1981). The presence of HeII λ 4686 emission in the halo suggests quite hard exciting radiation, possibly associated with the soft X-ray emission from the expanding blastwave rather than any normal stellar field. The rapidly moving filaments again display the oxygen-rich emission spectra of this class. The work of Tuohy & Dopita (1983) has suggested that a very distorted torus could conceivably account for the observed velocity and morphology of the oxygen-rich material. Observed velocities are in the range of -2,500 to +4,000 km s⁻¹ in the oxygen knots, and the dynamical age is estimated at around 1,000 years by Tuohy & Dopita. Blair and co-workers (1989) estimate an age of 2,150 years. In either case, it is obviously a young SNR like the rest of the OSNRs.

The optical spectra of SNR E102.2-7219 contain lines of [OIII], [OII], [OI], [NeIII] and [NeV] (Dopita & Tuohy 1984). The presence of [NeV] is indicative of more intense excitation than in remnants like SNR G292.0+1.8 or N132D which show no sign of this species. This remnant has been observed in the UV (Blair *et al.* 1989) and lines observed include CIII], CIV, SiIV and Mg in addition to oxygen and neon lines. This lends further support to the nucleosynthetic models which predict these elements to be present, even though they are not detected in the optical. Overall, the UV line spectrum is not particularly strong. It is also clear from the work by Blair *et al.* that, as expected, simple equilibrium photoionization models cannot account for the line ratios observed.

Hughes (1988) shows that the X-ray emission of SNR E102.2-7219 is non-spherical, concentrated in a narrow ring surrounding the optical filaments. The X-ray spectrum also indicates that the emitting plasma is of unusual composition and is probably SN ejecta as well.

SNR in NGC4449

The Magellanic type irregular galaxy NGC4449 contains an extreme example of the class of OSNRs. This object has broad lines of oxygen, neon and sulfur with line widths of up to 7,000 km s⁻¹ (Blair *et al.* 1983). The apparent angular radio diameter of between 0.04 and 0.06 arc seconds indicates a remnant diameter of

less than 1 pc. The expansion velocity of around $3,500 \text{ km s}^{-1}$ indicates an upper limit of only 200 years for the age of this object. There is evidence that the emitting material is very dense, of the order $10^5 - 10^6 \text{ cm}^{-3}$ (Blair *et al.* 1983). The luminosity in X-ray and radio is characteristic of the OSNRs, although the luminosities are very great in this case. The radio emission is some 25 times the emission of Cassiopeia A.

5.1.4 The Progenitors

As indicated above, there is considerable circumstantial evidence that the OSNRs may arise from massive, $15\text{--}40 M_{\odot}$ stars, which are possibly Wolf-Rayet stars at some point during their evolution. Theoretical nucleosynthetic evolutionary models predict that material with compositions like the oxygen-rich material is only produced in massive stars.

There is supporting environmental and morphological evidence for massive progenitors. The theme of toroidal geometry has recurred since the early 80s, both in optical and X-ray observations (see the review by Lozinskaya 1992). For the rapidly moving material this may related to the symmetry of the actual collapse/explosion mechanism, rather than other progenitor properties. Work by Woosley & Weaver (1981), with a $25 M_{\odot}$ rotating model, showed strong equatorial mass ejection and polar collapse in a 2D simulation where the rotation assisted the otherwise problematic explosion process. In the cases of N132D (Lasker 1980) and SNR E102.2-7219 (Tuohy & Dopita 1983) there is evidence that the rapidly moving oxygen-rich material is not spherically distributed. Some of the structures are probably not related to the explosion itself, and give some clues to the progenitor nature. The slow-moving material such as the QSF in Cassiopeia A and N132D shows evidence of the remains of a ring or toroidal structure, typical of WN7-9 ejecta type ring nebula, and the case of the N132D remnant also gives evidence of expansion inside a wind-blown bubble, of an extent typical of a WR bubble.

Given the evidence of the presence of a massive precursor and the correspondence of the elemental mixtures, it seems reasonable to assume that the oxygen-rich knots do indeed come from the inner layers of an evolved massive star. In this work the emphasis will be placed on knots which are actual products of nucleosynthesis deep in the OSNR progenitor star.

The work described in this and the following chapter is therefore predicated on the working hypothesis that the OSNRs are one end point in the evolution of the

more massive stars, usually occurring as WR stars in the mass range 25–40 $M_{\odot}$. This study will be focused on the analysis of the nuclear processed stellar ejecta of the supernova event, ignoring for the present the complexities of the surface ‘weather’ of the progenitor stellar atmospheres. The non-oxygen-rich material observed in the OSNR in this study alone represents material with a wide range of compositions and excitation. Important clues to the nature of the progenitor, as it might have been, are contained in the spectra and dynamics of this material. However, the detailed analysis of the spectra of the non-oxygen-rich material is deferred to future work.

The aim of this study is to produce a working excitation model for the oxygen-rich material that is consistent with both the spectra and the observed dimensions. In this way some insight into the internal composition of the progenitors is hoped for. Stellar nucleosynthesis from hydrogen on up, is thought to be the prime mechanism by which the observed universe is enriched in heavier elements. This is therefore a problem of general interest, and in this sense the detailed nature of the progenitors is of secondary interest. Similar processes are expected to occur in all massive stars, not just the progenitors of OSNRs.

5.2 Observations of Three Southern Remnants

Of the seven known OSNRs, three have been chosen for particular study in this thesis. The selection was based both on the perceived areas where the existing literature data can be improved upon, and on the geographical location of the available telescopes. This led to the selection of three of the southern remnants which have properties which make them suited to the available observational tools.

The main observational tool was the ANU 2.3m Telescope, with the double beam spectrograph (DBS) and the photon counting array (PCA) system. This instrument was configured to give spectral coverage from 3300Å to 8000Å at 1.5Å per pixel. This is designed to obtain both red and blue emission lines in a single observation, and also to give reasonable velocity resolution for the rapidly moving oxygen-rich material. The high precision tracking of the 2.3m telescope permitted accurate slit offsets, giving 2D spectrophotometric mapping. Narrow-band interference filter CCD images were also obtained with the AAO AAT 3.9m telescope.

The remnants studied here are N132D in the Large Magellanic Cloud, and the galactic remnants, Puppis A and SNR G292.0+1.8. Limited optical spec-

trophotometric data already exists in the literature (*i.e.* Lasker 1978,1980; Goss *et al.* 1979; Dopita & Tuohy 1984; Danzinger & Dennefeld 1976a,b; Danzinger & Liebowitz 1985 ; Winkler & Kirshner 1985). The aim here is to go back and make a more detailed study.

The Puppis A observations were intended to provide new data on known oxygen-rich material, and to search for new oxygen-rich knots using a [OIII] filtered Schmidt plate in conjunction with red [NII]+H α photographic material. In addition a global spectrum of the remnant SNR G292.0+1.8 was obtained. The N132D remnant provides an opportunity for a more detailed study, and a 2D spectrophotometric technique was applied to obtain both velocity field information of the oxygen-rich material as well as spectra of individual knots. N132D was the subject of the narrow-band imaging.

The other southern remnants: SNR 0540-69.3 (Dopita & Tuohy 1984; Kirshner *et al.* 1989) and SNR E102.2-7219 (Dopita & Tuohy 1984; Blair *et al.* 1989) already have good published spectra which could not be improved upon by the techniques employed here.

The details of the observations and data reduction methods used on all the remnants are described in this section. Details of the results and interpretation for each remnant are given in subsequent sections.

5.2.1 Spectrophotometry

All the spectrophotometry in this work was carried out using the Double Beam Spectrograph (DBS) (Rodgers *et al.* 1988a) on the Australian National University's 2.3m Advanced Technology Telescope (ATT) at Siding Spring Observatory. The DBS red and blue beams are each detected with wavelength optimized Photon Counting Arrays (PCAs) (Rodgers *et al.* 1988b). Using the 300 and 316 lines mm⁻¹ gratings, a spectral range from 3300 - 8000 Å is covered at approximately 1.5Å per pixel. The slit width of 1.5 - 2" degraded the FWHM resolution to around 6Å resolution overall.

Single slit exposures of 1,500 s exposures were taken of white dwarf flux standards, to provide relative flux calibration. The standards used were L745-46A and Wolf 485 from the list of Oke (1974). Spectra of standards were obtained twice per night. The observations of the targets used wide slit settings. However, the standard stars required narrow slits with defocussing to prevent detector count-rate saturation, and this prevented accurate absolute calibration. The defocussing of the narrow slit observations of the standards also compensated for

the normal atmospheric dispersion errors usually encountered with narrow slit observations. The optical design of the spectrograph does not produce significant vignetting in the cameras so that wavelength-dependent effects of defocussing are negligible.

Quartz flat-fields were taken at low count rates with exposures of up to 30,000s. For these, the grating angles were changed to give a more even illumination of the blue PCA detectors. The flat-fields were used to largely eliminate a number of large scale detector defects, dust contamination, and to a lesser extent the local up-down noise of the detectors. Some defects due to fiber packing discontinuities in the optical fiber boules varied slightly with time, and could not be eliminated by flat-fielding techniques. The main effect of these packing errors is that emission lines sometimes cross a discontinuity and apparently shift suddenly in wavelength. These discontinuous shifts could not be eliminated in the wavelength calibration procedure as the calibration uses polynomial fits which cannot reproduce them. Occasionally, these discontinuities produce a ridge in the final processed spectra that appear as weak emission lines. When such features have occurred in the final spectra presented in Appendix B, the spurious lines are marked as 'PCA'.

The spectrophotometry was reduced in the standard way using the *noao* packages in IRAF v2.9. Individual observations frequently resulted in several emission knot detections along a single slit. To make the strip-extraction of the knot spectra more reliable, a slit axis calibration was taken. The calibration was in the form of an aperture plate of artificial stars along the slit axis. The 'stars' were placed with 2mm spacings above and 3mm spacings below the central position so the orientation solution was included in the scale fitting procedure, since the red frames from the PCAs are inverted vertically compared to the blue frames in the raw data. The calibration plate was illuminated using the quartz flat-field lamp. The artificial star images were then fitted using normal arc identification methods, along the slit axis. The physical plate scale was 4.964" per mm at the plate plane in the Naysmith position of the DBS. The slit scales vary between 0.663" per pixel and 0.639" per pixel depending on the individual PCA chips. The resulting slit fit was combined with the He/Ne/Ar arc fits for the dispersion axis to make a 2D distortion correction in one operation. Once the distortions were corrected, all the PCA frames were standardized to 1.5Å per pixel along the dispersion axis and 0.665" per pixel along the slit axis.

Background sky subtraction was carried out on the distortion corrected long slit spectra before aperture strips were extracted. This was necessary, since often the emission observed was so extended that true sky values were only available

near the outer edges of the data frames, and apertures near the center could not define nearby sky values for subtraction during the extraction procedure. In the case of the N132D observations the series of long slit observations thus corrected and background subtracted, were also stacked into a λ - x - y data cube, resulting in $1.5\text{\AA} \times 2.5'' \times 0.665''$ volume elements.

Individual spectra were then extracted as simple summed rows of pixels, without using the automatic aperture tracing facilities, which are not useful for emission line objects with weak or no continuum. The rows to be summed were chosen interactively, using the apertures defined by the available imaging and velocity map information (see §5.3.1 and 5.4). In most cases, however, the individual knots were clearly isolated and extraction was straightforward. Final line fluxes were interactively measured using the IRAF *splot* package.

In the extraction of individual apertures in the N132D data, spectra were extracted from one, two or sometimes three slit positions and co-added. This procedure involved adding several spectra from different apertures along planes of the data cube. This further prevented absolute spectrophotometry, although relative fluxes were preserved.

The measured lines were all well within the detector range and away from both detector edges and the regions affected by the dichroic filter system. The final relative spectrophotometry was repeatable on the 10 - 15% level or better for $H\beta$ or $[\text{OIII}]\lambda 4959$ when observations from different nights were compared. This error is largely due to high thin cloud on some nights and difficulties in eliminating count-rate saturation in the PCA detector system. The I_{5007}/I_{4959} ratio is constrained by atomic theory to be 1 : 0.347. In the tables of flux ratios below, the observed ratio is given and the general agreement with this ratio indicates that serious saturation in the $[\text{OIII}]\lambda 5007$ line has not occurred.

2D Spectrophotometry

The precision tracking and slit positioning of the 2.3m ATT permitted the accurate offsetting of the 6 arc minute DBS slit in a regular grid. With the relatively poor seeing of 2" or more, offsets of 2.5 arc seconds East-West were taken with the 2" slit in a North-South orientation. A standard position star at 5h 25m 31.0s -69° 40' 09.6" B1950.0 (Mathewson *et al.* 1983) was used to maintain accuracy during the course of the observations, by resetting to that position and making relative offsets from there to the desired slit position. In this way 2D spectrophotometric observations resulting in a λ - x - y data cube of the remnant were taken and then reduced as described above.

were taken and then reduced as described above.

From the data cube, a section containing all the [OII] $\lambda\lambda 3727$ emission (the doublet is unresolved in these observations) was taken and a velocity map was constructed from this single line. The isolated nature of this emission prevents the ambiguities that are inherent in an [OIII] $\lambda 5007$ line observation, where high velocities can cause confusion with [OIII] $\lambda 4959$ emission.

Narrow-Band Imaging

Narrow-band imaging was carried out using the AAO AAT 3.9m telescope on February 16th and 17th 1991. The TAURUS II instrument (Atherton *et al.* 1982) was mounted at Cassegrain focus and used without the Fabry-Perot capability. The instrument functioned essentially as a focal reducer, giving an effective ratio of $f2.2$, and tilt-able filter holder. The 100mm and 76mm emission line filters were placed above the focal plane in the primary $f8$ beam, so that band-pass broadening due to off-axis rays was unimportant. Red and green continuum filters with diameters of 76mm were placed at the pupil plane. This meant that only the central 50 mm of these filters were used, avoiding the filter edges which were becoming somewhat degraded due to moisture damage.

Exposures of 1,000 seconds were taken with a 1024×1024 pixel Thompson CCD. The resulting pixel resolution was $0.467''$ per pixel in an ~ 8 arc minute field. Atmospheric seeing conditions during the observations were measured at $2.5''$. Narrow-band interference filters with band-passes of $5020 \pm 20\text{\AA}$ and $6565 \pm 7.5\text{\AA}$ were used for [OIII] and H α emission respectively. The off-line green and red continuum filters had band-passes of $5057 \pm 21\text{\AA}$ and $6626 \pm 27.5\text{\AA}$. The continuum images were subtracted from the emission line images after registration and normalization to minimize the residual stellar images. The CCD image reduction was done with the IRAF data reduction facility, using standard reduction methods. Final images were prepared with Graf, Imaj and Adobe Photoshop 2.0 packages on a 32 bit color Macintosh IIfx graphics workstation.

5.2.2 Observation Log

The observing log, giving dates, integration times and slit positions for all observations are given in tables 5.1 and 5.2.

TABLE 5.1: OBSERVATION LOG FOR N132D.

N132D	Coordinates (J2000.0) ^a			Date	Exposure
Oxygen-Rich	RA (h m s)	Dec (° ' ")	PA(°) ^b		(s) ^c
4	05 25 02.4	-69 38 50.5	180	Dec-89	1500(1)
5	05 25 04.3	-69 38 37.8	180	Dec-89	1500(1)
6 [†]	05 25 01.5	-69 38 41.6	180	Dec-89	3000(2)
7	05 25 00.7	-69 38 35.0	180	Dec-89	4500(3)
8	05 25 00.6	-69 38 28.0	180	Dec-89	4500(3)
9	05 25 01.9	-69 38 23.7	180	Dec-89	3000(2)
10	05 25 02.3	-69 38 31.2	180	Dec-89	3000(2)
11	05 25 03.6	-69 38 30.3	180	Dec-89	3000(2)
12	05 25 03.3	-69 38 23.8	180	Dec-89	3000(2)
14	05 25 06.0	-69 38 28.0	180	Dec-89	3000(2)
15	05 24 59.4	-69 38 48.1	180	Dec-89	1500(1)
16	05 25 00.7	-69 37 45.8	180	Dec-89	4500(3)
19 [‡]	05 25 03.7	-69 38 13.5	180	Dec-89	4500(3)
20	05 25 05.3	-69 38 12.1	180	Dec-89	4500(3)

Notes:

^a. Astrometry for individual filaments using narrow-band CCD imaging from Feb. 1991. See figure 5.5^b. Position Angle.^c. Total exposure and number contributing slit positions.[†] Normal composition filament for comparison in figure B.3[‡] Normal composition filament subtracted from filament 20 spectrum in figure B.13

TABLE 5.2: OBSERVATION LOG FOR PUPPIS A& SNR G292.0+1.8.

Puppis A		Coordinates (J2000.0) ^a .			Date	Exposure
Filament	RA (h m s)	Dec (° ' ")	PA(°) ^b .			(s) ^c .
Omega	08 22 42.2	-42 51 55.2	226	Dec-89		7000(3)
				Mar-90		
				Jan-91		
O2	08 24 15.9	-42 58 02.4	135	Mar-90		3000(1)
O3	08 22 50.3	-42 44 37.0	130	Mar-90		3000(1)
O4	08 22 39.1	-42 42 50.4	90	Dec-89		2000(1)
O5	08 24 18.8	-42 55 02.5	90	Mar-90		3000(1)
O11	08 23 28.7	-42 52 22.2	135	Mar-90		3000(1)
O12	08 22 55.0	-42 55 22.8	135	Dec-89		2000(1)
O13	08 23 20.0	-42 54 42.9	135	Mar-90		3000(1)

SNR G292.0+1.8		Coordinates (J1950.0) ^d .			Date	Exposure
Filament	RA (h m s)	Dec (° ' ")	PA(°)			(s)
Whole	11 22 32.73	-58 59 12.9	270	Mar-90		3000(1)

Notes:

^a. Astrometry for individual filaments using [OIII] schmidt plate of Dopita (1983)

^b. Position Angle.

^c. Total exposure and number of exposures in brackets

^d. DBS slit position, centered on filaments.

2.3m ATT Console readout, accurate to ~ 1 arc second.

5.2.3 Spectra, Line Fluxes and Ratios

The spectra for all observations containing oxygen-rich material are given in Appendix B. The spectra are plotted with rectilinear steps at the actual pixel resolution and no smoothing has been used. Defects such as night sky emission that subtracted poorly, or defects in the PCA, are noted. In the spectra up to 3 velocity components were observed, so components have been labeled with $v+$, $v0$ and $v-$ representing blue-shifted, local SNR rest frame and red-shifted material respectively. In the Puppis A observations some slit positions resulted in knots of different composition and are differentiated by the labels a , b , c etc

The measured line ratios relative to $I_{5007} = 1.00$ are given in tables 5.3a to 5.4b. In many cases, particularly the N132D observations, confusion and blending of lines prevented quantitative measurement of fluxes in some apertures. The tables also include line ratios between the various lines that are in subsequent analysis.

5.3 N132D

5.3.1 Images

Narrow-band images in both $H\alpha$ and [OIII] lines were taken of N132D using a large format CCD on the 3.9m Anglo Australian Telescope. By also taking images with narrow-band filters in adjacent continuum, the relatively crowded background stellar field has been accurately subtracted. The pure emission $H\alpha$ and [OIII] images can then be combined to differentiate the filaments into normal and oxygen-rich classes. While the [OIII] narrow-band filter excluded the highest velocity material with velocity Doppler shifts of more than $\pm 25\text{\AA}$, the images clearly show that the well known arc features in the remnant described by Mathewson *et al.* 1983 are not entirely oxygen-rich material. Much of the arc material is of more or less normal composition.

The 2D Spectrophotometry, resulting in a velocity map of the innermost regions, demonstrates that the highest velocity material, that is excluded from the narrow-band images, appears to fill the region interior to the inner arcs. Material is found inside the circular 'ring' found by Lasker (1980). This may be a result of the higher resolution achieved here, being 16 times the spatial resolution with elements of $0.65 \times 2.5''$, compared with $2.4 \times 7''$ in the previous work. The circular geometry found by Lasker may be at least partially a selection effect, where the

TABLE 5.3A: MEASURED LINE RATIOS IN N132D
 $I_{5007} = 1.00$

		Spectrum ^a					
	Transition	7v−	8v−	8v ₀	9v−	9v ₀	10v+
[OII]	λλ7320+30	0.09	0.11	...	...	...	...
[SII]	λ6731	...	...	...	...	...	...
[SII]	λ6717	:0.01	...	...	...	...	...
[NII]	λ6584	...	...	...	...	...	...
Hα	λ6563	...	...	...	...	...	...
[NII]	λ6548	...	...	...	...	...	...
[OI]	λ6300	:0.02	0.05	...	...	...	...
[OIII]	λ5007	1.00	1.00	0.30	1.00	0.36	1.00
[OIII]	λ4959	0.38	0.35	0.09	0.39	0.10	...
Hβ	λ4861	...	...	...	...	...	...
HeII	λ4686	...	...	...	...	...	...
[OIII]	λ4363	0.04	0.04	...	...	...	...
[NeIII]	λ3968	0.06	...	...	...	...	...
[NeIII]	λ3869	0.12	0.04	...	0.11	0.05	...
[OII]	λλ3727	1.66	1.75	0.36	1.82	0.36	1.63
	log(I_{5007} / I_{3727})	-0.22	-0.24	-0.07	-0.26	0.00	-0.21
	log(I_{3727} / I_{6300})	2.02	1.56	...	...	...	...
	log(I_{4363} / I_{5007})	-1.41	-1.39	...	...	...	...
	log(I_{3869} / I_{5007})	-0.92	-1.36	...	-0.94	-0.84	...
	log(I_{7325} / I_{3727})	-1.27	-1.19	...	...	...	...
Rad. Vel.	^b .(km s ⁻¹)	-1790	-1460	-400	-1620	-300	+1540

^a. Where multiple velocity components are observed, individual components are denoted by v+, v₀, or v− being blue-shifted, rest and red-shifted respectively. Fluxes are relative to the I_{5007} of the brightest component.

^b. at 3727Å using [OII]λλ3727 .

:Colons indicate uncertain values.

TABLE 5.3B: MEASURED LINE RATIOS IN N132D
 $I_{5007} = 1.00$

		Spectrum ^a					
	Transition	11v+	12v-	12v ₀	12v+	14v+	15
[OII]	$\lambda\lambda 7320+30$	...	...	...	...	...	...
[SII]	$\lambda 6731$	...	...	...	...	...	:0.04
[SII]	$\lambda 6717$	...	...	...	...	...	:0.01
[NII]	$\lambda 6584$	...	...	...	...	...	...
H α	$\lambda 6563$	...	...	...	...	...	0.16
[NII]	$\lambda 6548$	...	...	...	...	...	...
[OI]	$\lambda 6300$	0.05	...	...	0.07	0.05	...
[OIII]	$\lambda 5007$	1.00	1.00	0.44	...	1.00	1.00
[OIII]	$\lambda 4959$	0.32	0.45	0.34	...	0.34	0.43
H β	$\lambda 4861$	...	...	...	...	...	...
HeII	$\lambda 4686$	...	...	...	...	...	...
[OIII]	$\lambda 4363$	:0.03	...	...	...	:0.02	0.04
[NeIII]	$\lambda 3968$	...	...	...	...	...	...
[NeIII]	$\lambda 3869$	0.07	...	...	...	0.11	0.16
[OII]	$\lambda\lambda 3727$	1.43	1.34	0.34	0.34	1.57	2.11
	$\log(I_{5007} / I_{3727})$	-0.16	-0.13	0.11	...	-0.20	-0.32
	$\log(I_{3727} / I_{6300})$	1.46	1.28	...	0.69	1.51	...
	$\log(I_{4363} / I_{5007})$	-1.59	...	...	...	-1.62	-1.36
	$\log(I_{3869} / I_{5007})$	-1.17	...	...	...	-0.95	-0.81
	$\log(I_{7325} / I_{3727})$	...	...	...	...	...	...
	Rad. Vel. ^b (km s ⁻¹)	+2350	-1070	+50	+2640	+1790	-200

^a. Where multiple velocity components are observed, individual components are denoted by v+, v₀, or v- being blue-shifted, rest and red-shifted respectively. Fluxes are relative to the I_{5007} of the brightest component.

^b. at 3727Å using [OII] $\lambda\lambda 3727$.
:Colons indicate uncertain values.

TABLE 5.4A: MEASURED LINE RATIOS IN PUPPIS A
 $[\text{OIII}]\lambda 5007 = 1.00$

Transition	Ω	O2	Spectrum ^a			
			O3a	O3b	O4	O5
[OII] $\lambda\lambda 7320+30$	0.29	...	0.30	0.30	0.26	...
[SII] $\lambda 6731$	...	0.05	0.17	...	...	...
[SII] $\lambda 6717$	...	0.02	0.13	...	...	...
[NII] $\lambda 6584$	...	0.25	0.53	...	...	...
H α $\lambda 6563$	...	0.05	0.35	0.17	...	...
[NII] $\lambda 6548$	...	0.05	0.31	...	...	...
[OI] $\lambda 6300$	0.15	0.10	0.09	...	...	...
[OIII] $\lambda 5007$	1.00	1.00	1.00	1.00	1.00	1.00
[OIII] $\lambda 4959$	0.35	0.34	0.33	0.36	0.34	0.29
H β $\lambda 4861$	...	0.07	0.04	...	...	...
HeII $\lambda 4686$	...	0.03	...	...	...	...
[OIII] $\lambda 4363$	0.04	0.04	...	...	...	0.08
[NeIII] $\lambda 3968$	0.03	0.05	...	...	...	...
[NeIII] $\lambda 3869$	0.12	0.12	0.10	...	...	...
[OII] $\lambda\lambda 3727$	1.19	0.68	0.92	0.55	1.69	1.16
$\log(I_{5007} / I_{3727})$	-0.08	0.17	0.03	0.26	-0.23	-0.06
$\log(I_{3727} / I_{6300})$	0.92	0.84	1.00	...	...	...
$\log(I_{4363} / I_{5007})$	-1.40	-1.36	...	...	...	-1.10
$\log(I_{3869} / I_{5007})$	-0.92	-0.91	-1.00	...	...	...
$\log(I_{7325} / I_{3727})$	-0.61	...	-0.49	-0.26	-0.81	...

^a. Where multiple components are observed,
individual components are denoted by *a*, *b*, *c* etc.
Fluxes are relative to the I_{5007} of the brightest component.
: Colons indicate uncertain values.

TABLE 5.4B: MEASURED LINE RATIOS IN PUPPIS A & SNR G292.0+1.8
 $I_{5007} = 1.00$

		Spectrum ^a						
	Transition	O11a	O11b	O11c	O12	O13a	O13b	g292
[OII]	$\lambda\lambda 7320+30$	0.33	...	0.33	...	0.21	...	...
[SII]	$\lambda 6731$	...	...	...	0.20	0.13	...	...
[SII]	$\lambda 6717$	...	...	...	0.20	0.15	...	...
[NII]	$\lambda 6584$	...	1.26	0.28	1.13	...	...	...
H α	$\lambda 6563$	...	...	...	0.25	...	...	...
[NII]	$\lambda 6548$	...	0.23	0.09	0.40	...	...	...
[OI]	$\lambda 6300$	...	...	0.15	...	0.13	...	0.06
[OIII]	$\lambda 5007$	1.00	1.00	1.00	1.00	1.00	0.35	1.00
[OIII]	$\lambda 4959$	0.33	0.35	0.35	0.33	0.33	0.10	0.34
H β	$\lambda 4861$	...	...	...	...	...	...	...
HeII	$\lambda 4686$	...	...	...	...	...	...	...
[OIII]	$\lambda 4363$	...	...	...	0.06	0.04	...	0.05
[NeIII]	$\lambda 3968$	...	...	...	0.05	0.05	...	...
[NeIII]	$\lambda 3869$	...	0.10	0.08	0.12	0.13	0.01	0.11
[OII]	$\lambda\lambda 3727$	1.24	2.28	1.38	2.15	1.93	0.57	1.32
	$\log(I_{5007} / I_{3727})$	-0.09	-0.36	-0.14	-0.33	-0.28	-0.21	-0.12
	$\log(I_{3727} / I_{6300})$	...	...	0.97	...	1.17	...	1.35
	$\log(I_{4363} / I_{5007})$	...	...	...	-1.22	-1.41	...	-1.31
	$\log(I_{3869} / I_{5007})$	-1.00	...	-1.09	-0.92	-0.89	-1.40	-0.97
	$\log(I_{7325} / I_{3727})$	-0.57	...	-0.63	...	-0.97	...	...

^a. Where multiple components are observed,
individual components are denoted by *a*, *b*, *c* etc.
Fluxes are relative to the I_{5007} of the brightest component.
: Colons indicate uncertain values.

most extended oxygen-rich material has been neglected. The analysis by Lasker excluded slow material within 600 km s^{-1} of the nominal rest velocity. This would automatically exclude the most peripheral material which will be traveling across the line of sight. In addition, the analysis neglected some observed emission outside the 'ring' which showed both blue and red-shifted material. This important feature is discussed in some detail below.

Narrow-Band Imaging

The pure emission line images produced as described earlier are shown as grayscale images in figures 5.1 & 5.2. Contour plots have been overlaid to emphasize the image features.

A composite image with the [OIII] image in green and the $\text{H}\alpha$ image in red is reproduced in color in the frontispiece (on page xi). The composite shows the overall excitation level of the remnant compared to the adjacent red HII region to the south which is part of the outer 80 pc halo. The emission of the rapid oxygen-rich filaments that are slow or red-shifted is able to pass the filter, appear as pure green knots. Blue-shifted material will be excluded by the bandpass which is centered at $5020\text{\AA}$.

The images are in broad agreement with the images of Mathewson *et al.* (1983) and Lasker (1980), however the scale bar in the Mathewson *et al.* atlas appears to be in error. Unfortunately, the poor seeing conditions prevented a detailed comparison with the earlier epoch observations. Any changes in the emission due to appearance or disappearance of filaments similar to the changes noted in Cassiopeia A by the van den Bergh & Kamper studies (Kamper & van den Bergh 1976; van den Bergh & Kamper 1983, 1985), were not detectable.

The accurate continuum subtraction has brought out fainter diffuse emission throughout the remnant. The remnant also has a more nearly circular appearance than in the previous works, due to a faint emission region in the North-West of the remnant. The oxygen-rich material is located in the central ~ 25 arc seconds radius of the remnant, along with material which displays emission spectra consistent with shock excited material of more normal cosmic abundances (see §5.3.2 and aperture 6 in figure B.3). The oxygen-rich material appears in these images in the S-W regions of the central complex. The large bright knot in the N-E, later defined as aperture 20 in figure 5.5, also contains oxygen-rich emission but it is less clear as it is largely superimposed on a bright normal composition knot.

The relatively slow-moving and red-shifted oxygen-rich material that has

FIGURE 5.1: N132D [O III] λ 5007 grayscale image. This continuum subtracted image shows [O III] emission from both oxygen rich and normal composition material. Contours are overlaid to highlight features.

FIGURE 5.2: N132D H α Grayscale Image. This continuum subtracted image only shows H α emission from normal composition material. Contours are overlaid to highlight features.

been observed in the narrow-band images extends over a much larger spatial region than has been previously reported. The oxygen-rich material detected in apertures 20 and 15 (table 5.1, and defined later in figure 5.5) are separated by ~ 12 pc. This is about twice the extent of the circular annulus reported by Lasker in 1980. That structure reported by Lasker lies in the apparently empty center of the remnant in these images.

The innermost bright knots which display strong $H\alpha$ emission can be roughly fit with an ellipse. In figure 5.3 an ellipse is superimposed on the $H\alpha$ contours and simultaneously on the [OIII] contour plot. A circle is also fitted that shares a common center with the ellipse. The circle fit is constrained mainly by the south east quadrant of the remnant and has a diameter of 130 arc seconds (31 pc). When the the center location constraint is relaxed, a simple circular fit to the remnant still produces a diameter of about 130" but the overall fit is poor. The relaxed circle center is offset by 8.2" from the ellipse center. The ellipse is 60" (~ 14 pc) along the major axis and 35" along the minor axis. The aspect ratio 0.6, suggests that the slow-moving ring is inclined at about 53 degrees to the plane of the sky, if it is circular. This slow-moving ellipse of material would then correspond to the QSF of Cassiopeia A.

Under the observing conditions experienced here it is doubtful whether the bright knots have been fully resolved. Spectrophotometric apertures defined by the bright knots in the imaging and 2D spectrophotometry program often included two or three velocity components within a spectrum.

2D Spectrophotometry

A velocity map was constructed using nine 600 km s^{-1} velocity bins, centered around the velocity of the slow-moving normal composition material. This is shown in figure 5.4. The three middle bins (4, 5, & 6) show emission largely excluded from the Lasker analysis. Features that display spectra of oxygen-rich material are labeled O. Material with emission that included $H\alpha$ are labeled N. Finally a feature, designated as the 'broad-line' cloud, which showed very broad oxygen and neon emission lines is labeled B.

In comparison with the $H\alpha$ image, this map shows that rapidly moving oxygen-rich material exists throughout the central regions. The 'arc' features noted by Mathewson *et al.* (1983) are not the complete tally of the oxygen-rich material. The high velocity of some material has shifted its [OIII] $\lambda 5007$ emission out of the filter passband. Some knots of apparently normal composition material in the narrow-band images also display superimposed high velocity blue-shifted

FIGURE 5.3: N132D projected geometry. In these figures, an ellipse has been superimposed on the inner, bright knots of H α emission, corresponding to the slow-moving normal composition material. The ellipse is $60'' \times 35''$ and rotated 104° from the North-South line. The center is at RA: 05 25 01, Dec: -69 38 05. A circle fixed to this center can fit the outer remnant shock front to the South-East with a diameter of $130''$.

oxygen-rich material here. The eastern region of blue-shifted material was not recorded in the CCD images. Significantly, the circular ring structure for the high velocity oxygen-rich material found by Lasker (1980) is not at all obvious in the present [OII] line data. The only 'ring' structure is the incomplete ellipse of normal composition low velocity material seen earlier in the CCD images.

This velocity map observation demonstrates that the highest velocities occur in the central region, which appears to be fairly devoid in the narrow-band imaging reported in the previous section. The true extent of the oxygen-rich material is now apparent, and fills a broad swathe from the N-E to the S-W, about 25" wide and 60" long. It is not clear whether a hollow ring or ellipse geometry would provide a good fit. However the width of the region, around apertures 4-6 and 9-12, roughly corresponds to the size of the 6 pc diameter ring of Lasker.

This information was combined with the CCD images to define the final apertures for the spectra extraction. The complete set of apertures are indicated in figure 5.5 where the aperture positions are overlaid on a grayscale image formed by co-adding both the pure emission $H\alpha$ and [OIII] images in a single, monochrome, image.

The Broad-Line Cloud

An interesting feature detected in this observation is the broad-line oxygen emission feature, co-incident with a bright knot of slow, normal composition material. This broad-line cloud is apparent in the individual spectral as a broad component in the oxygen and neon lines of the spectrum of this knot. This is shown in appendix B, figure B.13 where the normal spectra from an adjacent knot has been normalized on the narrow $H\beta$ line and overlayed. The hydrogen, sulfur and nitrogen lines overlay nearly exactly, and only the oxygen and neon features display broad lines. This knot (**B**) shows clearly on the velocity map over several thousand km s^{-1} . This feature appears to be an example of a direct interaction of the supernova ejecta with circumstellar material. This would occur if a large cloud of oxygen-rich material has collided with a slow-moving cloud in front of it, and is now being deflected outwards and around the obstacle.

The Oxygen-Rich Velocity Ellipse

The oxygen-rich material detected in the apertures of figure 5.5 can be used in an expansion age analysis. Radial velocities relative to the slow-moving material were measured with the [OII] $\lambda\lambda 3727$ lines for each velocity component. Some of

N132D Radial Velocity Map. [OIII] λ 3727 line images.

FIGURE 5.4: A velocity map for the inner regions of N132D in the [OIII] λ 3727 line. This velocity map shows the rapidly moving oxygen-rich material in the inner-most regions of the remnant that were excluded by the narrow-band [OIII] filter used to produce figure 5.1. The small cross is close to the center marked by Mathewson *et. al.* (1984), and corresponds closely to the center of the fitted ellipse of figure 5.3.

FIGURE 5.5: Aperture Identifications for N132D. The apertures chosen for the extraction of individual spectra are shown superimposed on a grayscale version of composite [OIII] and $H\alpha$ image in the frontispiece. The central apertures 9-12 chosen from the [OII] velocity map, lie in an apparently empty region of the narrow-band images due to the high radial velocity of the material there.

the measured velocities are given in tables 5.3a and 5.3b. The others are simply given in the plot. This aperture selection avoids the exclusion of low velocity material that affected the Lasker (1980) analysis. For instance, the oxygen-rich emission in aperture 15 is of low velocity and would have been excluded in the earlier work. This knot appears a strong green knot in the composite image frontispiece (page xi) and is clearly oxygen-rich. There does appear to be some contamination from faint normal composition material, but this could easily be a superposition, and the remaining lines are typical of the oxygen-neon line ratios of oxygen-rich material, with strong [OII] $\lambda\lambda 3727$ and [OIII] $\lambda 4363$.

Velocities from apertures 4, 5, 7-12, 14, 15 and 20 were measured and plotted as a function of distance from the center of the fitted ellipse of §5.3.1. A velocity ellipse was fitted to the outer envelope of the admittedly small number of points in figure 5.6.

An upper value of 5310 km s^{-1} is estimated for the zero point velocity range and a relative error of about 500 km s^{-1} in this value was also estimated. Allowing a generous $5''$ radius error in the center position on a maximum extent of $26''$ gives $6.2 \pm 1.2 \text{ pc}$. This value is determined largely by the broad-line cloud in aperture 20 and the slow material in aperture 15. Apertures 5 and 14 also lend support to this radius, but they both lie in the same quadrants. The apertures 15 and 20 are opposite each other, constraining the center and radius quite well. The center lies directly between apertures 8 and 9. The smaller $14''$ radius of the Lasker (1980) analysis contains the emission from apertures 7-12 in the plot.

If the oxygen-rich material is all expanding steadily from a common origin then the expansion age of the material is estimated at 2,350 years with a relative error of ± 520 years, found by adding the measurement errors in quadrature. This is significantly larger than the 1,300 years given by Lasker (1980). This has implications for the cavity environment model discussed later.

A zero point offset from the slow-moving material is seen here and was also noted by Lasker. This suggests that the oxygen-rich material has not been perfectly spherically ejected, with a net systemic velocity of $\sim 400 \text{ km s}^{-1}$ compared to the bulk of the SNR. Unfortunately, the number of points is so small that no definite conclusions about asymmetries in the explosion can be made. The overall velocity field is not consistent with any special expansion geometry, such as a coherent ring.

FIGURE 5.6: N132D Oxygen-Rich Velocity Ellipse. The extrapolated zero point velocity is about 900 km/s faster than the maximum observed velocity range.

5.3.2 Spectra

Of the apertures defined in figure 5.5, only the apertures containing possible oxygen-rich spectra are discussed in the following sections. The spectra from apertures 4-12, 14-16 and 19 & 20 are shown in figures B.1 - B.13 in Appendix B, and most of these have oxygen rich material. Aperture 6 is included as a comparison spectrum representing the normal composition slow-moving material. The fluxes and ratios measured from the best of these spectra (*i.e.* high S/N and least confusion) have already been summarized in tables 5.3a and 5.3b.

Interstellar Reddening Constant

The normal logarithmic reddening constant formalism is used in the present work where $I = I_0 10^{cf(\lambda)}$. The observed intensity for a given line is given by I , the original intensity is I_0 , $f(\lambda)$ is the reddening curve (Kaler 1976) and c is the reddening constant. The curve of Kaler (1976) is based on the Whitford (1958) curve. When reddening has been expressed in other works in terms of A_v extinction or $E(B - V)$ color excess, these have been related to c approximately by:

$$c \approx 1.44E(B - V) = 0.863A_v \quad (5.1)$$

For N132D, spectra of some of the normal composition filaments were used to determine a reddening constant for that remnant of $c \approx 0.2$, using the observed Balmer decrement line ratios. This is consistent with normal reddening values determined for the LMC and is the same as the value given by Danzinger & Liebowitz (1985). As was also noted by Danzinger & Liebowitz, some of the slow-moving filaments display steep Balmer decrements. This could be due to partially ionized shocks, known to produce steep Balmer decrements due to collisional excitation effects. Those spectra were not used for the reddening determination.

N132D Aperture 12

The line ratios will be discussed in general terms along with the spectra of Pup-pis A and SNR G292.0+1.8 in section 5.5. Apart from the general comparisons made there, a peculiar feature was noted in the spectrum of aperture 12 that warrants further discussion here.

This aperture lies in the most central region of the remnant. It is situated adjacent to the bright knot of normal composition material covered by apertures 17 - 20. (see figure 5.5). The spectrum shown in Appendix B, figure B.9,

shows the complex velocity structure of the material in the central regions. The [OII] $\lambda\lambda 3727$ line has three separate velocity components. In particular, there is a very blue-shifted line. The [OIII] complex at 5007 Å is most easily interpreted as having only two velocity components. On the other hand, the [OI] $\lambda 6300$ line displays only a single line with a large blue-shift.

The radial velocities of the blue-shifted [OII] and [OI] lines are not exactly the same, when the [OI] $\lambda 6300$ wavelength is taken at face value. The first red CCD detector in these observations has the least accurate wavelength calibration due to poor coverage by the arc spectra. It is possible that the radial velocity of the [OI] line is different to the [OII] line, but this would further complicate the interpretation, requiring the existence of spectra with only single emission lines. At present it appears probable that the combined effects of less accurate red wavelength calibration, and the influence on the line shapes caused by the subtraction of strong night-sky [OI] emission, could conceivably produce the discrepancy observed (about 7 Å or about 4 pixels).

The [OI] line is affected by poor photon statistics and is non-Gaussian in shape. The line height is almost equal to the height of the blue-shifted [OII] line, and when a Gaussian fit is made anyway, the area is around a half of the [OII] line (see table 5.3b). No other such strongly blue-shifted lines are observed in this spectrum, and in the following discussion it is assumed that the two lines are related, and have a common physical origin.

Without preempting the results from Chapter 6, the ionization front models developed there provide a possible explanation for this type of spectrum. The time dependence of the line ratios in the ionization front structure are shown in figure 6.10. The early stages of the emission are dominated by [OI] emission, followed by [OII] emission. In the final stages, the [OIII] approaches the [OII] emission levels. The period when both the [OI] and [OII] emission are of comparable strength, while the [OIII] emission is weak, is confined to the first $10^6 - 10^7$ seconds, at the densities considered, a matter of months. The typical filaments would have an age of around $10^8 - 10^9$ seconds, consistent with the hydrodynamic arguments also presented in Chapter 6.

The conclusion is therefore that this filament is very young. While it is not possible to estimate the error induced by the limitations of the modeling procedures, the filament is probably genuinely young compared to the other knots of oxygen rich material. Follow-up observations over the next few years would be valuable in assessing the validity of this model.

5.3.3 A Dynamical Model

The velocity map of N132D reveals a number of significant features. Firstly, the normal composition material in the N132D remnant all displays low radial velocity, while the oxygen-rich material is almost exclusively of high velocity, except at the periphery of the expansion region as might be expected. Furthermore, as may be seen in the velocity map and the spectra of Appendix B, the oxygen-rich material is often spatially superimposed on material of more normal composition. This occurred not only for the obvious broad-line feature in aperture 20, but also in apertures 4, 5, 9, 10, 11, 14 and possibly 15 as well. This represents the majority of the oxygen-rich knots, and lends support to a model where the excitation is the result of direct interaction of the fast moving oxygen-rich material and the slow-moving, visible, normal composition material.

More specifically, the oxygen-rich material does not appear to form an expanding circular ring structure as was suggested by Lasker (1978,1980), but is found throughout the central regions of the remnant. The broad-line cloud, marked by **B** in figure 5.4, is incompatible with a simple expanding ring model. The most coherent structure in the remnant is formed by the low velocity normal composition material with spectra like that shown in aperture 6 (Appendix B, figure B.3).

Based on these observations, a simple qualitative model is proposed for this remnant to explain the remnant structure as currently observed. The ellipse of normal composition material represents the remains of a ring nebula, possibly produced in a dense stellar wind phase of the progenitor's evolution such as seen in WN ejecta-type ring nebulae. The expansion of the main SN blastwave has partially disrupted this material leaving behind only the densest knots rather than a complete ring or shell. The oxygen-rich ejecta is expanding ballistically in all directions, and interacting with reflected bowshocks from the circumstellar nebula knots, or colliding directly with the circumstellar material.

The X-ray work by Hughes (1987) suggested that the SNR is expanding into a low density cavity. Hughes used the discrepancy between the age of 1,300 years due to Lasker (1980) and the 4,000-7,000 year age derived from the X-ray observations, to conclude that the outer blast-front at 16 pc radius from the center has not decelerated, and is still expanding at at least $12,000 \text{ km s}^{-1}$. A very low density cavity environment was proposed to account for this. The age of $\sim 2,300$ years derived here gives a somewhat lower mean blast front velocity of $6,700 \text{ km s}^{-1}$. Thus some deceleration may have occurred, and the very low density cavity argument is weakened, but not ruled out, since age is still significantly

lower than the age that the X-ray Sedov solution gives.

Further evidence that N132D has not yet achieved the Sedov expansion phase is given by Australia Telescope 3 and 6 cm radio observations by Dickel & Milne (1993, private communication). The preliminary polarization results show that the magnetic field in the remnant is largely radial. This is usually interpreted as being characteristic of young SNR in the pre-Sedov stages of dynamical evolution. If this is the case, then this supports the cavity environment hypothesis, allowing the remnant to remain dynamically young by not having swept up a significant amount of interstellar medium after a period of 2300 years.

We therefore propose a model of N132D with a WR star progenitor to provide a large low density cavity and a small ring nebula environment, with which the supernova ejecta is continuing to interact. This model would then give a natural explanation for the range of velocities observed in the SNR material. The ejecta is simply freely expanding in all directions until it encounters density contrasts in the inner regions due to the ring material. The broad-line cloud is a case where a larger cloud of oxygen-rich material straddles a slow-moving knot. Finally, the outer blast-wave is continuing to expand rapidly into a low density cavity and has therefore not been decelerated into the dynamical Sedov expansion phase.

The model structure is summarized in figure 5.7.

5.4 Puppis A and SNR G292.0+1.8

5.4.1 Observations

In this study of Puppis A, spectra of 20 individual filaments have been obtained. Eight of the slit positions revealed classical oxygen-rich material, including the 'Omega' filament, and are discussed here. Other spectra taken, particularly in the North-West of the remnant, displayed unusual spectra with very strong emission of [NI] and [NII]. This is almost certainly due to actual nitrogen enhancements in that material, and a full presentation of that data will be made elsewhere. In some of the oxygen-rich spectra faint lines of species other than oxygen and neon have also been observed, including nitrogen and sulfur. This poses some problems for interpretation, but these spectra are not examined in detail in this study.

The Puppis A remnant offers the opportunity to observe individually resolved filaments without the confusion in velocity space seen in N132D. The SNR G292.0+1.8 observation represents the other extreme, where only a global spectrum of the remnant is obtained and the lines are broadened by the entire

N132D SNR Model

FIGURE 5.7: A structural model for the OSNR N132D. The observed oxygen-rich material is expanding and interacting with density discontinuities in the remnant medium. The 'reverse shock' indicated here is intended to represent reflected shocks, either from the blastwave itself or other secondary shocks. The slow moving material (*c.f.* the QSF of Cassiopeia A) may lie in a ring nebula and be providing reflecting surfaces for the shockwaves. This model can provide a natural explanation for the broad-line knot as a large mass of oxygen rich material straddles a cloud of normal material travelling across the line of sight while still expanding.

velocity range of many unresolved oxygen-rich clouds.

An [OIII] Schmidt plate was used as a finding chart for Puppis A (a part of which is reproduced in figure 5.8). This plate was obtained for Dopita on March 25th 1983 with the UK Schmidt 48 inch camera, in a 240 minute exposure through an [OIII] interference filter. Several [OIII] knots were identified in addition to the bright 'Omega' filament of Winkler & Kirshner (1985) and the filaments of Winkler *et al.* (1988). The filaments are identified in figure 5.8 and listed in table 5.2. The figure also shows the proper motion center obtained by Winkler *et al.* (1988). It is tantalizingly close to the small group of circular arcs at around RA 8h 22m 42s, Dec $-42^{\circ} 59m 15s$ (J2000) with a diameter of about 2 arc minutes. These arcs have already been noted by Winkler *et al.* (1989) and have been suggested as possibly being a second SNR embedded within the Puppis A bubble. This suggestion is based on the lack of separate X-ray or Radio emission from this region. The arcs are highly chemically inhomogeneous and contain strong and spatially segregated nitrogen, oxygen and sulfur emission. The proximity to the proper-motion center suggests that the arcs are in some way associated with the Puppis A remnant itself, perhaps associated with what ever remains of the progenitor star. Spectra of these central arcs were obtained and will be presented in a future study. They are not strictly oxygen-rich, containing sulfur and, importantly, nitrogen emission, indicating that they are probably not from deep layers of the progenitor.

Using the ANU 2.3m ATT DBS PCA system described earlier, individual knots were observed with exposures ranging from 2,000 to 3,000 seconds. Multiple observations were made of the bright 'Omega' filament in particular, totalling some 7,000 seconds of integration. The spectra obtained are shown in Appendix B figures B.14 - B.21. The measured fluxes and ratios have been summarized in tables 5.4a and 5.4b. Even with the extended integration, no new faint lines were identified in the 'Omega' filament. No emission due to magnesium, argon or calcium was detected in the oxygen-rich material.

The center-filled SNR G292.0+1.8 (Goss *et al.* 1979) suffers from heavy interstellar reddening along the line of sight, and it lies in a fairly crowded field. A CCD image obtained by S. D. Ryder with the ANU 40" telescope was used to position the slit so as to avoid the brightest of the field stars. The spectrum is of relatively poor S/N, but is important nevertheless as another data point in the all too small sample of oxygen-rich spectra.

The SNR G292.0+1.8 observation was a 3,000 second exposure. The spectrum is shown in Appendix B, figure B.22 and the reduction was carried out

FIGURE 5.5: Slit positions for Puppis A. The positions, size and position angles of the observed slit positions for oxygen rich filaments in Puppis A are overlaid on the [OIII] finding chart of Dopita (1989). The oval represents the proper motion center derived by Winkler *et. al.* (1988).

concurrently with the Puppis A observations. The measured fluxes and ratios are summarized along with the Puppis A results in table 5.4b.

Reddening

The galactic remnants suffer from quite strong and/or patchy reddening. The lack of Balmer emission lines makes it difficult to determine the reddening for individual oxygen-rich knots in Puppis A, and values for nearby knots with Balmer lines may not be appropriate. Ratios derived from oxygen lines alone are fraught with modeling assumptions, and are not used to derive a value of c here. A value of $A_v = 1.5$ ($c = 0.7$) was estimated by Winkler & Kirshner (1985), and for the estimated distance of 2-2.5 kpc this is not unreasonable. However, the presence of dusty clouds in the region (*c.f.* Arendt *et al.* 1990) is consistent with the patchy absorption across the face of this remnant. As a consequence, the reddening for the observations of this remnant remain quite uncertain on a filament-by-filament basis.

The SNR G292.0+1.8 observation does not show Balmer lines, although a reddening excess of $E(B - V) = 0.9$ ($c = 1.3$) has been quoted for the remnant (Goss *et al.* 1979), based on HI absorption measurements. The small apparent size of SNR G292.0+1.8 means that a single reddening constant is likely to be applicable to the remnant.

5.5 Results

The measured line ratios have been given in raw form without reddening corrections, and line ratios are plotted here as observed. The expected trends caused by reddening effects are estimated, so that the reliability or otherwise of the ratios can be inferred. Given the estimated reddening of $c = 0.2$ for the remnant N132D, and estimates from the literature for Puppis A and SNR G292.0+1.8 of $c = 0.7$ and $c = 1.3$ respectively (Winkler & Kirshner 1985; Goss *et al.* 1979), one can use the intermediate vector of $c = 0.5$ ($E(B - V) \approx 0.35$) given on the plots, to estimate the general effect of reddening with the minimum number of assumptions about each individual observation.

The spread of ratios in the diagnostic plots, particularly the I_{7325} / I_{3727} ratio in figure 5.11, is mostly along the reddening vectors, with considerable scatter. For the resolved Puppis A observations, it is not even obvious that one reddening value is appropriate to all the knots. Interestingly, the single point that repre-

sents the SNR G292.0+1.8 remnant on these raw plots does not appear to be particularly reddened, tending instead to lie closer to the N132D points. Rather than dispute the heavy reddening given for this remnant, this result highlights the problems inherent in attempting to make plasma diagnostics without a detailed model for the ionization structure.

5.5.1 Oxygen Line Ratios

The oxygen line ratios for all the remnants are plotted together in figures 5.9 - 5.11, for those spectra with sufficient lines. There are important selection effects, as the [OIII] λ 4363 and [OII] $\lambda\lambda$ 7320+30 lines are generally only detected where they are strong, biasing the distribution of points in the plots. This should be borne in mind before any conclusions are drawn. In all the plots, the x -axis is chosen to be the ionization sensitive I_{5007} / I_{3727} ratio.

These plots are sensitive to the physical parameters of the emitting plasma. The [OII] $\lambda\lambda$ 3727 line is sensitive to collisional quenching, so ratios of this line with other less sensitive lines such as [OIII] λ 5007 or [OII] $\lambda\lambda$ 7320+30 give density diagnostics. The [OIII] λ 4363 line is a well known temperature sensitive line when in ratio with the [OIII] λ 5007 and [OIII] λ 4959 lines.

The value of the temperature sensitive [OIII] I_{4363} / I_{5007} ratio (figure 5.9) immediately indicates a combination of photoionization and shock heating. Normal photoionization conditions cannot generate the high I_{4363} / I_{5007} values. These would normally be less than 0.01. Shock models do not typically produce the observed I_{5007} / I_{3727} ratio either. This type of problem has features in common with the Centaurus A filament emission studied in Chapter 4. An interpretation based on either a pure shock or a photoionization model is rendered even more untenable when the composition of the plasma is taken into account. The work by Dopita *et al.* (1984) and the results in Chapter 6 show that the oxygen-rich plasmas have photoionization equilibrium temperatures which are much lower than normal composition photoionization, exacerbating the [OIII] λ 4363 flux deficit. In contrast, the pure shock models in this type of plasma produce *too much* [OIII] λ 4363 radiation.

The scatter in this plot is not very great in the vertical direction. This result should not be strongly affected by uncertainty in the reddening. All three remnants appear to display similar line ratios, both in their density and temperature sensitive ratios, suggesting a common mechanism of excitation.

The mean $\log(I_{4363} / I_{5007})$ is calculated as -1.38, with a standard error in

the mean of 0.05 and a standard deviation of 0.15. If interpreted in terms of a homogeneous single slab model, this ratio would correspond to a mean electron temperature of 22,250 K in the low density limit, with a range from 18,000 K to 29,000 K. As discussed briefly above and in more detail in Chapter 6, such a simple interpretation is unlikely to be valid. The lower limit for reliable detection of the [OIII] λ 4363 line in these spectra is $\log(I_{4363} / I_{5007}) \approx -1.50$. Thus, although the points do seem to cluster around -1.38, lower values may in fact be more common but are not detected here. The very high values, outside the standard deviations, are the most reliable measurements and do not reflect simple measurement errors. In summary, while a number of points occur at $y \approx -1.4$ this does not exclude the possibility of a wider range of physical conditions actually occurring in reality.

The next plot (figure 5.10) considered combines all three observed stages of ionization of oxygen. In normal cosmic plasmas, charge-exchange reactions tie the oxygen ionization balance strongly to the hydrogen balance. In the plasmas considered here, it is not known whether other charge-exchange reactions take place, such as oxygen-neon reactions, and no atomic data exists yet to model them even if they do occur. With this in mind, the plot can be considered to be sensitive to both the ionization state of the plasma, as well as the density. This weakens the plot as a diagnostic tool for determining unique plasma properties. However, the scatter is not too great, and although there is some spread along the reddening direction, there does seem to be some remaining vertical separation between the N132D and Puppis A remnants implying a difference in temperature and/or density. The previous result on temperature suggests that some of the scatter here is density related.

The final plot (Figure 5.11) shows I_{7325} / I_{3727} on the vertical axis, with the I_{3727} / I_{5007} ratio along the horizontal, as in previous plots. The I_{7325} / I_{3727} ratio is a density sensitive ratio. The points on this plot display a clear correlation with a smaller scatter than the previous plots. Care should still be taken however, as the trend is also in the direction of the reddening vector. Given this caveat, this plot also supports the view that the Puppis A filaments may have higher densities than the N132D filaments, although the number of knots where the red [OII] lines have been measured is small. The spread along the observed trend either implies patchy reddening, or a range of densities.

In the temperature range of $(2 - 3) \times 10^4$ K, the I_{7325} / I_{3727} ratio is quite a good density diagnostic, while remaining somewhat sensitive to temperature. For a homogeneous model, the density may be estimated for a given temperature. The density behavior of the I_{7325} / I_{3727} ratio has been calculated with a single-slab,

oxygen-rich model at 20,000 K and 30,000 K. The results are shown as horizontal grey bands in the plot. These bands indicate the resulting temperature spread of the ratio, in density models, for decades of particle number densities. The bands are for oxygen ion densities of 10^2 , 10^3 and 10^4 cm^{-3} . The lower line shows the low-density limit. While such a homogeneous model is clearly too simplistic, it seems reasonable to assume that the [OII] emitting zones have densities somewhat less than 10^4 cm^{-3} , possibly $< 10^3 \text{ cm}^{-3}$ if reddening is moderate or heavy in the Puppis A knots. More precise estimates than this approximate limit are unjustified until a consistent model for the ionization and density structure has determined.

This $< 10^3 \text{ cm}^{-3}$ density is quite low, and suggests that much of the [OII] radiation does *not* come from the cooling zone of a shock structure. The oxygen-rich shocks in particular display enormous compression factors (10^3 – 10^4 or more) even with magnetic field support at μGauss levels. Any reasonable precursor density will result in much higher densities in the [OII] emitting zones than is seen here. This is a result of isobaric cooling from the very large shock jump temperatures, which are in turn due to the large mean particle mass in the plasmas.

The tables 5.3a - 5.4b in the previous section give all the relative line fluxes detected for each aperture in each remnant in turn, many of which cannot be plotted here due to non-detections, mostly in the [OII] $\lambda\lambda 7320+30$ lines.

5.5.2 Neon Lines

The [NeIII] $\lambda 3869$ line is the most commonly observed line apart from the oxygen lines, and it is present in most of the spectra. Importantly, the [NeV] $\lambda 3426$ line was not detected, indicating that it has an intensity significantly less than the observed [NeIII] lines in all cases. This may place constraints on the range of velocities allowable in any shock modeling. This constraint is independent to some degree from constraints that may be derived from the oxygen lines.

The presence of such universal neon emission provides supporting evidence that the majority of the emitting material indeed comes from the deep oxygen-neon layers of the proposed massive progenitor stars. Neon is a species common in all the published massive stellar evolution models, at levels high enough to give the general abundance level seen across all the remnants. An oxygen to neon ratio of around 0.4 by number has been successful in the modeling procedures presented in Chapter 6, consistent with the stellar models.

Although the [NeV] emission turns out to be a non-linear function of the shock velocity in the models of Chapter 6, it is generally true that the [NeV] emission

FIGURE 5.9: Raw line flux ratios. The solid line shows the mean $\log(I_{4363}/I_{5007})$ ratio and the dashed lines are the standard deviations. A reddening vector for $c = 0.5$ is shown.

FIGURE 5.10: Raw $\log(I_{3727}/I_{6300})$ vs $\log(I_{5007}/I_{3727})$ line ratios. These ratios are sensitive to both density and ionization, and it is hard to separate these effects in this plot. A reddening vector for $c = 0.5$ is shown. This indicates that the apparent trend may be simply due to reddening.

FIGURE 5.11: This plot shows the line ratios, $\log(I_{7325}/I_{3727})$ vs $\log(I_{3727}/I_{5007})$. The horizontal bands indicate the range of I_{7325}/I_{3727} ratio for a homogeneous, single-slab models with electron temperatures of 20,000 and 30,000 K. The bands are for number densities of oxygen atoms of 10^4 , 10^3 , and 10^2 cm^{-3} . The lower limit is for 1 cm^{-3} . If the density is as great as $c = 0.5$, then the density of the [OII] emitting zones are most likely 10^3 cm^{-3} or less.

only becomes strong in shocks above 150 km s^{-1} . Whether or not this places strong constraints on the final modeling remains to be seen.

5.5.3 Hydrogen, Nitrogen and Sulfur Lines

In the standard nucleosynthesis evolution models of massive stars, it is only in the outer layers that hydrogen and nitrogen can survive. Filaments were detected in both N132D and Puppis A which displayed hydrogen and nitrogen in various degrees. In the context of oxygen-rich plasmas, only those which also displayed strong oxygen emission are presented here.

In N132D, the aperture 16 lies on the edge of the faint north west ‘extension’ that makes the remnant more circular. It displays a spectrum that contains weak hydrogen recombination lines, and bears a remarkable resemblance to the cloud-cloud collision spectra observed in the Centaurus A EELR (see Chapter 4). It seems reasonable to suggest that this is the result of a normal composition cloud-cloud collision, and the strong [OII] and [OIII] emission may not be abundance related. Emission from all of the common species can be seen in the spectrum which is shown in Appendix B, figure B.12.

In Puppis A a more complex situation is observed. The slit positions O11, O12 and O13 lie along an apparently connected structure, which displays oxygen emission throughout. The positions towards the remnant center (O13 and O12) also display [SII] emission as might naively be expected. However, these spectra also display strong [NII] emission and aperture O12 shows weak $H\alpha$ emission. (see Appendix B, figures B.19, B.20, B.21) The explanation for this is not clear. Morphologically, the structure (seen poorly in figure 5.8) is suggestive of some type of surface instability. Whether this is another ring nebula remnant, or is an outer stellar layer which has been pushed out in an unstable fashion by hot oxygen-rich material (with subsequent mixing) is uncertain. A relatively weak conclusion is therefore that the sulfur is most likely of cosmic origin, like the observed nitrogen, and not direct nuclear processed material from the deepest layers of the progenitor star.

5.6 Summary

The observational program presented here provided some new data in the study of the class of oxygen-rich super nova remnants. The detailed analysis, beyond the derivation of global properties, has been deferred to Chapter 6. However, a

number of general conclusions can already be drawn.

The continuum subtracted narrow-band images of N132D have revealed the extent of the remnant. A faint extension to the North-West makes the remnant appear more nearly circular. The relatively poor seeing conditions prevented detailed comparisons with earlier epoch observations. When the [OIII] and H α images are combined, the chemical inhomogeneities in the well-known inner complex is clear. The [OII] velocity map shows that this conclusion is not affected by the selection effect of the narrow filter band-passes, which caused some high velocity oxygen-rich material to be excluded from the CCD imaging.

A coherent structure in the low velocity, normal composition material is proposed, and has been fitted by an ellipse with a semi-major axis of $\sim 30''$ (~ 14 pc). The oxygen-rich material appears distributed throughout the ellipse region. When the ellipse center is used to fit a circular geometry to the outer parts of the SNR, the South-East edge is well fitted by a radius of $65''$ (15.6 pc). The North-West edge falls somewhat short of this radius. This might suggest that there is a slightly higher density in the cavity medium in that direction.

A velocity expansion analysis of the oxygen-rich material, using the same center, gives a maximum extrapolated expansion velocity range of $5,310 \pm 500 \text{ km s}^{-1}$. The detection of oxygen-rich material well outside the 6 pc diameter ring of Lasker (1980), gives a maximum 12.4 ± 2.4 pc extent here. This results in an expansion age of $2,350 \pm 520$ years, between the Lasker value and the rough $\sim 3,400$ year value estimated by Danziger & Dennefeld (1976a,b). The Lasker (1980) age is certainly an underestimate of the true value

A model in which a Wolf-Rayet progenitor has substantially modified the circumstellar environment before the explosion is proposed for this remnant. This is based on the presence of a ring nebula, the cavity environment and the presence of oxygen-neon rich material, which all suggest such a massive progenitor.

The relative spectrophotometry obtained for the three remnants gives a consistent database for the sample, making spectral comparisons a little more meaningful. The spectral results for the oxygen-rich material in all three remnants shows that the observed knots may vary in density, but show a fairly consistent temperature. This suggests a common excitation mechanism in a range of knots of different densities. Quantitative estimates of the actual plasma temperatures and densities are deferred until the modeling framework is developed.

The sample here remains small, and these results will be combined with values from the literature for other remnants in the analysis of Chapter 6.

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Chapter 6

Oxygen–Rich Plasma Emission

6.1 Background

In the vast majority of cases, astrophysical plasma emission is dominated by emission from ions and molecules of hydrogen. The other elements can generally be considered as ‘contamination’ in the hydrogen plasma, although some elements such as carbon and oxygen can have a significant impact on the plasma properties, even at the low relative abundance levels observed. A small class of young supernova remnants exists in which emission has been detected from plasma with a very different composition, providing the exception to the hydrogen domination seen elsewhere. The archetypical example is the northern Cassiopeia A remnant (*c.f.* Chevalier & Kirshner 1979 and references therein), where emission in some small knots is apparently devoid of hydrogen emission altogether. Some knots show emission from sulfur, argon and calcium, and others show forbidden line emission, of purely oxygen, or oxygen and neon lines. This has been generally interpreted as the excitation of, and emission by, material from the deep layers of a massive star, laid bare by the supernova explosion.

The fragments of oxygen-rich material themselves may have been formed during expected phases of Rayleigh–Taylor (R–T) instability in the interface regions, between layers of different composition, during the early stages ($<20,000$ s) of the supernova explosion. The detailed multi-dimensional hydrodynamic models by Fryxell *et al.* (1991), in particular, suggest that the interface between the oxygen-rich layers and the overlying helium-rich layer will suffer strong R–T instabilities with only small initial perturbations. The resulting ‘fingers’ of core material that penetrate the outer layers also exhibit surface Kelvin–Helmholtz instabilities, which has been assumed will eventually lead to the fragmentation of

the fingers into clumps of material. These may then mix with the outer helium and hydrogen layers of the star. With the large oxygen–neon layers expected in the massive star models, it seems reasonable to assume that some of the resulting clumps would be oxygen–neon material, although the details of subsequent mixing and dissipation of the material is still very uncertain. There is also more direct observational evidence of the formation of a ‘clumpy’ distribution of oxygen material in SN 1987A by Stathakis *et al.* (1991) and Li & McCray (1992). These studies together suggest that the formation of oxygen–rich clouds are a natural consequence of the physics of a massive star supernova explosion.

In Wolf–Rayet progenitors, sometimes proposed for the oxygen–rich supernova remnants (OSNRs), the massive outer hydrogen layers of a red giant will not be present. This might help to make the eventual exposure of the oxygen–rich knots more likely to occur before they are dissipated.

At present there are seven OSNR known: Cassiopeia A, SNR G292.0+1.8, Puppis A, SNR 0540-69.3, N132D, SNR E102.2-7219 and an anonymous SNR in NGC 4449 (*c.f.* Chevalier 1975; Chevalier & Kirshner 1978; Goss *et al.* 1979; Murdin & Clark 1979; Winkler & Kirshner 1985; Mathewson *et al.* 1980; Danzinger & Dennefeld 1976a,b; Lasker 1978; Dopita *et al.* 1981; Balick & Heckman 1978; Blair *et al.* 1983). The observational background of these objects has already been covered in Chapter 5 §5.1. A summary of some observed properties of the OSNR is given in §6.2 below.

Despite the small sample, with a range of sizes and ages, a number of consistent features are apparent in the observed emission. With the exception of SNR 0540-69.3, which shows no neon, all display some material with both oxygen and neon line emission. This oxygen–rich material is always present in small, fast-moving knots of material. The limited plasma diagnostics available from the optical line ratios show remarkably similar values for the apparent electron temperature, and to a lesser extent, similar densities. Without a detailed model, however, the interpretations of the measured properties are not particularly well constrained. Unfortunately, when constraints are sought in UV observations, in the hope of detecting more emission lines to constrain the plasma diagnostics, the heavy reddening of the galactic remnants makes them undetectable. Only the relatively un-reddened Magellanic remnant SNR E102.2-7219 has had UV spectroscopy published to date (Blair *et al.* 1989). In that case it was clear that a simple photoionization or shock model is inappropriate, again leaving the interpretation of the spectra uncertain.

Our ability to take advantage of these observations, and gain an insight into

massive star, and supernova nucleosynthetic and explosion processes, therefore depends on our ability to model the emission process in the oxygen-rich clouds. In the past, attempts at modeling the oxygen-rich emission have concentrated largely on the consideration of the passage of fully radiative shocks passing through these fragments of stellar material. The shocks are assumed to be formed as the fragments, traveling on ballistic trajectories through the SNR, collide with reflected shockwaves that are generated as the main SN blast interacts with the circumstellar medium. The pioneering shock modeling investigations cast light upon a number of intrinsic difficulties caused by the unusually extreme composition of the model plasmas.

In this chapter we will consider a particular excitation model in some detail to determine its feasibility.

6.1.1 Radiative Shock Models

In the literature, a natural assumption has been made that the emission is due to slow, fully radiative shocks traveling through the emission knot material. Interestingly, the composition of the oxygen-rich material gives rise to some unusual structures in the shock models, that differ considerably from those of normal radiative shock models. The main feature is the enormous emissivity of the oxygen-rich material, resulting in extremely rapid cooling.

The highly efficient cooling of oxygen and neon ions can give rise to cooling timescales that are much shorter than the recombination timescales of the plasma. This results in the cooler plasma remaining far more highly ionized than expected (Itoh 1981a,b ; Dopita *et al.* 1984). The actual ionization state that is frozen into the cooling phase is determined by the competition of postshock ionization and cooling rate rates, which are of comparable magnitude. The plasma is usually far from equilibrium, even when compared to shock structures of similar temperatures in normal plasmas.

Shocks in oxygen plasma display very low temperatures in the recombination zone, even when the initial shock temperature is very high. For example, the 100 km s^{-1} shock computed here has a post shock temperature of $\sim 1.5 \times 10^6 \text{ K}$, but a temperature in the cooled zone of less than 300 K. This large ratio gives rise to very great compression factors, even when moderate magnetic fields are present. High compression causes collisional quenching in sensitive lines, such as [OII] $\lambda\lambda 3726+29$. The very low temperatures in the zones where OII and OI ions are formed means that the cooled zone does not radiate the [OII] $\lambda\lambda 3727$ or

[OI] λ 6300 lines that are normally associated with radiative shock models. Dopita *et al.* (1984) noted that in their models, most of the [OI] emission actually came from the head of the shock where the gas was being ionized, rather than in the downstream recombination zone.

In pure oxygen plasmas, when the electron temperature drops below a critical level, further cooling may be prevented due to the lack of efficient fine-structure cooling transitions in the p^3 OII ion. This might help produce optical [OII] emission in the recombination zone by maintaining the electron temperature. Unfortunately, when 'impurities' such as silicon, carbon and neon are introduced, many fine-structure channels for cooling exist, and the plasma cools rapidly to temperatures as low as 100 K, cutting off any optical forbidden emission, although recombination emission may possibly still occur.

The simple shock models to published date have suffered from these problems and exhibit a number of critical failures when compared to observations:

- The [OI] λ 6300 emission predicted in the models is too weak by orders of magnitude.
- The predicted value of $[\text{OIII}]I_{4363} / (I_{5007} + I_{4959})$ temperature sensitive ratio is not consistent with the observations.
- In order to accommodate both the observed $[\text{OII}]:[\text{OIII}] I_{3727} / I_{5007}$ and the $[\text{NeV}]:[\text{NeIII}] I_{3426} / I_{3869}$ ratios, the range of model shock velocities is restricted to 120 to 130 km s⁻¹ in all cases (Dopita *et al.* 1984). This is implausibly restrictive.

The work by Dopita *et al.* (1984) served to summarize the failings with the simple radiative shock models.

6.1.2 Alternative Models

Various alternatives to the simple radiative shock model have been proposed, having various degrees of success, namely:

- The oxygen fragments experience 'cosmic ray' heating from $\sim 10^4$ km s⁻¹ ions from the upstream medium. This will occur when the clouds are small compared to the ion Larmor radius or the magnetic field is not transverse, allowing ions to penetrate the oxygen-rich material, depositing energy by Coulomb interactions. (Dopita *et al.* 1984).
- A bow shock, consisting of high temperature plasma, builds up at the head of the oxygen cloud, creating a soft X-ray radiation field that produces ionization fronts, and shock waves, moving back into the body of the cloud

(Dopita 1987). This requires the cloud to be large enough to permit the formation of the bowshock–cloud shock structure.

- Knots are heated directly by thermal conduction from the surrounding hot material (Chevalier 1975; Dopita *et al.* 1984).
- ‘Normal’ radiative shocks passing through the oxygen–rich fragment, with the modification that the effects of electron thermal conduction have a significant effect on the thermal structure of the shock (Borkowski & Shull 1990).

These proposals share the common aim of trying to increase the electron temperature in the zones where OII and OI emission occurs, either the shock recombination tails or in photoionized ionization front zones. The present work is aimed specifically at taking the initial study by Dopita (1987) (hereafter D87) of the R-Type ionization front mechanism, and determining whether the model holds up under a set of more consistent physical conditions. The other models are not considered in the present work, and will not be discussed further except when they have direct implications for the present models.

The Ionization Front Models

In the model of D87, ionization fronts were formed in the oxygen–rich material when this was illuminated by the ionizing field, produced by relatively fast ($\gtrsim 500 \text{ km s}^{-1}$) shocks passing through the oxygen–rich material. In that work, the H- and He-like line emission of a fast oxygen–rich shock was approximated by an appropriate truncated power-law spectrum. Although the equilibrium photoionization temperatures of the irradiated plasmas were around 2–300 K, the initial deposition of energy by hard photons, through direct and Auger ionizations in the neutral plasma, produced a ‘super-heating’ effect. The peak temperature reached several tens of thousands of degrees in that study. The resulting spectra of the integrated ionization fronts were a significant improvement on the earlier radiative shock models. The low densities inferred for the resulting [OII] emitting regions is one of the more encouraging aspects of that model.

The present study tests whether a cloud–bowshock structure in an oxygen–rich medium can, in practice, achieve the conditions necessary to produce such ionization fronts. The formation of a suitable ionizing radiation field is critical to the model, and this rôle is filled by the shockwaves formed in the dynamical interaction. The emission from any resulting ionization fronts will be calculated, and the final spectra will be a sum of the shock and front spectra. The D87 work only considered the optical emission from the ionization front, since the very fast

shocks considered there as the source of soft X-rays, were unlikely to become radiative at optical wavelengths.

As has been seen in Chapter 5, the observed optical spectral data does not provide strong constraints on the plasma properties when considered as a homogeneous plasma slab. However, some general assumptions about temperatures and densities can be made to permit the modeling to begin. Other global properties, particularly size and observed lifetimes, provide important model parameters.

Therefore, the objectives of this chapter are:

1. To use the observation data to determine what physical constraints on spatial scales, temperatures and densities of the oxygen-rich emission material can be made.
2. To use these to describe a cloud-bowshock model in semi-qualitative terms.
3. To investigate the details of the expected shock structures, with particular reference their cooling timescales, and suitability as an ionizing source capable of driving an ionization front.
4. To provide constraints on the structure and properties of the ionization front models.
5. Based on these properties, to examine the parameter space of the modeling problem, to determine the parameters for the final modeling procedure.
6. Finally, to generate models, applicable to the the chosen parameter space, and to compared these with the observations.

6.2 Observational Summary

The literature of observations of the OSNRs covers multiple wavelengths. The optical spectra provide means to clearly differentiate the oxygen-rich material from other material and give limited temperature and density information. Imaging, photographic and CCD, provides information on morphology. Proper motion studies, combined with radial velocities from spectroscopy, give space velocity information. UV spectroscopy, when it has been possible, has detected other species (notably carbon, magnesium and possibly silicon) that do not radiate in the optical in any strength. X-ray observations have been made of some of the OSNRs, and this gives information about the hot phase that fills the SNRs. Information on the SNR plasma pressure and some composition information has been determined. Finally, IR and Radio 21 cm observations have proved useful in determining line of sight absorption and inferred distances for the galactic

remnants, in particular. More recently, the IR emission from dust within the hot X-ray plasma has been modeled (*i.e.* Dwek 1987; Arendt *et al.* 1991) which appreciably augment the X-ray diagnostics. Some selected observations of the OSNRs, concentrating on the global SNR properties and the hot X-ray SNR medium, are summarized in table 6.1.

The optical emission from oxygen-rich material has been summarized in table 6.2. This table includes observations from the literature, and the highest quality observations of Chapter 5. The literature observations have been taken from the published raw observations, and all the spectra have been de-reddened using the same reddening curve method of Kaler (1976), for consistency. The normal logarithmic reddening constant formalism is used, where $I = I_0 10^{cf(\lambda)}$. The observed intensity for a given line is given by I , the original intensity is I_0 , $f(\lambda)$ is the reddening curve and c is the reddening constant. The curve of Kaler (1976) is based on the Whitford (1958) curve. When reddening has been expressed in other works in terms of A_v extinction or $E(B - V)$ color excess, these have been related approximately by:

$$c \approx 1.44E(B - V) = 0.863A_v \quad (6.1)$$

The reddening constants themselves have been collated from the literature and observations in this thesis.

6.3 The Cloud–Bow Shock Model

The proposed model structure is that of an individual knot, or cloud, of oxygen-rich material which is traveling on a ballistic trajectory in a low density medium. The cloud encounters a density discontinuity at a relative velocity of several thousand km s^{-1} . The discontinuity may be the reverse shock of the main SN blastwave, or some other local density contrast. The collision is highly supersonic in all the media. If a nominal density contrast of 1:100 is assumed between the ambient material and the cloud itself, cloud shocks of hundreds of km s^{-1} result.

The cloud in this model is classed as ‘small’ by the criterion of McKee (1988), but not so small that the hydrodynamic treatment is invalid. A characteristic size of about 10^{17} cm has been taken on the basis of the Kamper and van den Bergh work (1976,1983,1985) on Cassiopeia A, and Winkler *et al.* (1988) on Puppis A, the two most spatially resolved remnants.

To permit a hydrodynamic treatment, the ballistic penetration of upstream ions should be small. The presence of a magnetic field B , results in a Larmor

TABLE 6.1: OXYGEN-RICH SNR DIMENSIONS

SNR (<i>refs.</i>)	Distance (kpc)	Diameter (pc)	L_X $\times 10^{36} \text{ ergs s}^{-1}$	T_X $\times 10^6 \text{ K}$	n_e (cm^{-3})	Age ($\times 10^{10} \text{ s}$)
Cassiopeia A ^a	2.9	1.3-1.7	5	7.5/33	10-60	1.3
Puppis A ^b	1.8-2	12-14	~ 1	1-15	0.3-1	11.0
SNR G292.0+1.8 ^c	3.6	3(6)	1.3	6/46	1	4.7
N132D ^d	50	6/32(80)	45-83	6.6/46	1.6	7.4
SNR 0540-69.3 ^e	50	2	8.4	...	...	2.4
SNR E102.2-7219 ^f	60	7(12)	15-20	6/46	3.6	6.8

NOTES:

Sizes: Hyphens give a range for non-circular shapes.

Brackets enclose value for outer structures such as diffuse halos.

Slashes separate radii for structures in the main SNR.

Luminosities & Temperatures: These are uncertain.

The luminosities refer to various bands in the 1-20 keV range, mostly 0.2-4.5 keV, from *Einstein* observations.

The older references often make assumptions about CIE ionization, and may overestimate the densities as a result.

Slashes separate temperatures for two component fits.

SELECTED REFERENCES:

^a. Fabian *et al.* (1980), Jansen *et al.* (1988)

^b. Winkler *et al.* (1981), Winkler *et al.* (1983), Arendt *et al.* (1991)

^c. Clark *et al.* (1980), Clark *et al.* (1982), Tuohy *et al.* (1982)

^d. Lasker (1978), Long *et al.* (1981), Hughes (1987), Chapter 5

^e. Clark *et al.* (1982), Long *et al.* (1981), Seward & Harnden (1984)

^f. Seward & Mitchel (1981), Dopita & Tuohy (1984)

TABLE 6.2: OXYGEN-RICH REMNANT OBSERVATIONS.
DE-REDDENED OPTICAL OXYGEN AND NEON SPECTRA, $I_{5007} = 1.000$

		SNR 0540-69.3									
Transition		Cas. A ^{a.}	G292 ^{b.}	E102. ^{b.}	N132D ^{b.}	D&T84 ^{b.}	K89 ^{c.}	Pup. A ^{d.}			
Est. Red. (c)		2.06 ^{1.}	1.3 ^{2.}	0.04 ^{3.}	0.2 ^{4.}	0.2 ^{4.}	0.3 ^{5.}	0.7 ^{6.}			
[OII]	$\lambda\lambda 7320+30$	0.17	0.03	...	0.09	0.02	0.05	0.07			
[OI]	$\lambda 6300$	0.04	0.02	0.03	0.10	0.03	0.05	0.06			
[OIII]	$\lambda 5007$	1.00	1.00	1.00	1.00	1.00	1.00	1.00			
[OIII]	$\lambda 4959$	0.26	0.33	0.34	0.34	0.30	...	0.28			
[OIII]	$\lambda 4363$	0.03	0.05	0.04	0.05	0.03	0.07	0.04			
[NeIII]	$\lambda 3869$	0.30	0.16	0.14	0.10	...	0.02	0.16			
[OII]	$\lambda\lambda 3727$	0.58	2.12	1.34	2.39	0.63	0.39	1.69			
[NeV]	$\lambda 3426$	...	...	0.04	...	...	...	...			
$\log(I_{7325}/I_{3727})$		-0.54	-1.84	...	-1.44	-1.58	-0.86	-1.36			
$\log(I_{5007}/I_{3727})$		0.23	-0.33	-0.13	-0.38	0.20	0.40	-0.23			
$\log(I_{3727}/I_{6300})$		1.18	1.95	1.67	1.39	1.39	0.89	1.46			
$\log(I_{4363}/I_{5007})$		-1.52	-1.26	-1.36	-1.32	-1.46	-1.18	-1.35			
$\log(I_{3426}/I_{3869})$		...	...	-0.60	...	...	...	...			
Transition		Ω	Puppis A ^{e.}	O3	O4	7A	N132D ^{e.}	8A	11	G292 ^{e.}	global
Est. Red. (c)		0.7 ^{6.}	0.7 ^{6.}	0.7 ^{6.}	0.7 ^{6.}	0.2 ^{7.}	0.2 ^{7.}	0.2 ^{7.}	0.2 ^{7.}	1.3 ^{2.}	
[OII]	$\lambda\lambda 7320+30$	0.15	0.16	0.14	0.07	0.09	...	...	...	...	
[OI]	$\lambda 6300$	0.10	...	...	...	0.01	0.04	0.04	0.04	0.03	
[OIII]	$\lambda 5007$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
[OIII]	$\lambda 4959$	0.35	0.36	0.35	0.38	0.35	0.35	0.33	0.33	0.35	
[OIII]	$\lambda 4363$	0.05	...	...	...	0.04	0.04	0.03	0.03	0.08	
[NeIII]	$\lambda 3869$	0.19	...	...	...	0.14	0.05	0.08	0.08	0.26	
[OII]	$\lambda\lambda 3727$	2.03	0.93	2.87	1.94	2.03	2.03	1.66	1.66	3.54	
[NeV]	$\lambda 3426$	...	...	...	...	...	...	...	...	...	
$\log(I_{7325}/I_{3727})$		-1.13	-0.77	-1.32	-1.41	-1.33	...	...	...	...	
$\log(I_{5007}/I_{3727})$		-0.31	0.03	-0.46	-0.29	-0.31	-0.22	-0.22	-0.22	-0.55	
$\log(I_{3727}/I_{6300})$		1.32	...	...	...	2.13	1.67	1.57	1.57	2.10	
$\log(I_{4363}/I_{5007})$		-1.29	...	...	...	-1.38	-1.36	-1.55	-1.55	-1.10	
$\log(I_{3426}/I_{3869})$		...	...	...	...	...	...	...	...	...	

^{1.} Chevalier & Kirshner 1979, based on Searle 1971

^{2.} Goss *et al.* 1979; Braun *et al.* 1986

^{3.} Blair *et al.* 1989

^{4.} Danzinger & Leibowitz 1985

^{5.} Kirshner *et al.* 1989

^{6.} Winkler & Kirshner 1985

^{7.} Present Work, Chapter 5

^{a.} Chevalier & Kirshner 1979 (C&K79)

^{b.} Dopita & Tuohy 1984 (D&T84)

^{c.} Kirshner *et al.* 1989 (K&T89)

^{d.} Winkler & Kirshner 1985 (W&K85)

^{e.} Present Work, Chapter 5

radius r_L for ions of mass m , velocity v and charge Z of:

$$r_L = vmc/(ZeB) \text{ cm} \quad (6.2)$$

With a relatively small field of $1.0 \mu\text{G}$, penetration of ions into the cloud is of the order $r_L = 3.1 \times 10^{12} \text{ cm}$ for $5,000 \text{ km s}^{-1}$ O VIII ions, and less for lighter ions. This is much less than the 10^{17} cm clouds considered here, so that we may assume that ion penetration is not important, and bowshock structures can form. The shock models in subsequent modeling include a $1.0 \mu\text{G}$ transverse magnetic field to remain consistent with this assumption.

The model structure is shown in schematic form in figure 6.1. The present modeling assumes supersonic flow v_A of the ambient medium relative to the cloud, producing a stand-off bowshock (B). In such a cloud-bowshock model, a number of characteristic pressure ratios, velocities and timescales are applicable. Following McKee & Cowie (1975):

When the Mach number of the collision is large, $M_A \geq 1$, the ratio of the ambient pressure and the pressure at the stagnation point, at the leading edge of the cloud, is given by:

$$F = \frac{p_A}{p_C} = \left(\frac{\gamma + 1}{2} \right)^{(\gamma+1)/(\gamma-1)} M_A^2 \left(\gamma - \frac{\gamma - 1}{2M_A^2} \right) \quad (6.3)$$

where M_A is the Mach number of the shock at A, p_A and p_C are the pressures at A and C, and γ is the usual ratio of specific heats ($\gamma = 5/3$ for the monatomic plasmas here). An approximation for the pressure ratio is:

$$F \approx 3.15 - 4.78x + 2.63x^2 \quad (6.4)$$

where $x = v_C/v_A$. This is a maximum when the internal cloud shock is slow compared to the flow velocity into the bowshock. Equations (6.3) and (6.4) assume spherical geometry near the stagnation point.

The stagnation pressure at (B) drives a shock into the cloud (C), called the cloud shock, at a velocity v_C . In this structure, the dynamic ram pressure of A and C can be related approximately by:

$$\rho_C v_C^2 \approx F \rho_A v_A^2 \quad (6.5)$$

This expression may be used to make order of magnitude estimates of the cloud density ρ_C from the observed X-ray emitting plasma pressure, if the X-ray pressure can be equated to p_A and the velocities can be assumed. In the model here, as opposed to main blastwave-cloud interaction of the McKee and Cowie model

FIGURE 6.1: The Schematic structure of the cloud-bowshock model. The cloud encounters a density contrast (A) (i.e. a reverse shock) at a relative velocity of several thousand km/s. The collision results in an approximately isobaric bowshock, an internal shock structure (B & C), and a supersonic, isochoric ionization front (D) that precedes the internal shock into the cloud (E). The present simplified model is limited these components, evolving over a cloud-crushing timescale. Other shock structures formed in the ablation and compression of the knot in the hydrodynamic crushing process are not considered.

description, the velocity of interaction is taken to be of the order of the cloud space velocity, as it collides with a standing discontinuity. The discontinuity is either another bowshock around a slow-moving dense cloud of normal composition, or else is the reverse shock of the main blastwave.

As seen above, the relationship between the cloud velocity and the internal shock velocity will be proportional to the square root of the cloud/medium density contrast, χ . The stagnation pressure ratio, F , will in practice be geometry dependent, and usually somewhat less than 3. In plane parallel geometry $F = 1.0$, so that $v_A/v_C = \chi^{1/2}$. The modeling presented in the following sections assumes that if the range of cloud shock velocities is between 50–250 km s⁻¹, then the density contrast should be of order ≈ 100 . Therefore, models with cloud number densities from 10 to 1,000 cm⁻³ will be considered. With $\chi = 100$, this range is both consistent with the observed ambient densities in the range of 0.1 - 10 cm⁻³ (*c.f.* table 6.1), and will produce only minor line quenching complications. Models outside this range are both difficult to model, and harder to justify observationally. The exceptional densities in the Cassiopeia A remnant shown in table 6.1 suggests that these models may have difficulty matching the observed spectra of the Cassiopeia A knots.

For a cloud of radius a , and a density contrast, $\chi \gg 1$, the relevant timescales of the interaction are (McKee 1988):

$$\tau_c = \frac{a}{v_D} = \frac{\chi^{0.5} a}{v_A} \quad (\text{The cloud crushing time.}) \quad (6.6)$$

$$\tau_x = \frac{2a}{v_A} \quad (\text{The cloud crossing time.}) \quad (6.7)$$

With a typical knot velocity of 2,000 km s⁻¹ and knot dimensions of order 10¹⁷ cm, a crossing timescale is about 5×10^8 seconds. With χ between 10 and 100, a crushing timescale of $\sim 1 - 2.5 \times 10^9$ seconds is appropriate. These timescales are small compared to the SNR evolution timescales (*c.f.* table 6.1). The recent 3D numerical hydrodynamic of Stone & Norman *et al.* (1992), with a density contrast of $\chi = 10$, lends support to this estimate of the crushing timescale, and indicates that the cloud might expect to survive in a relatively complete state for about two crossing timescales (equation (6.7)). Therefore, the value of order 10⁹ s will be adopted as the hydrodynamic timescale. This is in very encouraging correspondence with the individual knot lifetime measurements for both the QSF and fast moving knots in Cassiopeia A, by the combined efforts of Kamper and van den Burgh (1976,1983,1985).

For the present work, the details of the cloud ablation, compression and disruption are not taken into consideration in their effects on the spectral modeling, other than to place an upper limit on the timescale of the problem. The geometry is assumed to be constant up to the crushing time, and after 10^9 s the cloud is assumed to be dispersed and destroyed, terminating the calculations. The simple shock and photoionization modeling here is based on a plane-parallel geometry. The ionization fronts travel at velocity v_D , which is supersonic in the cloud medium. This is therefore modeled as an isochoric, time-dependent photoionization problem, since the crossing, ionization heating and cooling timescales are all much faster than the sound crossing time.

The model of D87 assumed that non-radiative shocks (*i.e.* **B** in figure 6.1) in front of the cloud of oxygen-rich material, produced the local X-ray field in the cloud, which drove the ionization front. This locally generated field relieves the problem of trying to provide the intense field needed to drive an ionization front, using only the ambient radiation from the diffuse hot gas in the remnant as a whole (*c.f.* Blair *et al.* 1989). The radiation from non-equilibrium models by Hamilton *et al.* (1983) was approximated by power-law radiation fields, with different spectral indices and cut-off frequencies. Furthermore, it was assumed that the ionizing field was constant throughout the evolution of the ionization front. This approximation means that the field generated by the shocks must turn on, and become steady, very rapidly compared to the evolution timescale of the ionization front. The model of D87 used an ‘instant illumination’ approximation, where the full radiation field was applied from the start. Here, the extended MAPPINGS II code can consistently model both the shock emission and the ionization from models, within the one model framework, and this approximation can be tested by studying the emission evolution of the shocks in detail. This allows us to achieve a much greater degree of self-consistency.

The initial set of abundances for the preliminary models used to determine the parameters of the cloud collision model are given in table 6.3. These abundances are loosely based on the oxygen-neon layers from the 25 $M_\odot$ evolutionary and explosive models of Weaver *et al.* (1978), Woosley *et al.* (1984) and Johnston & Yahil (1984), and were measured manually from the plots of the composition structure.

The observations presented here of N132D, Puppis A and SNR G292.0+1.8 consistently failed to display any sulfur emission, so a set is used that does not include a contribution from the deepest, heavy elements, using only carbon, oxygen, neon, magnesium and silicon. This composition is probably applicable to the

TABLE 6.3: INITIAL ABUNDANCES
LOG NUMBERS RELATIVE TO O = 0.00

H	-6.00	C	-1.05	Ne	-0.34
He	-6.00	O	0.00	Mg	-1.34
				Si	-2.72

majority of the remnants, except SNR 0540-69.3 and some knots in Cassiopeia A.

The hydrogen and helium abundances are set to insignificant levels, but were explicitly included in the modeling, because some aspects of the MAPPINGS code design (*c.f.* Binette 1982) require at least a token presence of these ions. Their presence had no effect on the models. The modeling code, MAPPINGS II, used here, is described in more detail in Chapters 2 and 3. It has accommodation for up to 16 atoms, although only a subset will be used here. All stages of ionization are allowed for.

6.4 The Shock Models

It is proposed that the radiation that drives the cloud ionization fronts comes from the shockwaves in the model structure (**A** and **B** in figure 6.1). The evolution of these shocks, especially the slower, oxygen-rich cloud shock, is an important factor in the feasibility of the ionization front model. The complete self-consistent time-dependent solution to the evolution of such a shock wave entering a neutral oxygen plasma presents considerable computational difficulty. Accordingly, a number of simplifying assumptions have been made and are presented in the following sections.

The bowshock is formed by material from the ambient SNR medium, and is likely to be composed of the fairly normal composition material detected in X-Ray observations (*i.e.* Clark *et al.* 1982). In contrast, the cloud shock is in the oxygen-rich material that gives rise to the unusual optical emission that characterizes the OSNRs. Shocks that form in such plasmas are extreme in many ways. The high molecular weight of these super metal-rich plasmas result in high post-shock temperatures. This is apparent from the relationship between the temperature jump (T_s), the shock velocity, v , and the mean molecular weight, μ , $T_s = 3\mu v^2/16k$ K. Thus, a shock moving into atomic oxygen at 200 km s^{-1} may achieve $\sim 1.5 \times 10^7$ K. In practice, the preshock plasma is often fairly highly pre-ionized and ratios of 5 or more electrons per ion are common. This has a

strong effect on the mean molecular weight (μ), and hence the pre-ionization has a strong effect on the shock thermal structure. This is in contrast to normal composition shocks where the electron to ion ratio is always around 1.2 once ionization has occurred. To simplify the subsequent calculations, a steady pre-ionization will be assumed for the shockwave models. It remains to be shown that the pre-ionization can be set up on a rapid enough timescale so that this assumption has some validity.

Finally, due to the simplified radiative transfer treatment used, we require a steady ionizing source. To meet this requirement, it needs to be shown that, with some reasonable parameters, shocks can form rapidly and become radiative in a timescale short compared to the cloud crushing timescale τ_c , (equation (6.6)). This implies both a rapid cooling timescale, and a steady pre-ionization of the gas entering the shock so that the thermal structure is constant.

6.4.1 The Thermal Stability of Oxygen-Rich Shocks

Following the arguments developed in the cloud-cloud collision models in the Centaurus A modeling of Chapter 4 §4.3, the question arises of the stability of the shocks involved in the present oxygen-rich models. Without a hydrodynamic code with radiative cooling, it is difficult to predict the detailed stability properties of these oxygen-neon mixtures. The criterion of Schwartz *et al.* (1972) (Chapter 3; equation (3.64)), is not strictly satisfied by the oxygen-rich cooling functions, shown by the curves in figure 6.2. Nevertheless, while the overall cooling rates are many orders of magnitude greater than the cosmic abundance curves of Chapter 3, the slopes of the cooling functions are at least monotonically decreasing, and the slopes as great as 2 in some regions, with an average slope of about unity. The slopes are comparable to the slope of the non-equilibrium cooling function below 10^5 K (from Chapter 3), shown in gray, which corresponds to the range of temperatures reached in stable, normal composition shock models. The plot suggests that the oxygen-rich shocks are probably thermally stable up to 250 km s^{-1} . Above 250 km s^{-1} , the $300\text{--}500 \text{ km s}^{-1}$ models show regions of negative slope, and are thermally unstable.

Fortunately, the stability or otherwise of the ionizing shocks may turn out to be unimportant to the emitted optical spectra. In normal radiative shock models (*c.f.* Chapters 2 & 4), the cooled, recombination zone is several thousand degrees, and the optical emission is strongly affected by photoionization due to the downstream radiation field of the shock. The [OI], [SII] and other low ionization emission lines are particularly affected, and hence are sensitive to the radiative

Cooling Functions for Oxygen-Rich Plasma

FIGURE 6.2: Cooling functions for oxygen-rich self-consistent shock models with velocities of 50 to 500 km/s. Below 300 km/s the curves are monotonically decreasing and it is likely that the shocks will be thermally stable. The 300, 400 and 500 km/s models may not be stable. A full-field NEQ curve from Chapter 3, for $\log(T_0) = 7.5$, is shown on the same scale, in gray.

transfer effects resulting from any shock flow instability. In the oxygen-rich case, the cooled, recombined zone is so cold that no collisional emission occurs, even in the full diffuse field models. Thus the downstream radiative transfer has little effect on the emitted spectrum. Since instabilities will form on a cooling timescale, the hotter emitting regions will not be affected either. In this sense then, the instability or otherwise of the shocks, will not greatly affect the ionizing radiation, or the optical spectra of the models.

One effect of the shock stability that may still be important is the transfer of the bow-shock radiation which will have to penetrate the cloud shock to reach the interior of the cloud, and any ionization fronts. If the cloud shock is unstable, or otherwise disrupted, then the hard bowshock radiation can reach the interior. Whether this is important or not will be determined in the subsequent bowshock and photoionization modeling. If significant, the bowshock spectrum can simply be added to the ionizing source vectors.

The ionizing radiation field of the cloud shock will be calculated with normal, smooth shock models which are terminated at a temperature of 300 K, defining the cooling length in these models.

6.4.2 The Cloud Shock

Cloud shock models were computed with a preshock density of 10 to 1,000 cm^{-3} and a velocity range of 50–500 km s^{-1} . A transverse magnetic field of 1.0 μG was assumed for all models. A self-consistent equilibrium pre-ionization of the precursor gas entering the shock front was assumed. The oxygen–neon abundance mixture used is that of table 6.3.

The model structure and its properties are summarized in table 6.4. The cooling timescales and lengths are given in a normalized form, since they scale as the inverse of the plasma density over the density range considered. This table shows that for shock velocities less than 300 km s^{-1} (Models OS050 – OS250), the cooling timescale will be short compared to the cloud crushing time of 10^9 s, even with the lowest density of 10 cm^{-3} . If the faster shock velocities must be used (models OS300, OS400 and OS500), then the density would have to be increased to 100 cm^{-3} or more, to shorten the cooling timescales. The upstream ionization parameter (Q) is very great. All the models, even the 50 km s^{-1} OS050 model, are capable of producing significant pre-ionization.

The thermal and ionization structure of the 200 km s^{-1} shock is shown in figure 6.3. This figure clearly demonstrates the unusual features of the oxygen–

TABLE 6.4: OXYGEN-RICH SHOCK MODELS
 $n_0 =$ PRECURSOR OXYGEN ATOMS cm^{-3}

Model	$\log(v_s)$ (cm s^{-1})	$\log(T_s)$ (K)	$\log(d_3 n_0)$ (cm^{-2})	$\log(\tau_3 n_0)$ (s cm^{-3})	$\log(Q)$ ($\text{cm}^{-2} \text{s}^{-1}$)
OS050	6.70	5.68	12.93	7.47	7.27
OS075	6.88	5.96	13.18	7.40	7.76
OS100	7.00	6.16	13.45	7.48	8.17
OS150	7.18	6.44	13.93	7.67	8.61
OS200	7.30	6.64	14.38	7.99	8.93
OS250	7.40	6.77	15.00	8.58	9.33
OS300	7.48	6.89	16.09	9.62	9.49
OS400	7.60	7.08	17.69	10.08	9.65
OS500	7.70	7.27	17.23	10.45	9.70

FIGURE 6.3: The thermal structure of the 200 km/s cloud shock. The lower panel shows the oxygen ionization structure for the model. The principal variable used here is T , the temperature. This allows the structure to be resolved in the plots, whereas if a time or distance coordinate were used the structure changes are too rapid to be clearly seen. The flow time variable, t , is shown as a function of temperature. Most time is spent at a high temperature followed by very rapid cooling.

rich shock models. The initial ionization is very rapid, due to the large number of free electrons entering the shock, and the cooling is similarly rapid. Once ionized, the highly ionized species like OV and OVI remain at virtually constant levels throughout the model, down to 300 K, due to their slow recombination rates. By the time the plasma has cooled, it is still dominated by OIII and OV. The [OI] emission is very weak, and the [OII] lines are considerably weaker than the [OIII] lines in the final spectrum, in contrast to models of normal composition material. The suppression of the [OII] and [OI] emission, caused by the very low temperature in the recombination zone, is the main reason that simple radiative shock models fail to reproduce the observed spectra.

6.4.3 Pre-ionization

The degree of plasma pre-ionization critically affects the molecular weight, and hence the shock jump conditions. Even one ionization per atom effectively halves the molecular weight of plasma, and hence the shock temperature. To determine the extent of the effects of the pre-ionization, limiting cases are considered. Test models were run where the gas entering a 200 km s^{-1} shock was held to be artificially neutral, singly or fully self-consistently ionized, to measure limits on the build-up of the upstream radiation field, and thence the timescales over which pre-ionization may occur.

The shock without pre-ionization has a much higher temperature initially, but the lack of electrons limits the emission processes. In the models with pre-ionization, the initial temperature is lower, a factor that is compensated by the immediate availability of electrons. The question of how soon the field can build up in the precursor zone will then be a matter of the competing factors of electron availability and the range of electron energies.

The radiation field build-up is given in figure 6.4 where the potential ionization front velocity is plotted as a function the shock development. The ionization front velocity is approximated by:

$$v_f = \frac{Q}{\bar{N}_i} \text{ cm s}^{-1} \quad (6.8)$$

where v_f is the nominal front velocity, $\bar{N}_i$ is the mean number of ionizations per particle cm^{-3} , and Q is the number of ionizing photons per particle $\text{cm}^{-2} \text{ s}^{-1}$. The velocity estimates in this test sequence used $\bar{N}_i = 2.54$ stages per ion, as achieved in the steady-flow equilibrium pre-ionization model, thus the velocities will be underestimates of the spread of the early ionization fronts when less ionization

has occurred. The model thermal structures are given in figure 6.5, and the effect on the shock temperature can be seen clearly.

The radiation build-up timescale, to the point where an ionization front velocity could exceed the shock velocity, is very short. This result holds irrespective of the actual pre-ionization state in the precursor material. The model where the precursor is held artificially neutral provides an upper limit, and gives a value of $2 \times 10^8 \text{ s cm}^{-3}$, or $\sim 20\%$ of the cooling timescale of the model. The limiting factor is the electron availability, causing the neutral model (A in the figure) to lag until some ionization has occurred. At this point the ionizing flux effectively switches on to nearly full power. This timescale, along with the overall shock cooling timescale, will scale inversely with density, so that the ionization front will always form on a timescale that is rapid compared with the other cloud timescales, at all reasonable cloud densities.

This result allows the simplification that the shock is traveling into a full equilibrium pre-ionization balance determined for each shock velocity. The pre-ionization is limited only by the response time of the ionizing plasma in the precursor zone, and not by the build-up timescale of the ionizing radiation. Once a complete ionization front structure is established, the shock structure, and hence the exciting radiation source, will be steady. It merely remains to show that the ionization fronts structures can complete, producing equilibrium ionization, well within the cloud crushing timescale. This will permit the formation of a steady-state model where the ionization front has completely detached from the shock front, allowing the two components to be calculated independently.

6.4.4 Radiation from the Bowshock

The very fast bowshock structure may be an important X-ray ionizing source, in addition to any internal cloud shocks. In the present model, the cloud is assumed to be encountering the reverse shock reflected from behind the main SN blastwave as it sweeps up interstellar material and begins to slow down. There is some evidence for such a structure in the Cassiopeia A remnant in radio observations of Fabian *et al.* (1980). In the case of N132D, the SNR may be expanding into a low density cavity, and the evolutionary status of the main reverse shock is uncertain. In that remnant there is some evidence that the oxygen-rich material is spatially associated with the remains of some dense circumstellar material of more normal composition (*c.f.* Chapter 5). In this case, the encounter may be between the oxygen-rich cloud and a reflected shock from the slow-moving material, or the slow-moving material itself.

FIGURE 6.4: Normalized Pre-ionization Timescales. The times required to generate an ionization front that travels faster than the generating 200 km/s shock. The curves represent initial front velocities for artificially neutral (A), singly (B) and fully (C) pre-ionized shock models. Once the curves exceed 2.0×10^7 cm/s, pre-ionization can occur. The field build-up is very rapid, compared to the cooling timescale (D), irrespective of the pre-ionization.

FIGURE 6.5: Pre-ionization effect on thermal structures. The effect of the pre-ionization on the post shock temperature and cooling length may be clearly seen here. The models labeled A, B and C correspond to the artificially neutral, singly ionized and fully preionized shock models respectively, as in figure 6.4. Oxygen-rich composition models are particularly sensitive to the pre-ionization.

To determine the importance of the bowshock to the total radiation field in the ionization front modeling, fast shock models have been constructed. A bowshock spectrum for a $2,000 \text{ km s}^{-1}$ plane parallel shock was evolved for a length of 10^{17} cm . The length was estimated for the typical standoff distance of a bowshock of about one cloud diameter, guided by the 3D models of Stone & Norman (1992). This should be good to an order of magnitude. The pre-ionization was estimated for a 10^7 K plasma in collisional equilibrium at a density of 0.1 cm^{-3} , in broad agreement with the observed global X-ray spectra of the remnants (table 6.1), at the density implied by a 100:1 density contrast. The composition was taken to be normal cosmic abundances in one model, and a comparison model of oxygen-rich composition was also made.

In both models, cooling over this length is negligible, $\Delta T \ll 1 \%$. The shock jump conditions predict a post-shock temperature of $1.8 \times 10^8 \text{ K}$ in the oxygen rich material, near the upper limits of the modeling code, and $6.5 \times 10^7 \text{ K}$ for the normal material. The difference between these is not very great because the very large number of free electrons in the oxygen-rich plasma greatly reduce the mean molecular weight. As the precursor gas entering the bowshock is already highly collisionally ionized, photoionization precursors do not exist for these models.

The bowshock model is truncated at 10^{17} cm , on a timescale that is very short compared to other timescales in the shock models, and the emitted spectrum is produced essentially by a homogeneous slab of under-ionized hot plasma, that grows linearly with time for a cloud crossing time, and would then remain roughly constant until the cloud is destroyed in another crossing time. The two spectra, from the normal and oxygen-rich models, are therefore very similar in shape, but the intensity of the oxygen-rich model is very much greater than the normal composition model. The flux incident on the cloud itself, in terms of the ionization parameter, Q , is $1.9 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ for the oxygen-rich model, and only $2.8 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ for the normal model. The ionizing bowshock spectra are shown in figure 6.6 along with the cloud shock spectra.

The case where the bowshock occurs in oxygen-rich material presents a serious difficulty for the subsequent modeling, as it generates a photon source that is very strong compared to those generated by the cloud shocks, and is capable of modifying both the cloud shock and the ionization front. The intensity will increase linearly throughout the evolution of the cloud shock and its ionization front. The radiative transfer problem this presents may not be modeled with the present code. However, the X-ray observations of the OSNR suggest that this type of oxygen-rich bowshock probably does not occur. The surface brightness

of such a bowshock, of order $100 \text{ ergs cm}^{-2} \text{ s}^{-1}$ over an area of $\sim \pi a^2 \approx 3 \times 10^{34} \text{ cm}^2$ would imply that a *single* knot would provide $\sim 3 \times 10^{36} \text{ ergs s}^{-1}$ or roughly the total measured X-ray luminosity of Cassiopeia A (see table 6.1). This is *not* observed. For this reason, the normal composition bowshock has been chosen. In this case, the ionization parameter is much lower than the cloud shock emission by a factor of 10 – 100, a factor that would be further reduced by geometrical dilution, so it has therefore been neglected in the subsequent modeling.

This indication that the inter-cloud medium has a normal composition, whereas the clouds are oxygen-rich, clearly is an important constraint of theoretical models of the stellar explosion itself.

6.5 The R-Type Ionization Front Models

At an ionization front, an incident photon radiation field is absorbed in a thin layer. The velocity is limited by the ratio of the number of available photons and the number of absorbing particles. When the particles can be multiply ionized, as in the oxygen-rich plasmas, the effective number of absorbing particles, N_i , is increased and the ionization front velocity is slower (equation 6.8). The theory of ionization fronts is due to Kahn (1954), Goldsworthy (1961) and Axford (1961). This area was further expanded on by Mendis (1968a,b; 1969). In the nomenclature developed by those authors, the current ionization front models represent weak R-Type ionization fronts.

In order to approximate this situation within the framework of the present modeling code, the procedure of D87 is adopted. The improvement afforded by the new developments of MAPPINGS II lies in the detailed shock models of the previous section. The photoionization model computed here benefits from more recent atomic data as described in Chapter 3, but otherwise the models are very similar.

6.5.1 Ionization Front Model Structure

The ionization front model consists of a thin slab of plasma that is subject to the radiation field of the shocks calculated previously. The radiation field is assumed to be not attenuated by material between the front and the shock. This assumption is justified as long as the distance remains significantly shorter than the Strömgren column of the ionizing radiation. For the present modeling of a 10^{17} cloud, this optically thin assumption will place an upper limit on the cloud

Oxygen Rich Shock Ionizing Spectra

FIGURE 6.6: Ionizing Radiation. The radiation fields of the cloud shock models and the bowshock models are shown. These form the sources for the subsequent ionization front models.

density that may be modeled. This limit is determined in §6.6.

The most serious restriction on the model is that the slab element is assumed to be optically thin. In this sense, the results calculated are the response of a volume element to the total incident field, but the internal absorption across a real ionization front is not taken into account. This approximation will produce a higher average ionization in the models than in reality. These ionization front models are analogous to the Lagrangian shock flow models, where a single parcel of material is followed through the shock structure, and the final spectrum of the whole is the averaged sum of emission of the parcel traveling through the structure. The ionization front spectrum is taken as the time weighted sum of the slab element over the course of the model evolution.

As an alternative to setting up a large grid of points and solving the radiative transfer differential equations simultaneously, this method provides a very easy approximation. The deficiencies will lie in the computation of the emission from the low ionization species, such as OI, which may be underestimated. The calculation of the more highly ionized stages should be a more reasonable approximation, since these species will occur in the optically thin regions of the ionization front. In addition, the heating effect of the radiation field will be overestimated, and an actual front may not reach the high temperatures achieved here.

The thermal structure of an oxygen-rich ionization front is shown schematically in figure 6.7. The parameters used to describe the ionization front models in subsequent sections are shown on the diagram. The peak temperature is denoted T_p . The timescale to reach this peak is τ_p , and in those models that achieve a cold equilibrium, a cooling timescale τ_3 is also defined. Integration of the emission over this time defines the long term steady emission of the front structure. Some of the faster ionization fronts result in such strong ionization that the efficient coolants such as OIII, CIV and OIV are depleted, and cooling is reduced to the point where a hot equilibrium becomes possible. The integrated spectrum of these models is a continuing function of time and no τ_3 exists. A general equilibrium timescale τ_{eq} is defined, in this case, by the time required to reach thermal photoionization equilibrium.

The ionization front models (OP050 - OP500) for the range of shock velocities considered in § 6.4 displayed the thermal structures shown in figure 6.8. The models are also summarized in table 6.5.

Generally the front models achieve quite high temperatures. However, the OP050 model (the 50 km s⁻¹ shock source) only barely achieves 10⁴ K, and as

Schematic Ionization Front Structure

FIGURE 6.7: The thermal structure of an ionization front model. The parameters τ_3 , τ_p , T_p and τ_{eq} used to describe the front models are shown. The models achieved either a hot equilibrium (B), or a cold equilibrium (A).

FIGURE 6.8: The thermal structure of the ionization front models. The faster models end when photoionization equilibrium is achieved ($\bullet$). A normalized timescale is used and this should be valid for the range of low densities considered ($<1000 \text{ cm}^3$). The model OP250 reached a very finely balanced equilibrium and produced the numerical oscillations after $\log(\tau n) = 10 \text{ s cm}^3$ which are an artifact.

FIGURE 6.9: The oxygen ionization structure of the OP200 ionization front model.

TABLE 6.5: OXYGEN-RICH IONIZATION FRONT MODELS
 n = NUMBER DENSITY OF OXYGEN ATOMS

Model	N_i (cm ⁻³)	$\log(v_f)$ (cm s ⁻¹)	$\log(T_p)$ (K)	$\log(\tau_p n)$ (s cm ⁻³)	$\log(\tau_3 n)$ (s cm ⁻³)	$\log(\tau_{eq} n)$ (s cm ⁻³)
OP050	1.04	7.26	3.94	9.44	10.17	...
OP075	1.42	7.61	4.09	8.98	9.83	...
OP100	1.69	7.94	4.15	8.68	9.73	...
OP150	2.25	8.26	4.33	8.35	9.77	...
OP200	2.54	8.52	4.43	8.09	9.84	...
OP250	3.02	8.85	4.47	7.97	10.08	...
OP300	3.80	8.91	4.56	7.91	...	9.62
OP400	4.56	8.99	4.69	7.81	...	10.08
OP500	5.03	9.00	4.77	7.74	...	10.45

the radiation flux should vary as v^3 , this model represents the lower limit of cloud-shock velocities that will produce this type of ionization front structure.

In one group of models, for shock velocities of 250 km s^{-1} or less, the temperature rises and then falls to a very cold state, which is nevertheless highly ionized. For these cold models, τ_3 is clearly defined. The equilibrium timescale τ_{eq} in these models is essentially the same as the cooling timescale. The second group of models (OP300, OP400 and OP500) stay hot, as the plasma becomes so ionized that the efficient coolants of OIII and OIV are only present in small amounts. For these models only the equilibrium timescale, τ_{eq} , is appropriate.

The ionization structure of the OP200 model is shown in figure 6.9. This shows the rapid ionization, and eventual equilibration in a highly ionized state, when the temperature is much less than 1,000 K, as can be seen by comparison with figure 6.8. This figure agrees in general with figure 2 of D87.

6.5.2 General Features of Ionization Front Spectra

The detailed integrated spectra of the ionization front models are discussed in §6.7, when the final models are presented.

The time dependent optical emission of the model OP200 (200 km s^{-1} shock) is shown in figure 6.10. The timescale here is normalized to density. The figure shows the integrated emission of the optical forbidden oxygen lines of OI, OII and OIII, normalized to $[\text{OIII}]\lambda 5007 = 1.00$, as a function of time, as the gas element traverses the ionization front. The spectrum is dominated initially by $[\text{OI}]\lambda 6300$, and then $[\text{OII}]\lambda\lambda 3727$ and $[\text{OIII}]\lambda 5007$ together become the main emission. In this model the final $[\text{OII}]\lambda\lambda 3727$ and $[\text{OIII}]\lambda 5007$ lines are of comparable intensity, the $[\text{OII}]$ lines being slightly brighter (as observed). The $[\text{OI}]\lambda 6300$ line diminishes until it is reduced to about 1 % of $[\text{OIII}]\lambda 5007$, and is comparable to the $[\text{OIII}]\lambda 4363$ line. This is one of the distinguishing features of these ionization front models, which produce much more $[\text{OI}]$ emission than any equilibrium models with the same radiation fields, even though the $[\text{OI}]$ emission may still be underestimated in these models. The $[\text{OIII}]\lambda 4363$ line rises rapidly with the temperature, and peaks with the temperature peak before slowly dropping to about 1 % of $[\text{OIII}]\lambda 5007$. This final value is somewhat low compared to the observed ratio of 2-8 % (*c.f.* table 6.2). It must be stressed that this figure represents the ionization front emission in isolation, and does not include the important contribution from the shock emission. As will be seen, the shocks contribute strongly to the $[\text{OIII}]$ emission and little to the $[\text{OI}]$ and $[\text{OII}]$ emission.

FIGURE 6.10: Time dependence of the OP200 ionization front model optical oxygen emission

6.5.3 Ionization Front Summary

The present ionization front model thermal structures display the high temperature peaks, predicted by D87. The peak temperatures achieved in these models are higher, alleviating the need for separate electron and ion temperatures, suggested in the earlier work as a means of increasing the excitation temperature.

It has been shown that the cloud shock models can drive rapid ionization fronts that will precede the cloud shock. Provided that the bowshock of the cloud occurs in normal composition material, the radiation field due to the bowshock has been shown to be overwhelmed by the cloud shock emission. The cloud shocks may be thermally stable and optically thick to any bowshock radiation. This represents a departure from the original D87 model, and it arises because the bowshock can only radiate a small fraction of the incident energy flux during the time available, while the cloud shock is fully radiative and highly efficient at converting mechanical energy into ionizing radiation.

The ionization fronts can achieve photoionization equilibrium (either cold or hot) in a short timescale given a high enough density, justifying the equilibrium pre-ionization assumption used in the shock modeling. The final modeling will have to balance the inverse density effects on the front evolution timescale, to meet the requirement for shock pre-ionization, with the direct density effect on the total cloud optical depth.

For the present work, the models are separated into the cold and hot equilibrium models. Detailed modeling of the hot equilibrium models is deferred to possible future work. This is due mainly to the problem presented by the continuing integration of the hot models throughout the cloud crushing timescale. Cloud crushing will affect the radiative transfer in the models throughout the emission evolution, and the simple plane parallel formalism is inadequate. On this basis, then, we proceed to the final model selection, taking the OP050 to OP250 models as being appropriate to the present modeling technique.

6.6 Selection of Model Parameters

Given the properties of the shock and ionization front models in the preceding sections, it remains to select a set of modeling parameters with which the models retain a degree of validity. The problem here is not to determine the conditions that need to be modeled, but rather to choose the conditions that *may* be modeled.

The structure envisaged is of a steady-flow, non-equilibrium model, where the cloud shock structure is fully radiative, and where the ionization front has detached and is traversing the main body of the cloud. This is depicted in figure 6.1 in the lower panel. This detached, steady-state is necessary if the preionization assumptions of the shock modeling are to be satisfied. By requiring that the front be detached and fully evolved, the Lagrangian modeling procedure, of integrating the emission of a small ‘parcel’ of material as it traverses the structure, may be used. This method cannot be used for early stages of the evolution, where the shock and front structure are closely coupled, or when the front evolves slowly compared to the hydrodynamic evolution of the cloud.

The selection of model parameters will be made on the basis of the model structure results of the previous sections, in combination with the characteristic timescales of the problem as outlined in §6.3. The main selection criteria will be to remain within the limitations of the present simplified modeling procedure as well as remaining within physically reasonable limits. The final models will *not* be selected on the basis of a detailed fit to the observed spectra.

Characteristic Timescales

The cloud crushing timescale, τ_c (equation (6.6)), is the fundamental timescale in the problem. The other characteristic timescales, those of the front evolution, τ_3 (*c.f.* figure 6.7), and shock cooling τ_{cool} will determine a range of parameters where the modeling is valid.

For a given composition (table 6.3), we need to choose a range of velocities and densities where the front evolves much faster than the cloud crushing timescale, and the shock evolves much more rapidly than the ionization front. Therefore, we require that τ_c is more than about three times τ_3 , which is in turn more than 3 times τ_{cool} . This gives each structure, both ionization front and cloud shock, ample time to form and achieve a steady state, within the overall problem timescale. Figure 6.11 plots the normalized timescales τ_3/τ_c (or τ_{eq}/τ_c) for the ionization fronts, against the normalized cooling timescale τ_{cool}/τ_c for the shock models. The curves are plotted for cloud densities of 10 and 100 cm⁻³. The faster shock models (300–500 km s⁻¹) have been included for comparison, although they have already been eliminated from the range of validity in the previous sections. These fast shock models produce a hot precursor photoionization equilibrium, and the integrated spectrum will continue to grow throughout the cloud crushing time. This is indicated by the dashed horizontal lines.

The figure is divided into 4 quadrants, **A**, **B**, **C** and **D**. Points that fall within

quadrant **A** are models where the shock structure evolves slowly compared to the crushing time of the cloud. This makes the radiation source variable throughout the emission process, thereby invalidating the modeling procedure adopted here. Quadrant **B** contains models where both the shock and ionization models evolve too slowly. In quadrant **D** the ionization front models evolve too slowly. Finally, the points that fall within quadrant **C** represent models where the ionization fronts have time to form and evolve much more quickly than the dynamic lifetime of the cloud. At the same time, the shock models evolve more quickly still, reaching a steady emission state very rapidly, thus allowing the steady source approximation. As can be seen, the models with a cloud density of 10 cm^{-3} fall in quadrant **D**, and cannot be modeled with the present methods, although this density regime is of course not excluded in actual clouds. Some of the 100 cm^{-3} models fall in the desired quadrant **A**. From this diagram, it is clear that if these models are to be used, then the cloud density must be 100 cm^{-3} or greater.

Cloud Optical Depth

Another limitation in the modeling lies in the steady, constant source approximation of the ionization fronts. This requires that the material between the hot ionization front and the source, the cloud shock, remains optically thin. The Strömngren length for the shock radiation to be absorbed in a plane parallel geometry has been modeled explicitly for $n_0 = 100 \text{ cm}^{-3}$, and the results for the radiation from the range of shock velocities are shown in figure 6.12. Scaled curves for 10, and $1,000 \text{ cm}^{-3}$ are also shown. All the models remain optically thin in the low density, 10 cm^{-3} , case, marginally thin in the 100 cm^{-3} case, and largely optically thick in the $1,000 \text{ cm}^{-3}$ case. For this reason, the final models will be made with a cloud density of 100 cm^{-3} . This density is happily consistent with the observations. From table 6.1, is apparent that, except for Cassiopeia A, the hot X-ray emitting plasma has a density in the range of $0.1\text{--}10 \text{ cm}^{-3}$. By taking a cloud density of 100 cm^{-3} , a reasonable density contrast of $\chi \approx 100$ is achieved. This type of density contrast also lends validity to the hydrodynamic arguments in §6.3.

6.7 Final Models

Models were constructed from the shock models OS050 - OS250 and the corresponding ionization front models OP050 - OP250, scaled to a preshock density of 100 cm^{-3} . The spectra of the shocks and the ionization fronts models were

Characteristic Timescales

FIGURE 6.11: Characteristic Timescales. The photoionization (τ_3) and shock (τ_{cool}) timescales are compared with the cloud crushing timescale. Models that fall in quadrant C satisfy the modeling restrictions. See text for details.

FIGURE 6.12: Cloud optical depths. The middle curve (**B**) shows the estimated length of an optical depth of the oxygen rich material to the ionizing fields for model densities of 100 cm^{-3} . The other curves represent the 10 (**A**) and 1,000 (**C**) cm^{-3} densities. Only models that are larger than, or similar to, the cloud length (dashed line) have validity.

integrated and co-added. First, The isolated optical shock spectra are compared with the observations, and then the combined models (designated OSP050 - OSP250) are compared. In addition, the UV spectra are compared with the UV observations of Blair *et al.* (1989) of the remnant SNR E102.2-7219.

6.7.1 The Shock Spectra

The optical spectra of the shock models in table 6.6 display some unusual features. The principal optical emission in these models is the [OIII] λ 5007 line. The cooling in the oxygen–neon mixtures, with contributions from carbon, magnesium and silicon is very strong. The other species provide fine–structure cooling mechanisms when the oxygen is at the OII stage, so the mixture is cooler even than the pure oxygen plasmas of Itoh (1981a,b) and [OII] emission is suppressed. The principal contribution of the shock to the overall optical spectra will come from the [OIII] λ 5007 , [OIII] λ 4959 and [OIII] λ 4363 lines.

As already mentioned, the shock spectra are not in good agreement with the observations. The $I_{4363} / (I_{5007} + I_{4959})$ ratio in the models of table 6.6 is very high, considerably higher than those observed. This clearly indicates that shocks cannot be solely responsible for the observed emission. The [OII] and [OI] emission is far too weak in the shock models as well. The [NeV] λ 3426 to [NeIII] λ 3869 ratio was not determined by the observations made this thesis, as [NeV] was not observed. This places a limit on the shock velocity, as the predicted [NeV] emission increased rapidly for shock velocities over 200 km s⁻¹. Interestingly, this line is observed in SNR E102.2-7219 (Dopita & Tuohy 1984) suggesting more rapid shock velocities occur in that remnant.

6.7.2 The Combined Spectra

The optical forbidden oxygen line ratios are compared with observations in figures 6.13 – 6.14. The observations are from table 6.2, and the model spectra are given in table 6.7. Analogously to figures 5.9 – 5.11 in Chapter 5, a de–reddening vector for the correction due to $c = 0.5$ are shown, to indicate, in this case, the direction along which errors in the reddening estimates would have moved the observations.

It is clear from figure 6.13 that the previously problematic I_{4363} / I_{5007} ratio is now well reproduced in the models. The OSP150 to OSP250 models lie in the range defined by the observational points. However, the modeled I_{5007} / I_{3727} ratio is generally greater than the observations. Most of the observations are between

TABLE 6.6: OXYGEN-RICH SHOCK MODEL SPECTRA
 $I_{5007} = 1.000$, $n_0 = 100.0 \text{ cm}^{-3}$

		Models					
Transition		OS050	OS075	OS100	OS150	OS200	OS250
[OII]	$\lambda\lambda 7320+30$	0.045	0.003	0.001	0.000	0.000	0.003
[OI]	$\lambda 6300$	0.000	0.000	0.000	0.000	0.000	0.000
[OIII]	$\lambda 5007$	1.000	1.000	1.000	1.000	1.000	1.000
[OIII]	$\lambda 4363$	0.098	0.128	0.151	0.167	0.177	0.177
[NeIII]	$\lambda 3869$	0.026	0.051	0.063	0.023	0.071	0.294
[OII]	$\lambda\lambda 3727$	0.132	0.008	0.002	0.001	0.000	0.000
[NeV]	$\lambda 3426$	0.000	0.001	0.043	0.414	0.621	1.738
$\log(I_{4363} / I_{5007})$		-1.007	-0.894	-0.822	-0.777	-0.751	-0.752
$\log(I_{3727} / I_{5007})$		0.881	2.079	2.629	3.056	3.531	3.479
$\log(I_{7325} / I_{3727})$		-0.469	-0.397	-0.591	-0.530	0.017	1.007
$\log(I_{3727} / I_{6300})$		2.479	2.552	2.488	2.128	1.394	0.692

TABLE 6.7: FINAL OPTICAL EMISSION SPECTRA
 $I_{5007} = 1.000$, $n_0 = 100.0 \text{ cm}^{-3}$

		Models					
Transition		OSP050	OSP075	OSP100	OSP150	OSP200	OSP250
[OII]	$\lambda\lambda 7320+30$	0.046	0.007	0.014	0.047	0.041	0.024
[OI]	$\lambda 6300$	0.047	0.026	0.029	0.020	0.008	0.002
[OIII]	$\lambda 5007$	1.000	1.000	1.000	1.000	1.000	1.000
[OIII]	$\lambda 4363$	0.098	0.125	0.140	0.063	0.022	0.026
[NeIII]	$\lambda 3869$	0.026	0.050	0.062	0.091	0.144	0.142
[OII]	$\lambda\lambda 3727$	0.315	0.257	0.625	1.617	1.148	0.540
[NeV]	$\lambda 3426$	0.000	0.001	0.040	0.144	0.052	0.182
$\log(I_{4363} / I_{5007})$		-1.010	-0.903	-0.852	-1.203	-1.656	-1.585
$\log(I_{3727} / I_{5007})$		0.501	0.589	0.204	-0.209	-0.060	0.267
$\log(I_{7325} / I_{3727})$		-0.835	-1.538	-1.663	-1.536	-1.452	-1.348
$\log(I_{3727} / I_{6300})$		0.823	1.003	1.333	1.911	2.162	2.551

De-Reddened Line Ratios

FIGURE 6.13: De-reddened line ratios of $[\text{OIII}]\lambda 4363$, $[\text{OIII}]\lambda 5007$ and $[\text{OII}]\lambda 3727$, for combined shock and ionization front models. The OSP150 and OSP200 models bracket the observations of the temperature sensitive $[\text{OIII}]$ ratio. Overall the $[\text{OII}]$ emission is weak in the models. Observation identifications are given in table 6.2.

FIGURE 6.14: As for 6.13, but for line ratios of [OI] λ 6300, [OII] λ 3727 and [OIII] λ 5007.

De-Reddened Line Ratios

FIGURE 6.15: As for figure 6.13, but for ratios of $[\text{OII}]\lambda\lambda 7325$, $[\text{OII}]\lambda\lambda 3727$ and $[\text{OIII}]\lambda 5007$.

the OSP150 and OSP200 models, although the SNR 0540-69.3 observation by Kirshner *et al.* (1989) and the Cassiopeia A observations lie closer to the OPS250 model. The slower shocks, producing models, OSP050 to OSP100, are a poor fit, due largely to the relatively smaller contribution from the ionization front emission, and the consequent dominance of the shock spectrum, which fits the observations very poorly. The low velocity models have too much [OIII] λ 4363 emission and not enough [OII] λ 3727, in line with the conclusions of Dopita *et al.* (1984).

In figure 6.14 the OSP150 model is once again in the observed range. This consistency gives some credence to the model structure presented here, even with the modeling simplifications adopted. Care should still be taken in the interpretation, as the outliers, Cassiopeia A and SNR 0540-69.3, are nearer to the OSP100 model, rather than the faster OSP250 model in the previous plot. In these cases, the observed points are displaced along the direction that might be expected from an increase in density sufficient to quench the [OII] λ 3727 emission. This trend happens to lie along the direction of the velocity progression, and the reddening vector. This combines to make the interpretation of these point uncertain, especially given the limitations on the density regime that may be modeled with the present method. As noted in the observational Chapter 5, this plot remains a weak diagnostic tool.

Finally, in figure 6.15 these same OSP150 and OSP200 models are once again near the main clump of observations, although there is considerable scatter of the observed points along the reddening vector. In addition, the locus of the model points is quite non-linear, covering a wide range of the I_{7325}/I_{3727} ratio. This highlights the perils of a homogeneous model interpretation of the density diagnostics. On the positive side, the majority of the models do lie in the region where the emission is largely from the homogeneous low density ionization front zone, as the simple models of Chapter 5 predicted, but the variable density shock contribution can cause strong deviations. The Cassiopeia A observation remains an exceptional point, as it lies in a region where at least some high density material must be contributing to the spectrum, and hence may not be modeled accurately here. The SNR 0540-69.3 measurements of Dopita & Tuohy (1984) and Kirshner *et al.* (1989) (which uses spectra from 1982) are in disagreement over the [OII] λ 7320+30 flux, making the interpretation of this remnant difficult as well. The Dopita & Tuohy (1984) value puts the remnant closer to the other OSNR observations, but this may be co-incidental. More observations of this remnant are needed.

The correspondence of the observations with the locus of the OSP150 - OSP200

models is very encouraging. A general lack of [OII] $\lambda\lambda 3727$ radiation is predicted, but this may be the result of the optically thin ionization front model assumptions. Otherwise, the fit is very reasonable. The fact that the model parameters were selected by global dimensional considerations, albeit additionally limited by modeling assumptions, and yet points for the resulting models lie in the same general regions of the diagnostic plots as the observational points, is taken as strong support for the emission mechanism outlined here.

One final, general prediction of the models is that when the emission lines of a species are produced in both the shock and the ionization front line splitting or broadening up to the shock velocity may be observed, depending on the projection. Other lines that come from only one component, such as [OI] emission from the front or [NeV] from the shock, should have different velocities. Details of the line splitting are not modeled here, and will be the subject of future work.

6.7.3 UV spectrum of SNR E102.2-7219

The UV observations of Blair *et al.* (1989) are an important observational data set. A number of points arose from the Blair work. They found that the UV emission is relatively weaker than might have been expected from a simple shock model, and that a simple photoionization model is inadequate as well. In addition, the UV resonance lines of carbon and oxygen appear to have strong recombination components. While the MAPPINGS II code does not compute the details of the recombination contribution to the UV carbon and oxygen spectrum, it still serves to make a comparison of the ionization front mechanism models presented here with the SNR E102.2-7219 data. Table 6.8 compares the OSP150 and OSP200 models, that were most successful in modeling the optical spectra, with the SNR E102.2-7219 spectrum in both the optical and near UV.

The overall fit to the specific SNR E102.2-7219 spectrum is quite good in the optical. The modeled UV line spectrum is also generally weak, as observed. Given the observational error of up to 50% in the UV fluxes by Blair and co-workers, only limited detailed conclusions should be drawn from the models; namely:

1. The modeled MgII $\lambda 2799$ emission is brighter than the observed flux, by a factor of 7 or so. Barring a strong contribution from recombination, this suggests that the magnesium level in the initial abundance set was too high, and a [Mg/O] ratio of -2.2 may be more appropriate. This measurement is highly uncertain, being based on a single measurement, and should not be taken as definitive.

TABLE 6.8: OPTICAL-UV SPECTRUM COMPARISON
 $I_{5007} = 1.000$, MODELS $n_0 = 100.0 \text{ cm}^{-3}$

		Observed ^a	Models	
Transition		E102.2-7219.	OSP150	OSP200
[OII]	$\lambda\lambda 7320+30$	0.090	0.047	0.041
[OI]	$\lambda 6300$	0.047	0.020	0.008
[OIII]	$\lambda 5007$	1.000	1.000	1.000
[OIII]	$\lambda 4363$	0.048	0.063	0.022
[NeIII]	$\lambda 3869$	0.207	0.091	0.144
[OII]	$\lambda\lambda 3727$	1.640	1.617	1.148
[NeV]	$\lambda 3426$	0.108	0.144	0.052
C I]	$\lambda 2967$	...	0.006	0.001
MgII	$\lambda 2799$	0.064	0.421	0.431
[Ne IV]	$\lambda\lambda 2423$	0.183	0.029	0.030
CII]	$\lambda 2326$	...	0.037	0.015
CIII]	$\lambda 1909$	0.106	0.019	0.039
[Mg VI]	$\lambda\lambda 1806$	...	0.011	0.004
OIII]	$\lambda 1664$	0.084	0.006	0.007
CIV	$\lambda\lambda 1549$	0.520	0.514	0.080
OIV]	$\lambda 1401$	0.315	0.071	0.012
SiIV	$\lambda\lambda 1397$	(incl. above)	0.003	0.001
OI]	$\lambda 1357$	0.202	0.018	0.016
CII	$\lambda 1335$	...	0.053	0.044
OV]	$\lambda 1218$	...	0.694	0.088

^a. Dopita & Tuohy (1984) and Blair *et al.* (1989)

2. The correspondence between the observed and modeled strengths of the CIV resonance line is good for the OSP150 model, but the line is too weak in the OSP200 model. The agreement for OSP150 may be fortuitous, as recombination contributions have not been included, and the OSP200 model may be a better overall fit.
3. The other strong carbon line, CIII] λ 1909, which should not have a recombination component, is within a factor of 2.5 - 5 of the observed flux. The ratio of this line with the CIV resonance line in the two models brackets the observed ratio.
4. Finally, the [NeIII]:[NeIV]:[NeV] ratios are not too dissimilar to the observed ratios, given the measurement uncertainties. This gives some confidence in the ionization structures developed here. Neither the optical nor the UV neon emission fluxes conflict significantly with the chosen abundance levels of [Ne/O] = -0.34.

6.8 Conclusions

The simple ionization front model of D87 has been shown to be feasible, in the case where the front is driven by the detailed upstream radiation of a radiative shock traversing a knot of oxygen-rich material. The model structure can form and produce the observed spectra within the global constraints of a cloud-bowshock model, with reasonable cloud densities, sizes and velocities. In particular, the problematic I_{4363}/I_{5007} ratio has been reproduced, as a result of the combination of shock and photoionization components in the model. This relatively high [OIII] ratio has been maintained, whilst still retaining some levels of [OI] and [OII] emission, as is observed.

Present modeling still suffers from a number of difficulties, due as much to the simplified radiative transfer used as to the uncertain atomic physics. However, it seems reasonable that the proposed structure is possible, and the development of more sophisticated models should be undertaken.

6.8.1 Abundances

The primary aim of this work was to test the feasibility of an emission mechanism. It is clear that the model is indeed feasible, but that a more rigorous radiative transfer method is still needed before really reliable quantitative models become

possible. In this context, the details of the composition, beyond some qualitative conclusions, are probably not justified yet.

The abundances of the elements with respect to oxygen are not very well constrained by the observations. The optical spectra do not place strong constraints on even the neon abundance, because of the sensitivity to the excitation conditions and uncertainties in the models. Nevertheless, the initial abundances of table 6.3 do give a good overall fit to the observed spectra, and result in a reasonable model structure. The model shock structures depend somewhat on the additional cooling provided by the carbon, magnesium and silicon ions. The same applies to the photoionization models, where the additional absorption cross-sections of these ions is important to the heating achieved. The abundances used, chosen on the basis of massive star evolution models, are therefore generally consistent with the observations.

The $[\text{Ne}/\text{O}]$ ratio is estimated to be -0.34; the observations do not suggest that this is significantly in error (except for SNR 0540-69.3, of course). Furthermore, the UV spectrum of SNR E102.2-7219 does not give strong indications that the initial ratio of $[\text{C}/\text{O}]$ of -1.05 is greatly in error, either. The magnesium abundance chosen initially may be too high for the case of SNR E102.2-7219, based on the single $\text{MgII}\lambda 2799$ measurement. A ratio of $[\text{Mg}/\text{O}] = -2.2$ is estimated, with large uncertainty. Nothing in the observations places any reliable limitations on the silicon levels, except on the basis of non-detection in the difficult observations of SNR E102.2-7219. In the present models, the silicon levels would have to be raised a hundred-fold, or have a strong recombination contribution in the $\text{SiIV}\lambda\lambda 1397$ emission line, to come into conflict with the (lack of) observed emission. The uncertainties here are too great to warrant any conclusions on Si abundances.

6.8.2 Remaining Difficulties

This examination of the ionization front model supports the view that this mechanism is a reasonable model for the oxygen-rich emission in OSNRs. Having said this, a number of areas in the modeling have, perforce, been simplified or even neglected for lack of data and/or theoretical understanding. Before this model may be used for detailed quantitative measurements, these areas will need to be addressed further.

The total cooling function calculations used here are expected to be reasonably accurate and the cooling timescales of the shocks should be reliable. The main weaknesses in the computation of the atomic processes lie in the details of

the emission line spectra. The recombination spectra of the heavier ions are not calculated at all. This should not affect the cooling rates very much, as discussed in Chapter 3 § 3.3.7 where recombination is shown to not be a cooling process in the first approximation. Recombination may only affect the temperature indirectly, by removing selective ranges of electron energies from the existing thermal distribution. The recombination zones of the shock models are already very cool, and any recombination cooling will have little effect in any case. However, the observed resonance lines, particularly the UV resonance lines of carbon, oxygen and magnesium, can have significant recombination components under the conditions modeled here, and this aspect of spectrum synthesis should be addressed.

Electron conduction was not considered, due to the computational complexity of incorporating such effects into the explicit 1D Lagrangian structures used. Modeling of the effects of electron conduction by Borkowski & Shull (1990), showed that, while there is some effect in the hot zones, in the cooled recombination zones of the shock structures conduction was only significant when the plasma was pure oxygen, and fine-structure cooling less important. When significant levels of neon, silicon, magnesium and carbon are introduced, the subsequent fine-structure cooling completely dominates any effects of electron conduction heating. So, electron conduction may not be a serious omission in the oxygen–neon–carbon mixtures used here.

Another important assumption used is the strong coupling of the electron and ion temperatures in the model structures. The present modeling assumes that the electron and ion temperatures are equal for both the shock and ionization front models. Some justification for this may be made for the shock models. There is some observational evidence for rapid electron heating in collisionless shocks (*i.e.* Pravdo & Smith 1979), possibly due the plasma turbulence in the shock front itself. Therefore, in the face of the general theoretical ignorance of the detailed processes in collisionless shocks (see the review by McKee & Hollenbach 1980), it seemed that the construction of a two fluid shock model (electrons and ions), was an unnecessary complication in the already highly simplified model being considered here, especially since electron conduction has been ignored. The earlier work of Dopita & Tuohy (1984) compared results of the equilibrated electron–ion models and separated two–fluid models, and found that the shock spectra were very similar when a somewhat higher shock velocity was used for the two–fluid models. It should also be mentioned that the more recent observational test of collisionless shock heating of electrons in Cassiopeia A and Puppis A, by Jerius & Teske (1988), proved inconclusive so the matter remains an open question.

The effects of molecules and dust are not included in the MAPPINGS II code, as yet, and so could not be included in the modeling. Fortunately, the cool plasmas considered here are unlikely to be molecular, as they are highly ionized by the strong radiation fields present. The effect of dust grains is uncertain, even more so as the dust composition is likely to be abnormal. Dust, if present, might be expected to affect the hot ambient OSNR medium (Dwek 1987 ; Arendt *et al.* 1991), but the ambient plasma was taken as an observable and not modeled here.

The last major omission from the atomic processes is charge-exchange reactions involving only heavy atoms. While in normal calculations MAPPINGS II incorporates many exchange reactions, these are all with neutral and ionized hydrogen or helium. The direct reaction rates between ions of oxygen, neon and carbon are not known, and the complexity of the reaction mechanism rate calculations makes even rough estimations impossible. Dopita *et al.* (1984) argue that this omission may not be too serious in the shock models considered, since in the zones where charge exchange may be expected, the temperatures are so low that their effect on the emission spectra would be minimal. The effect on the ionization fronts is not so clear however, and the omission of charge exchange in the absence of available data is a caveat that simply has to be borne in mind for the present models, until the atomic data becomes available.

As has been discussed earlier, the simplified modeling neglected the internal photon absorption near the ionization front. This is expected to suppress the low ionization [OI] and [OII] emission, compared to an actual ionization front. Whether internal absorption will, in practice, maintain higher levels of [OI] λ 6300 and [OII] λ 3727 over a wider range of velocities is not certain, and will require more sophisticated modeling. The present models therefore overestimate the excitation and temperatures achieved for a given shock velocity. It is hoped that a fuller radiative transfer treatment will result in the same effects being achieved at a higher velocity than the corresponding models here. The infinite plane parallel treatment will also tend to overestimate the radiation field, and a 2 or 3D treatment may be necessary.

6.8.3 Future Work

Overall, the current model is an oversimplification of the physics of the situation. Nonetheless, given the lack of success of previous models, the results obtained here are very encouraging and give confidence that the elements of the correct physics have been identified. In the light of this, the added effort required to address some of the problems outlined above should prove worthwhile. The need

for more complete atomic data is apparent, notably charge exchange reactions and recombination data. The effect of the charge exchange reaction, if any, may prove particularly important in the ionization front models, because of the density and temperature regimes involved.

Clearly more constraints can be obtained by further observations. In particular, more UV observations of the Magellanic remnants need to be undertaken. The galactic remnants are hopelessly reddened for UV observations and the Magellanic remnants provide the best chance for this type of observation.

The present modeling then, while producing a good fit to the observations for a given velocity, continues to suffer from only fitting the observations with a relatively narrow range of cloud shock velocities ($130 \lesssim v_s \lesssim 230 \text{ km s}^{-1}$). Nevertheless this represents a significant improvement over previous models.

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Appendix A

Cooling Functions

TABLE A.1: COEFFICIENTS FOR THE COLLISIONAL IONIZATION BALANCE OF CHLORINE.

A. YOUNGER IONIZATION COEFFICIENTS FOR CHLORINE

ION Shell	I	A	B	C	D	ION Shell	I	A	B	C	D
CIXVII						CI VIII					
1s1	3.946E+03	1.28E+01	-4.35E+00	1.90E+00	-1.05E+01	2p6	3.473E+02	7.20E+01	-2.41E+01	1.31E+01	-5.00E+01
						2s2	4.157E+02	1.96E+01	-7.05E+00	2.80E+00	-1.68E+01
CIXVI						CI VII					
1s2	3.658E+03	2.35E+01	-7.70E+00	3.95E+00	-1.94E+01	3s1	1.135E+02	9.00E+00	-2.75E+00	7.50E-01	-5.40E+00
CI XV						2p6	3.208E+02	7.40E+01	-2.70E+01	1.50E+01	-5.99E+01
2s1	8.085E+02	9.65E+00	-2.80E+00	1.40E+00	-6.30E+00	2s2	3.770E+02	2.33E+01	-8.15E+00	3.30E+00	-1.90E+01
1s2	3.498E+03	2.30E+01	-7.20E+00	4.10E+00	-1.80E+01	CI VI					
CIXIV						3s2	9.678E+01	1.98E+01	-5.70E+00	1.75E+00	-1.19E+01
2s2	7.493E+02	1.83E+01	-4.50E+00	2.70E+00	-1.19E+01	2p6	3.013E+02	7.40E+01	-2.70E+01	1.50E+01	-5.99E+01
1s2	3.436E+03	2.30E+01	-7.20E+00	4.10E+00	-1.80E+01	2s2	3.530E+02	2.33E+01	-8.15E+00	3.30E+00	-1.90E+01
CIXIII						CI V					
2p1	6.551E+02	1.40E+01	-4.60E+00	1.45E+00	-8.50E+00	3p1	6.737E+01	5.04E+01	-3.34E+01	6.00E-01	-3.69E+01
2s2	6.821E+02	1.84E+01	-4.85E+00	2.80E+00	-1.27E+01	3s2	7.934E+01	5.51E+01	-3.72E+01	1.40E+00	-4.10E+01
CI XII						CI IV					
2p2	5.910E+02	2.70E+01	-8.50E+00	3.15E+00	-1.68E+01	3p2	5.329E+01	7.45E+01	-4.94E+01	1.30E+00	-5.46E+01
2s2	6.160E+02	1.87E+01	-5.25E+00	2.80E+00	-1.35E+01	3s2	6.379E+01	5.38E+01	-3.58E+01	1.40E+00	-4.07E+01
CI XI						CI III					
2p3	5.279E+02	3.83E+01	-1.24E+01	5.15E+00	-2.51E+01	3p3	3.983E+01	9.87E+01	-6.54E+01	1.90E+00	-7.23E+01
2s2	5.519E+02	1.89E+01	-5.70E+00	2.80E+00	-1.44E+01	3s2	4.873E+01	5.25E+01	-3.45E+01	1.40E+00	-4.05E+01
CI X						CI II					
2p4	4.543E+02	4.95E+01	-1.63E+01	7.45E+00	-3.34E+01	3p4	2.411E+01	6.44E+01	-5.17E+01	1.13E+01	-5.50E+01
2s2	5.054E+02	1.92E+01	-6.15E+00	2.80E+00	-1.51E+01	3s2	3.615E+01	5.13E+01	-3.32E+01	1.40E+00	-4.02E+01
CI IX						CI I ^a					
2p5	3.988E+02	6.08E+01	-2.02E+01	1.01E+01	-4.17E+01	3p5	2.462E+01	1.93E+02	-1.38E+02	1.60E+00	-1.39E+02
2s2	4.598E+02	1.94E+01	-6.55E+00	2.80E+00	-1.60E+01	3s2	3.720E+01	6.69E+01	-4.61E+01	1.20E+00	-5.42E+01

B. RECOMBINATION COEFFICIENTS FOR CHLORINE

ION	— Radiative —		— Di-electronic —			
	Arad	η_{rad}	Adi	Bdi	To	Ti
CI XVII	3.650E-10	0.847	0.2690	0.2790	2.84E+07	5.92E+06
CI XVI	2.550E-10	0.813	0.4390	0.2960	2.71E+07	5.36E+06
CI XV	2.165E-10	0.870	0.0152	0.2745	3.23E+05	1.07E+06
CI XIV	1.770E-10	0.765	0.0823	1.3250	5.20E+05	4.59E+06
CI XIII	2.090E-10	0.795	0.0932	0.8670	5.61E+05	2.49E+06
CI XII	9.850E-11	0.709	0.0713	1.2000	6.67E+05	2.61E+06
CI XI	7.525E-11	0.752	0.0375	1.5350	5.61E+05	3.36E+06
CI X	5.460E-11	0.754	0.0294	1.3900	6.42E+05	3.10E+06
CI IX	3.800E-11	0.767	0.0172	1.4800	7.60E+05	2.83E+06
CI VIII	2.625E-11	0.880	0.0159	0.1145	2.25E+06	2.53E+06
CI VII	1.945E-11	0.723	0.0194	0.1535	1.59E+05	1.93E+05
CI VI	1.075E-11	0.774	0.0475	0.1045	1.89E+05	1.48E+05
CI V	5.910E-12	0.778	0.0618	0.0714	2.20E+05	2.45E+05
CI IV	3.915E-12	0.749	0.0399	0.0495	2.24E+05	2.00E+05
CI III	1.820E-12	0.750	0.0178	0.0285	1.82E+05	3.00E+05
CI II	3.200E-13	0.680	0.0015	0.0100	1.80E+05	4.50E+05

a. Values for CI I were extrapolated, while the other ionisation stages were interpolated between other ions of the same isoelectronic sequence. The values for CI I ionisation and CI II recombination rates, are therefore the least certain..

TABLE A.2 : RECOMBINATION TERMS S AND σ FOR $0.02 \leq x \leq 0.15$

FOR EQUATIONS (11) AND (17)						
x	$xS^{(0)}$	$xS^{(1)}$	$xS^{(2)}$	$x\sigma^{(0)}$	$x\sigma^{(1)}$	$x\sigma^{(2)}$
0.020	0.0685	0.0042	-0.0012	0.0877	0.0053	-0.0012
0.022	0.0734	0.0044	-0.0013	0.0944	0.0057	-0.0014
0.024	0.0781	0.0047	-0.0014	0.1010	0.0061	-0.0015
0.026	0.0827	0.0049	-0.0015	0.1074	0.0065	-0.0016
0.028	0.0871	0.0052	-0.0016	0.1137	0.0069	-0.0017
0.030	0.0915	0.0054	-0.0018	0.1199	0.0073	-0.0018
0.032	0.0957	0.0056	-0.0019	0.1259	0.0076	-0.0020
0.034	0.0998	0.0058	-0.0020	0.1318	0.0080	-0.0021
0.036	0.1039	0.0060	-0.0021	0.1376	0.0083	-0.0022
0.038	0.1078	0.0061	-0.0022	0.1434	0.0086	-0.0023
0.040	0.1163	0.0063	-0.0023	0.1490	0.0089	-0.0024
0.045	0.1209	0.0067	-0.0025	0.1627	0.0097	-0.0027
0.050	0.1297	0.0070	-0.0028	0.1759	0.0104	-0.0030
0.055	0.1382	0.0073	-0.0030	0.1886	0.0111	-0.0033
0.060	0.1462	0.0076	-0.0033	0.2010	0.0118	-0.0035
0.065	0.1540	0.0078	-0.0035	0.2130	0.0124	-0.0038
0.070	0.1615	0.0080	-0.0038	0.2247	0.0130	-0.0041
0.075	0.1687	0.0082	-0.0040	0.2361	0.0135	-0.0044
0.080	0.1757	0.0083	-0.0043	0.2472	0.0141	-0.0046
0.085	0.1824	0.0085	-0.0045	0.2581	0.0146	-0.0049
0.090	0.1889	0.0086	-0.0047	0.2687	0.0150	-0.0051
0.095	0.1953	0.0087	-0.0050	0.2791	0.0155	-0.0054
0.100	0.2015	0.0087	-0.0052	0.2892	0.0160	-0.0057
0.110	0.2133	0.0088	-0.0056	0.3090	0.0168	-0.0062
0.120	0.2245	0.0088	-0.0061	0.3281	0.0176	-0.0067
0.130	0.2352	0.0088	-0.0065	0.3464	0.0183	-0.0072
0.140	0.2454	0.0087	-0.0070	0.3642	0.0189	-0.0077
0.150	0.2552	0.0086	-0.0074	0.3815	0.0195	-0.0082
0.160	0.2646	0.0084	-0.0078	0.3983	0.0201	-0.0087
0.170	0.2736	0.0083	-0.0082	0.4146	0.0206	-0.0092

TABLE A.3: CONTINUUM DATA

A. FREE-FREE AND FREE-BOUND DATA

Z	ion	n_0	ξ	z	Z	ion	n_0	ξ	z	Z	ion	n_0	ξ	z	Z	ion	n_0	ξ	z
1	1	1	2	1.000	12	9	2	7	9.822	17	7	3	18	8.694	26	5	3	7	7.069
2	1	1	1	1.345	12	10	2	8	10.397	17	8	2	1	10.123	26	6	3	8	8.135
2	2	1	2	2.000	12	11	1	1	11.383	17	9	2	2	10.853	26	7	3	9	9.215
6	1	2	5	1.820	12	12	1	2	12.014	17	10	2	3	11.577	26	8	3	10	10.001
6	2	2	6	2.678	13	1	3	16	1.990	17	11	2	4	12.478	26	9	3	11	12.471
6	3	2	7	3.753	13	2	3	17	3.530	17	12	2	5	13.196	26	10	3	12	13.171
6	4	2	8	4.356	13	3	3	18	4.342	17	13	2	6	13.902	26	11	3	13	13.864
6	5	1	1	5.370	13	4	2	1	5.941	17	14	2	7	14.851	26	12	3	14	14.801
6	6	1	2	6.003	13	5	2	2	6.725	17	15	2	8	15.430	26	13	3	15	15.457
7	1	2	4	2.068	13	6	2	3	7.485	17	16	1	1	16.402	26	14	3	16	16.107
7	2	2	5	2.951	13	7	2	4	8.427	17	17	1	2	17.074	26	15	3	17	17.392
7	3	2	6	3.736	13	8	2	5	9.150	18	1	3	11	3.230	26	16	3	18	17.990
7	4	2	7	4.774	13	9	2	6	9.856	18	2	3	12	4.276	26	17	2	1	19.298
7	5	2	8	5.366	13	10	2	7	10.828	18	3	3	13	5.193	26	18	2	2	19.987
7	6	1	1	6.372	13	11	2	8	11.403	18	4	3	14	6.292	26	19	2	3	20.695
7	7	1	2	7.004	13	12	1	1	12.386	18	5	3	15	7.047	26	20	2	4	21.572
8	1	2	3	2.001	13	13	1	2	13.017	18	6	3	16	7.761	26	21	2	5	22.290
8	2	2	4	3.214	14	1	3	15	2.323	18	7	3	17	9.078	26	22	2	6	23.004
8	3	2	5	4.020	14	2	3	16	3.289	18	8	3	18	9.744	26	23	2	7	23.950
8	4	2	6	4.772	14	3	3	17	4.708	18	9	2	1	11.150	26	24	2	8	24.527
8	5	2	7	5.788	14	4	3	18	5.466	18	10	2	2	11.869	26	25	1	1	25.480
8	6	2	8	6.374	14	5	2	1	7.004	18	11	2	3	12.592	26	26	1	2	26.121
8	7	1	1	7.374	14	6	2	2	7.767	18	12	2	4	13.483	28	1	4	31	2.997
8	8	1	2	8.005	14	7	2	3	8.515	18	13	2	5	14.205	28	2	4	32	4.624
10	1	2	1	2.519	14	8	2	4	9.443	18	14	2	6	14.913	28	3	3	3	4.825
10	2	2	2	3.471	14	9	2	5	10.163	18	15	2	7	15.857	28	4	3	4	6.028
10	3	2	3	4.320	14	10	2	6	10.866	18	16	2	8	16.433	28	5	3	5	7.069
10	4	2	4	5.345	14	11	2	7	11.834	18	17	1	1	17.408	28	6	3	6	8.455
10	5	2	5	6.093	14	12	2	8	12.409	18	18	1	2	18.042	28	7	3	7	9.418
10	6	2	6	6.816	14	13	1	1	13.389	20	1	4	31	2.682	28	8	3	8	10.419
10	7	2	7	7.808	14	14	1	2	14.021	20	2	4	32	3.737	28	9	3	9	11.302
10	8	2	8	8.386	16	1	3	13	2.619	20	3	3	11	5.805	28	10	3	10	12.192
10	9	1	1	9.378	16	2	3	14	3.930	20	4	3	12	6.667	28	11	3	11	14.576
10	10	1	2	10.009	16	3	3	15	4.801	20	5	3	13	7.475	28	12	3	12	15.264
11	1	3	18	1.844	16	4	3	16	5.595	20	6	3	14	8.485	28	13	3	13	15.942
11	2	2	1	3.730	16	5	3	17	6.936	20	7	3	15	9.193	28	14	3	14	16.870
11	3	2	2	4.591	16	6	3	18	7.634	20	8	3	16	9.877	28	15	3	15	17.524
11	4	2	3	5.394	16	7	2	1	9.076	20	9	3	17	11.176	28	16	3	16	18.173
11	5	2	4	6.381	16	8	2	2	9.828	20	10	3	18	11.826	28	17	3	17	19.440
11	6	2	5	7.116	16	9	2	3	10.560	20	11	2	1	13.192	28	18	3	18	20.044
11	7	2	6	7.831	16	10	2	4	11.468	20	12	2	2	13.902	28	19	2	1	21.325
11	8	2	7	8.815	16	11	2	5	12.185	20	13	2	3	14.614	28	20	2	2	22.018
11	9	2	8	9.392	16	12	2	6	12.892	20	14	2	4	15.503	28	21	2	3	22.728
11	10	1	1	10.380	16	13	2	7	13.845	20	15	2	5	16.226	28	22	2	4	23.604
11	11	1	2	11.011	16	14	2	8	14.423	20	16	2	6	16.927	28	23	2	5	24.316
12	1	3	17	2.250	16	15	1	1	15.397	20	17	2	7	17.882	28	24	2	6	25.037
12	2	3	18	3.155	16	16	1	2	16.030	20	18	2	8	18.448	28	25	2	7	25.983
12	3	2	1	4.855	17	1	3	12	2.930	20	19	1	1	19.421	28	26	2	8	26.559
12	4	2	2	5.671	17	2	3	13	3.970	20	20	1	2	20.056	28	27	1	1	27.495
12	5	2	3	6.446	17	3	3	14	5.120	26	1	4	31	3.043	28	28	1	2	28.169
12	6	2	4	7.407	17	4	3	15	5.948	26	2	4	32	4.361					
12	7	2	5	8.135	17	5	3	16	6.694	26	3	3	5	4.504					
12	8	2	6	8.844	17	6	3	17	8.014	26	4	3	6	6.022					

B. 2-PHOTON DATA		Hydrogenic Ions		Helium Like Ions	
$(\lambda_0 = 12398/E_{2\gamma})$		Z	$E_{2\gamma}$ (eV)	Z	$E_{2\gamma}$ (eV)
		1	10.199		
		2	40.813	2	20.615
		6	367.48	6	304.39
		7	500.26	7	426.32
		8	653.51	8	568.66
		10	1021.5	10	914.7
		11	1236.3	11	1094.2
		12	1471.7	12	1330.2
		13	1730.2	13	1556.1
		14	2004.5	14	1815.6
		16	2619.8	16	2402.7
		17	2958.7	17	2716.5
		18	3318.4	18	3133.6
		20	4100.4	20	3795.2
		26	6931.4	26	6537.5
		28	8038.8	28	7581.9

TABLE A.4 : SOLAR ABUNDANCES AND PRIMORDIAL RATIOS.

Solar ^a -log(n/n _H)	Primordial ^b log(ratio)	Solar -log(n/n _H)	Primordial log(ratio)	Solar -log(n/n _H)	Primordial log(ratio)	Solar -log(n/n _H)	Primordial log(ratio)
H+0.00	+0.00	He ...-1.01	-0.08382	C-3.44	+0.00	N-3.95	+0.00
O-3.07	+0.50	Ne ...-3.91	+0.50	Na ...-5.67	...	Mg ..-4.42	+0.40
Al-5.53	-0.30	Si-4.45	+0.40	S-4.79	+0.00	Cl-6.5	...
Ar ...-5.44	+0.50	Ca ...-5.64	+0.40	Fe ...-4.33	+0.00	Ni ...-5.75	+0.00

a. Anders and Grevesse 1989

b. Wheeler *et al.* 1989, Bessell *et al.* 1991 and Silk 1991, (Private Communication)

TABLE A.5: COLLISIONAL IONIZATION EQUILIBRIUM: IONIZATION BALANCE. CONTINUED.

OXYGEN IONIZATION BALANCE, CONT.

Log(T)	I	II	III	IV	V	VI	VII	VIII	IX
6.15	...	...	...	...	5.042	2.498	0.100	0.699	2.526
6.20	...	...	...	...	5.201	2.538	0.171	0.507	1.948
6.25	...	...	...	...	5.379	2.602	0.264	0.378	1.459
6.30	...	...	...	...	5.581	2.696	0.382	0.304	1.059
6.35	...	...	...	...	5.816	2.826	0.530	0.283	0.740
6.40	...	...	...	...	6.088	2.969	0.712	0.312	0.498
6.45	...	...	...	...	6.399	3.213	0.928	0.388	0.326
6.50	...	...	...	...	6.739	3.461	1.169	0.500	0.211
6.55	...	...	...	...	...	3.731	1.425	0.632	0.137
6.60	...	...	...	...	...	4.015	1.689	0.779	0.090
6.65	...	...	...	...	...	4.302	1.949	0.926	0.060
6.70	...	...	...	...	...	4.587	2.203	1.071	0.041
6.75	...	...	...	...	...	4.867	2.447	1.211	0.029
6.80	...	...	...	...	...	5.142	2.682	1.343	0.021
6.85	...	...	...	...	...	5.410	2.907	1.469	0.016
6.90	...	...	...	...	...	5.672	3.122	1.588	0.012
6.95	...	...	...	...	...	5.927	3.329	1.701	0.009
7.00	...	...	...	...	...	6.177	3.527	1.807	0.007
7.05	...	...	...	...	...	6.420	3.718	1.908	0.006
7.10	...	...	...	...	...	6.658	3.902	2.003	0.004
7.15	...	...	...	...	...	6.891	4.079	2.093	0.004
7.20	...	...	...	...	...	...	4.250	2.180	0.003
7.25	...	...	...	...	...	...	4.415	2.262	0.002
7.30	...	...	...	...	...	...	4.575	2.341	0.002
7.35	...	...	...	...	...	...	4.731	2.417	0.002
7.40	...	...	...	...	...	...	4.882	2.490	0.001
7.45	...	...	...	...	...	...	5.029	2.560	0.001
7.50	...	...	...	...	...	...	5.172	2.628	0.001
7.55	...	...	...	...	...	...	5.312	2.694	0.001
7.60	...	...	...	...	...	...	5.448	2.758	0.001
7.65	...	...	...	...	...	...	5.582	2.820	0.001
7.70	...	...	...	...	...	...	5.712	2.881	0.001
7.75	...	...	...	...	...	...	5.839	2.940	0.000
7.80	...	...	...	...	...	...	5.964	2.998	0.000
7.85	...	...	...	...	...	...	6.086	3.054	0.000
7.90	...	...	...	...	...	...	6.206	3.109	0.000
7.95	...	...	...	...	...	...	6.323	3.163	0.000
8.00	...	...	...	...	...	...	6.437	3.215	0.000
8.05	...	...	...	...	...	...	6.548	3.265	0.000
8.10	...	...	...	...	...	...	6.656	3.314	0.000
8.15	...	...	...	...	...	...	6.844	3.443	0.000
8.20	...	...	...	...	...	...	6.955	3.498	0.000
8.25	...	...	...	...	...	...	...	3.551	0.000
8.30	...	...	...	...	...	...	...	3.657	0.000
8.35	...	...	...	...	...	...	...	3.709	0.000
8.40	...	...	...	...	...	...	...	3.759	0.000
8.45	...	...	...	...	...	...	...	...	0.000
8.50	...	...	...	...	...	...	...	3.810	0.000

NITROGEN IONIZATION BALANCE, CONT.

Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
7.60	...	...	...	...	...	6.152	3.132	0.000	...	...	...
7.65	...	...	...	...	...	6.280	3.190	0.000	...	...	...
7.70	...	...	...	...	...	6.404	3.248	0.000	...	...	...
7.75	...	...	...	...	...	6.527	3.304	0.000	...	...	...
7.80	...	...	...	...	...	6.647	3.358	0.000	...	...	...
7.85	...	...	...	...	...	6.764	3.411	0.000	...	...	...
7.90	...	...	...	...	...	6.879	3.463	0.000	...	...	...
7.95	...	...	...	...	...	6.991	3.513	0.000	...	...	...
8.00	...	...	...	...	...	...	3.638	0.000	...	...	...
8.05	...	...	...	...	...	...	3.693	0.000	...	...	...
8.10	...	...	...	...	...	...	3.747	0.000	...	...	...
8.15	...	...	...	...	...	...	3.800	0.000	...	...	...
8.20	...	...	...	...	...	...	3.853	0.000	...	...	...
8.25	...	...	...	...	...	...	3.905	0.000	...	...	...
8.30	...	...	...	...	...	...	3.957	0.000	...	...	...
8.35	...	...	...	...	...	...	4.008	0.000	...	...	...
8.40	...	...	...	...	...	...	4.058	0.000	...	...	...
8.45	...	...	...	...	...	...	4.107	0.000	...	...	...
8.50	...	...	...	...	...	...	4.155	0.000	...	...	...

NEON IONIZATION BALANCE											
Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
4.00	0.000	6.889	...	...	...	...	...	...	...	...	...
4.05	0.000	5.649	...	...	...	...	...	...	...	...	...
4.10	0.000	4.537	...	...	...	...	...	...	...	...	...
4.15	0.000	3.540	...	...	...	...	...	...	...	...	...
4.20	0.001	2.645	...	...	...	...	...	...	...	...	...
4.25	0.006	1.846	...	...	...	...	...	...	...	...	...
4.30	0.032	1.147	...	...	...	...	...	...	...	...	...
4.35	0.129	0.591	6.427	...	...	...	...	...	...	...	...
4.40	0.368	0.243	5.023	...	...	...	...	...	...	...	...
4.45	0.738	0.088	3.924	...	...	...	...	...	...	...	...
4.50	1.142	0.033	3.032	...	...	...	...	...	...	...	...
4.55	1.505	0.016	2.281	...	...	...	...	...	...	...	...
4.60	1.798	0.017	1.651	5.979	...	...	...	...	...	...	...
4.65	2.027	0.037	1.140	4.755	...	...	...	...	...	...	...
4.70	2.227	0.089	0.748	4.755	...	...	...	...	...	...	...
4.75	2.435	0.182	0.470	3.755	...	...	...	...	...	...	...
4.80	2.667	0.317	0.288	2.940	...	...	...	...	...	...	...
4.85	2.926	0.485	0.177	2.273	...	...	...	...	...	...	...
4.90	3.204	0.672	0.115	1.719	5.806	...	...	...	...	...	...
4.95	3.481	0.875	0.091	1.256	4.695	...	...	...	...	...	...
5.00	3.812	1.098	0.104	0.876	3.729	6.879	...	...	...	...	...
5.05	4.195	1.381	0.189	0.510	2.804	5.634	...	...	...	...	...
5.10	4.596	1.682	0.307	0.319	2.150	4.556	...	...	...	...	...
5.15	5.024	2.019	0.472	0.201	1.610	3.625	...	...	...	...	...
5.20	5.506	2.388	0.678	0.144	1.167	3.025	...	...	...	...	...
5.25	6.001	2.779	0.915	0.142	0.812	2.826	...	...	...	...	...
5.30	6.531	3.206	1.189	0.194	0.540	2.151	5.669	...	...	...	...
5.35	...	3.667	1.503	0.303	0.351	1.594	4.040	...	...	...	...
5.40	...	4.160	1.856	0.467	0.242	1.149	3.164	6.138	...	...	...
5.45	...	4.692	2.254	0.682	0.203	0.806	2.427	4.937	6.805	...	...
5.50	...	5.254	2.685	0.942	0.229	0.555	1.815	3.904	3.502	...	...
5.55	...	5.844	3.147	1.244	0.315	0.388	1.317	3.025	3.998	...	...
5.60	...	6.462	3.641	1.586	0.435	0.299	0.923	2.287	2.875	...	...
5.65	...	...	4.167	1.968	0.648	0.283	0.626	1.681	1.922	...	...
5.70	...	...	4.728	2.391	0.894	0.359	0.424	1.216	1.140	...	...
5.75	...	...	5.343	2.874	1.211	0.480	0.325	0.934	0.572	...	...
5.80	...	...	6.063	3.468	1.649	0.755	0.380	0.934	0.372	...	...
5.85	...	...	6.936	4.219	2.252	1.207	0.628	0.873	0.250	...	...
5.90	...	...	...	5.072	2.965	1.780	1.009	0.970	0.110	0.053	...
5.95	...	...	...	5.937	3.697	2.380	1.431	1.130	0.053	...	...
6.00	...	...	...	6.769	4.403	3.060	1.845	1.303	0.029	4.771	...
6.05	...	...	...	...	5.697	3.505	1.515	1.404	0.018	4.392	...
6.10	...	...	...	...	6.697	4.023	2.607	1.634	0.012	3.342	...
6.15	...	...	...	...	6.284	4.502	2.948	1.781	0.008	2.762	6.957
6.20	...	...	...	...	6.832	4.947	3.263	1.915	0.008	2.247	5.855

TABLE A 5. COLLISIONAL IONIZATION EQUILIBRIUM: IONIZATION BALANCE. CONTINUED.

[illegible]

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. CONTINUED.

MAGNESIUM IONIZATION BALANCE													
Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
4.00	0.784	0.078	3.540	...	...	...	...	...	...	...	...	...	...
4.05	1.041	0.043	2.619	...	...	...	...	...	...	...	...	...	...
4.10	1.294	0.029	1.831	...	...	...	...	...	...	...	...	...	...
4.15	1.553	0.045	1.155	...	...	...	...	...	...	...	...	...	...
4.20	1.862	0.130	0.612	...	...	...	...	...	...	...	...	...	...
4.25	2.291	0.351	0.261	...	...	...	...	...	...	...	...	...	...
4.30	2.839	0.705	0.096	...	...	...	...	...	...	...	...	...	...
4.35	3.428	1.114	0.035	...	...	...	...	...	...	...	...	...	...
4.40	4.000	1.516	0.013	...	...	...	...	...	...	...	...	...	...
4.45	4.535	1.893	0.006	...	...	...	...	...	...	...	...	...	...
4.50	5.029	2.237	0.002	...	...	...	...	...	...	...	...	...	...
4.55	5.485	2.551	0.001	...	...	...	...	...	...	...	...	...	...
4.60	5.905	2.837	0.001	...	...	...	...	...	...	...	...	...	...
4.65	6.292	3.096	0.000	6.581	...	...	...	...	...	...	...	...	...
4.70	6.650	3.332	0.000	5.379	...	...	...	...	...	...	...	...	...
4.75	6.978	3.544	0.000	4.329	...	...	...	...	...	...	...	...	...
4.80	...	3.728	0.000	3.406	...	...	...	...	...	...	...	...	...
4.85	...	3.882	0.001	2.612	...	...	...	...	...	...	...	...	...
4.90	...	3.995	0.005	1.944	6.127	...	...	...	...	...	...	...	...
4.95	...	4.067	0.018	1.400	4.865	...	...	...	...	...	...	...	...
5.00	...	4.117	0.057	0.914	3.735	...	...	...	...	...	...	...	...
5.05	...	4.162	0.123	0.611	2.889	...	...	...	...	...	...	...	...
5.10	...	4.232	0.232	0.391	2.182	5.848	...	...	...	...	...	...	...
5.15	...	4.343	0.387	0.248	1.598	4.669	...	...	...	...	...	...	...
5.20	...	4.502	0.587	0.177	1.125	3.656	...	...	...	...	...	...	...
5.25	...	4.712	0.832	0.171	0.754	2.794	6.550	...	...	...	...	...	...
5.30	...	4.981	1.126	0.232	0.481	2.074	5.275	...	...	...	...	...	...
5.35	...	5.311	1.471	0.361	0.303	1.489	4.186	...	...	...	...	...	...
5.40	...	5.700	1.867	0.553	0.213	1.027	3.266	6.680	...	...	...	...	...
5.45	...	6.144	2.308	0.803	0.204	0.678	2.500	5.397	...	...	...	...	...
5.50	...	6.635	2.788	1.109	0.270	0.432	1.872	4.300	...	...	...	...	...
5.55	...	...	3.317	1.463	0.403	0.278	1.371	3.371	6.410	...	...	...	...
5.60	...	...	3.876	1.859	0.593	0.206	0.978	2.590	5.161	...	...	...	...
5.65	...	...	4.458	2.287	0.832	0.202	0.681	1.939	4.082	6.657	...	...	...
5.70	...	...	5.069	2.752	1.117	0.264	0.472	1.405	3.158	5.262	...	...	...
5.75	...	...	5.707	3.250	1.448	0.390	0.349	0.983	2.379	4.053	5.703	...	...
5.80	...	...	6.384	3.792	1.833	0.582	0.310	0.670	1.737	3.021	4.256	...	...
5.85	...	...	...	4.380	2.272	0.842	0.356	0.464	1.229	2.156	3.016	...	...
5.90	...	...	...	5.024	2.776	1.179	0.495	0.369	0.856	1.457	1.977	...	...
5.95	...	...	...	5.759	3.379	1.624	0.753	0.412	0.641	0.943	1.155	...	...
6.00	...	...	...	6.643	4.135	2.234	1.188	0.645	0.636	0.663	0.595	...	...
6.05	...	...	...	...	5.051	3.010	1.801	1.069	0.840	0.615	0.292	...	...
6.10	...	...	...	...	6.045	3.872	2.508	1.600	1.164	0.706	0.151	6.293	...
6.15	...	...	...	...	...	4.735	3.226	2.153	1.524	0.851	0.085	5.397	...
6.20	...	...	...	...	...	5.566	3.918	2.690	1.881	1.008	0.052	4.617	...
6.25	...	...	...	...	...	6.351	4.572	3.197	2.219	1.160	0.034	3.928	...
6.30	...	...	...	...	...	...	5.180	3.665	2.529	1.297	0.024	3.317	...
6.35	...	...	...	...	...	...	5.739	4.093	2.807	1.414	0.019	2.774	6.789
6.40	...	...	...	...	...	...	6.250	4.478	3.052	1.507	0.016	2.295	5.771
6.45	...	...	...	...	...	...	6.715	4.824	3.264	1.576	0.018	1.876	4.866
6.50	...	...	...	...	...	...	...	5.136	3.449	1.628	0.024	1.516	4.065
6.55	...	...	...	...	...	...	...	5.424	3.616	1.669	0.038	1.211	3.362
6.60	...	...	...	...	...	...	...	5.698	3.776	1.709	0.061	0.958	2.748
6.65	...	...	...	...	...	...	...	5.968	3.936	1.756	0.097	0.753	2.215
6.70	...	...	...	...	...	...	...	6.241	4.104	1.817	0.148	0.592	1.755
6.75	...	...	...	...	...	...	...	6.524	4.287	1.898	0.217	0.472	1.363
6.80	...	...	...	...	...	...	...	6.824	4.491	2.005	0.308	0.392	1.034
6.85	...	...	...	...	...	...	...	...	4.719	2.139	0.422	0.353	0.767
6.90	...	...	...	...	...	...	...	...	4.976	2.307	0.566	0.350	0.558
6.95	...	...	...	...	...	...	...	...	5.260	2.506	0.737	0.384	0.398
7.00	...	...	...	...	...	...	...	...	5.566	2.730	0.927	0.446	0.282
7.05	...	...	...	...	...	...	...	...	5.886	2.972	1.132	0.529	0.201
7.10	...	...	...	...	...	...	...	...	6.213	3.224	1.344	0.624	0.145
7.15	...	...	...	...	...	...	...	...	6.543	3.482	1.537	0.726	0.106
7.20	...	...	...	...	...	...	...	...	6.871	3.740	1.769	0.830	0.078
7.25	...	...	...	...	...	...	...	...	...	3.996	1.976	0.934	0.059
7.30	...	...	...	...	...	...	...	...	...	4.249	2.178	1.035	0.045
7.35	...	...	...	...	...	...	...	...	...	4.497	2.373	1.133	0.035
7.40	...	...	...	...	...	...	...	...	...	4.741	2.562	1.228	0.028
7.45	...	...	...	...	...	...	...	...	...	4.979	2.745	1.319	0.022
7.50	...	...	...	...	...	...	...	...	...	5.212	2.921	1.406	0.018
7.55	...	...	...	...	...	...	...	...	...	5.439	3.091	1.489	0.015
7.60	...	...	...	...	...	...	...	...	...	5.662	3.256	1.570	0.012
7.65	...	...	...	...	...	...	...	...	...	5.879	3.416	1.647	0.010
7.70	...	...	...	...	...	...	...	...	...	6.093	3.571	1.721	0.008
7.75	...	...	...	...	...	...	...	...	...	6.301	3.721	1.793	0.007
7.80	...	...	...	...	...	...	...	...	...	6.505	3.867	1.862	0.006
7.85	...	...	...	...	...	...	...	...	...	6.705	4.009	1.930	0.005
7.90	...	...	...	...	...	...	...	...	...	6.902	4.147	1.995	0.004
7.95	...	...	...	...	...	...	...	...	...	...	4.282	2.058	0.004
8.00	...	...	...	...	...	...	...	...	...	...	4.413	2.120	0.003
8.05	...	...	...	...	...	...	...	...	...	...	4.541	2.180	0.003
8.10	...	...	...	...	...	...	...	...	...	...	4.666	2.239	0.002
8.15	...	...	...	...	...	...	...	...	...	...	4.789	2.296	0.002
8.20	...	...	...	...	...	...	...	...	...	...	4.908	2.352	0.002
8.25	...	...	...	...	...	...	...	...	...	...	5.025	2.407	0.002
8.30	...	...	...	...	...	...	...	...	...	...	5.138	2.461	0.001
8.35	...	...	...	...	...	...	...	...	...	...	5.249	2.513	0.001
8.40	...	...	...	...	...	...	...	...	...	...	5.357	2.563	0.001
8.45	...	...	...	...	...	...	...	...	...	...	5.462	2.611	0.001
8.50	...	...	...	...	...	...	...	...	...	...	5.645	2.740	0.001

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. *CONTINUED.*

ALUMINIUM IONIZATION BALANCE															
Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV
4.00	1.459	0.015	6.078	...	...	...	...	...	...	...	...	...	...	...	...
4.05	1.655	0.010	5.117	...	...	...	...	...	...	...	...	...	...	...	...
4.10	1.803	0.007	4.282	...	...	...	...	...	...	...	...	...	...	...	...
4.15	1.922	0.005	3.550	...	...	...	...	...	...	...	...	...	...	...	...
4.20	2.024	0.005	2.903	...	...	...	...	...	...	...	...	...	...	...	...
4.25	2.119	0.005	2.328	...	...	...	...	...	...	...	...	...	...	...	...
4.30	2.212	0.009	1.816	5.662	...	...	...	...	...	...	...	...	...	...	...
4.35	2.310	0.022	1.363	4.367	...	...	...	...	...	...	...	...	...	...	...
4.40	2.420	0.051	0.971	3.219	...	...	...	...	...	...	...	...	...	...	...
4.45	2.570	0.114	0.652	2.220	...	...	...	...	...	...	...	...	...	...	...
4.50	2.776	0.236	0.425	1.380	...	...	...	...	...	...	...	...	...	...	...
4.55	3.083	0.460	0.330	0.733	...	...	...	...	...	...	...	...	...	...	...
4.60	3.546	0.841	0.419	0.324	...	...	...	...	...	...	...	...	...	...	...
4.65	4.150	1.363	0.672	0.129	...	...	...	...	...	...	...	...	...	...	...
4.70	4.808	1.939	1.002	0.051	...	...	...	...	...	...	...	...	...	...	...
4.75	5.456	2.505	1.340	0.022	...	...	...	...	...	...	...	...	...	...	...
4.80	6.069	3.037	1.661	0.010	6.210	...	...	...	...	...	...	...	...	...	...
4.85	6.641	3.529	1.957	0.005	5.108	...	...	...	...	...	...	...	...	...	...
4.90	...	3.978	2.226	0.003	4.127	...	...	...	...	...	...	...	...	...	...
4.95	...	4.385	2.464	0.002	3.260	...	...	...	...	...	...	...	...	...	...
5.00	...	4.746	2.668	0.002	2.504	...	...	...	...	...	...	...	...	...	...
5.05	...	5.122	2.831	0.007	1.857	6.309	...	...	...	...	...	...	...	...	...
5.10	...	5.398	2.963	0.022	1.321	5.072	...	...	...	...	...	...	...	...	...
5.15	...	5.645	3.074	0.060	0.892	4.017	...	...	...	...	...	...	...	...	...
5.20	...	5.890	3.189	0.136	0.571	3.131	...	...	...	...	...	...	...	...	...
5.25	...	6.154	3.331	0.260	0.350	2.400	6.045	...	...	...	...	...	...	...	...
5.30	...	6.448	3.507	0.428	0.214	1.801	4.857	...	...	...	...	...	...	...	...
5.35	...	6.770	3.717	0.632	0.144	1.312	3.834	...	...	...	...	...	...	...	...
5.40	...	...	3.961	0.865	0.130	0.916	2.952	6.499	...	...	...	...	...	...	...
5.45	...	...	4.244	1.134	0.171	0.610	2.204	5.203	...	...	...	...	...	...	...
5.50	...	...	4.576	1.446	0.272	0.394	1.586	4.088	...	...	...	...	...	...	...
5.55	...	...	4.965	1.807	0.437	0.269	1.094	3.144	6.192	...	...	...	...	...	...
5.60	...	...	5.411	2.219	0.666	0.233	0.723	2.362	4.923	...	...	...	...	...	...
5.65	...	...	5.914	2.682	0.957	0.280	0.464	1.728	3.848	6.924	...	...	...	...	...
5.70	...	...	6.468	3.189	1.303	0.403	0.307	1.229	2.947	5.557	...	...	...	...	...
5.75	...	...	...	3.739	1.699	0.592	0.239	0.849	2.202	4.388	6.933	...	...	...	...
5.80	...	...	...	4.325	2.139	0.841	0.253	0.577	1.597	3.395	5.481	...	...	...	...
5.85	...	...	...	4.948	2.623	1.147	0.343	0.405	1.120	2.564	4.231	5.892	...	...	...
5.90	...	...	...	5.608	3.151	1.508	0.507	0.327	0.763	1.882	3.168	4.431	...	...	...
5.95	...	...	...	6.312	3.728	1.930	0.743	0.342	0.522	1.342	2.280	3.181	...	...	...
6.00	...	...	...	...	4.359	2.413	1.055	0.450	0.394	0.939	1.561	2.134	...	...	...
6.05	...	...	...	...	5.068	2.985	1.467	0.671	0.398	0.689	1.020	1.296	...	...	...
6.10	...	...	...	...	5.906	3.691	2.025	1.050	0.574	0.630	0.696	0.701	...	...	...
6.15	...	...	...	...	6.889	4.550	2.743	1.602	0.938	0.777	0.599	0.358	...	...	...
6.20	...	...	...	...	...	5.495	3.556	2.261	1.420	1.055	0.655	0.189	6.048	...	...
6.25	...	...	...	...	...	6.450	4.385	2.944	1.940	1.385	0.776	0.109	5.182	...	...
6.30	...	...	...	...	...	...	5.190	3.611	2.452	1.720	0.918	0.067	4.434	...	...
6.35	...	...	...	...	...	...	5.949	4.240	2.936	2.038	1.058	0.045	3.778	...	...
6.40	...	...	...	...	...	...	6.659	4.826	3.384	2.330	1.185	0.032	3.197	...	...
6.45	...	...	...	...	...	...	...	5.365	3.794	2.592	1.292	0.025	2.684	6.503	...
6.50	...	...	...	...	...	...	...	5.858	4.163	2.823	1.377	0.022	2.231	5.544	...
6.55	...	...	...	...	...	...	...	6.309	4.497	3.025	1.443	0.023	1.836	4.692	...
6.60	...	...	...	...	...	...	...	6.726	4.801	3.205	1.494	0.029	1.496	3.937	...
6.65	...	...	...	...	...	...	...	...	5.085	3.370	1.538	0.042	1.206	3.272	...
6.70	...	...	...	...	...	...	...	...	5.357	3.529	1.582	0.064	0.964	2.690	...
6.75	...	...	...	...	...	...	...	...	5.626	3.691	1.634	0.098	0.765	2.181	...
6.80	...	...	...	...	...	...	...	...	5.899	3.861	1.701	0.146	0.607	1.740	...
6.85	...	...	...	...	...	...	...	...	6.182	4.045	1.786	0.212	0.487	1.363	...
6.90	...	...	...	...	...	...	...	...	6.481	4.249	1.895	0.299	0.404	1.045	...
6.95	...	...	...	...	...	...	...	...	6.798	4.476	2.031	0.408	0.360	0.788	...
7.00	...	...	...	...	...	...	...	...	...	4.731	2.199	0.545	0.352	0.579	...
7.05	...	...	...	...	...	...	...	...	...	5.010	2.394	0.707	0.377	0.420	...
7.10	...	...	...	...	...	...	...	...	...	5.310	2.613	0.887	0.430	0.304	...
7.15	...	...	...	...	...	...	...	...	...	5.623	2.849	1.082	0.503	0.221	...
7.20	...	...	...	...	...	...	...	...	...	5.944	3.095	1.284	0.589	0.162	...
7.25	...	...	...	...	...	...	...	...	...	6.268	3.347	1.488	0.682	0.120	...
7.30	...	...	...	...	...	...	...	...	...	6.591	3.600	1.691	0.778	0.090	...
7.35	...	...	...	...	...	...	...	...	...	6.909	3.851	1.891	0.875	0.069	...
7.40	...	...	...	...	...	...	...	...	...	...	4.099	2.086	0.971	0.053	...
7.45	...	...	...	...	...	...	...	...	...	...	4.343	2.276	1.064	0.042	...
7.50	...	...	...	...	...	...	...	...	...	...	4.582	2.459	1.154	0.033	...
7.55	...	...	...	...	...	...	...	...	...	...	4.816	2.637	1.240	0.027	...
7.60	...	...	...	...	...	...	...	...	...	...	5.045	2.808	1.324	0.022	...
7.65	...	...	...	...	...	...	...	...	...	...	5.269	2.974	1.404	0.018	...
7.70	...	...	...	...	...	...	...	...	...	...	5.488	3.135	1.482	0.015	...
7.75	...	...	...	...	...	...	...	...	...	...	5.702	3.291	1.557	0.012	...
7.80	...	...	...	...	...	...	...	...	...	...	5.912	3.443	1.629	0.011	...
7.85	...	...	...	...	...	...	...	...	...	...	6.117	3.589	1.699	0.009	...
7.90	...	...	...	...	...	...	...	...	...	...	6.318	3.732	1.767	0.008	...
7.95	...	...	...	...	...	...	...	...	...	...	6.514	3.871	1.832	0.007	...
8.00	...	...	...	...	...	...	...	...	...	...	6.707	4.006	1.896	0.006	...
8.05	...	...	...	...	...	...	...	...	...	...	6.896	4.138	1.958	0.005	...
8.10	...	...	...	...	...	...	...	...	...	...	...	4.267	2.019	0.004	...
8.15	...	...	...	...	...	...	...	...	...	...	...	4.392	2.078	0.004	...
8.20	...	...	...	...	...	...	...	...	...	...	...	4.514	2.136	0.003	...
8.25	...	...	...	...	...	...	...	...	...	...	...	4.634	2.192	0.003	...
8.30	...	...	...	...	...	...	...	...	...	...	...	4.750	2.247	0.002	...
8.35	...	...	...	...	...	...	...	...	...	...	...	4.864	2.301	0.002	...
8.40	...	...	...	...	...	...	...	...	...	...	...	4.975	2.354	0.002	...
8.45	...	...	...	...	...	...	...	...	...	...	...	5.083	2.405	0.002	...
8.50	...	...	...	...	...	...	...	...	...	...	...	5.187	2.454	0.001	...

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. *CONTINUED.*

SILICON IONIZATION BALANCE															
Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV
4.00	1.309	0.022	4.532	...	...	...	...	...	...	...	...	...	...	...	...
4.05	1.474	0.015	3.559	...	...	...	...	...	...	...	...	...	...	...	...
4.10	1.648	0.011	2.695	...	...	...	...	...	...	...	...	...	...	...	...
4.15	1.818	0.012	1.923	...	...	...	...	...	...	...	...	...	...	...	...
4.20	1.992	0.030	1.245	...	...	...	...	...	...	...	...	...	...	...	...
4.25	2.208	0.102	0.692	6.439	...	...	...	...	...	...	...	...	...	...	...
4.30	2.525	0.284	0.321	4.899	...	...	...	...	...	...	...	...	...	...	...
4.35	2.940	0.571	0.136	3.720	...	...	...	...	...	...	...	...	...	...	...
4.40	3.350	0.859	0.066	2.788	...	...	...	...	...	...	...	...	...	...	...
4.45	3.666	1.059	0.044	2.034	...	...	...	...	...	...	...	...	...	...	...
4.50	3.887	1.175	0.046	1.466	6.992	...	...	...	...	...	...	...	...	...	...
4.55	4.084	1.259	0.063	1.100	5.465	...	...	...	...	...	...	...	...	...	...
4.60	4.273	1.341	0.085	0.881	4.186	...	...	...	...	...	...	...	...	...	...
4.65	4.468	1.435	0.110	0.730	3.139	...	...	...	...	...	...	...	...	...	...
4.70	4.680	1.548	0.144	0.606	2.249	...	...	...	...	...	...	...	...	...	...
4.75	4.920	1.690	0.197	0.505	1.501	...	...	...	...	...	...	...	...	...	...
4.80	5.206	1.882	0.296	0.453	0.890	...	...	...	...	...	...	...	...	...	...
4.85	5.595	2.178	0.488	0.505	0.449	...	...	...	...	...	...	...	...	...	...
4.90	6.121	2.614	0.820	0.689	0.193	...	...	...	...	...	...	...	...	...	...
4.95	6.774	3.177	1.280	0.965	0.077	6.510	...	...	...	...	...	...	...	...	...
5.00	...	3.822	1.818	1.290	0.030	5.379	...	...	...	...	...	...	...	...	...
5.05	...	4.427	2.318	1.573	0.014	4.391	...	...	...	...	...	...	...	...	...
5.10	...	4.998	2.785	1.832	0.007	3.516	...	...	...	...	...	...	...	...	...
5.15	...	5.522	3.209	2.060	0.005	2.743	...	...	...	...	...	...	...	...	...
5.20	...	5.999	3.587	2.253	0.006	2.065	6.530	...	...	...	...	...	...	...	...
5.25	...	6.427	3.918	2.411	0.016	1.484	5.272	...	...	...	...	...	...	...	...
5.30	...	6.828	4.225	2.555	0.046	1.008	4.185	...	...	...	...	...	...	...	...
5.35	...	...	4.526	2.702	0.113	0.645	3.271	...	...	...	...	...	...	...	...
5.40	...	...	4.845	2.875	0.228	0.393	2.522	5.989	...	...	...	...	...	...	...
5.45	...	...	5.188	3.080	0.389	0.238	1.917	4.825	...	...	...	...	...	...	...
5.50	...	...	5.551	3.312	0.582	0.155	1.426	3.827	...	...	...	...	...	...	...
5.55	...	...	5.931	3.567	0.800	0.127	1.029	2.969	6.122	...	...	...	...	...	...
5.60	...	...	6.334	3.849	1.043	0.148	0.715	2.235	4.872	...	...	...	...	...	...
5.65	...	...	6.769	4.168	1.320	0.222	0.484	1.622	3.791	6.866	...	...	...	...	...
5.70	...	...	...	4.534	1.640	0.354	0.338	1.129	2.872	5.458	...	...	...	...	...
5.75	...	...	...	4.955	2.011	0.549	0.281	0.755	2.111	4.253	...	...	...	...	...
5.80	...	...	...	5.435	2.436	0.811	0.310	0.495	1.501	3.240	5.823	...	...	...	...
5.85	...	...	...	5.973	2.917	1.137	0.423	0.345	1.033	2.404	4.572	...	...	...	...
5.90	...	...	...	6.568	3.450	1.523	0.614	0.296	0.694	1.732	3.520	5.773	...	...	...
5.95	...	...	...	...	4.036	1.971	0.877	0.340	0.475	1.208	2.649	4.618	6.197	...	...
6.00	...	...	...	...	4.669	2.471	1.206	0.469	0.364	0.820	1.943	3.675	4.873	...	...
6.05	...	...	...	...	5.349	3.024	1.600	0.678	0.354	0.555	1.386	2.914	3.767	...	...
6.10	...	...	...	...	6.071	3.625	2.051	0.957	0.433	0.402	0.964	2.312	2.851	...	...
6.15	...	...	...	...	6.832	4.269	2.554	1.301	0.592	0.347	0.660	1.846	2.101	...	...
6.20	...	...	...	...	...	4.952	3.103	1.702	0.821	0.377	0.462	1.498	1.494	...	...
6.25	...	...	...	...	...	5.671	3.694	2.155	1.114	0.487	0.359	1.255	1.014	...	...
6.30	...	...	...	...	...	6.427	4.329	2.659	1.470	0.672	0.345	1.111	0.654	6.145	...
6.35	...	...	...	...	...	...	5.006	3.212	1.883	0.927	0.414	1.054	0.404	5.161	...
6.40	...	...	...	...	...	...	5.713	3.801	2.341	1.235	0.549	1.069	0.245	4.342	...
6.45	...	...	...	...	...	...	6.425	4.401	2.816	1.570	0.723	1.127	0.150	3.656	...
6.50	...	...	...	...	...	...	...	4.990	3.287	1.909	0.908	1.202	0.097	3.072	...
6.55	...	...	...	...	...	...	...	5.552	3.737	2.233	1.090	1.276	0.067	2.571	6.146
6.60	...	...	...	...	...	...	...	6.082	4.159	2.536	1.257	1.340	0.051	2.137	5.242
6.65	...	...	...	...	...	...	...	6.579	4.552	2.817	1.409	1.391	0.045	1.763	4.442
6.70	...	...	...	...	...	...	...	...	4.923	3.079	1.550	1.434	0.047	1.442	3.735
6.75	...	...	...	...	...	...	...	...	5.278	3.331	1.686	1.474	0.057	1.169	3.112
6.80	...	...	...	...	...	...	...	...	5.625	3.578	1.823	1.518	0.077	0.940	2.565
6.85	...	...	...	...	...	...	...	...	5.970	3.828	1.968	1.572	0.110	0.751	2.087
6.90	...	...	...	...	...	...	...	...	6.320	4.087	2.126	1.641	0.157	0.601	1.672
6.95	...	...	...	...	...	...	...	...	6.681	4.358	2.302	1.729	0.221	0.486	1.315
7.00	...	...	...	...	...	...	...	...	...	4.648	2.499	1.840	0.305	0.408	1.017
7.05	...	...	...	...	...	...	...	...	...	4.960	2.724	1.980	0.414	0.364	0.771
7.10	...	...	...	...	...	...	...	...	...	5.295	2.974	2.148	0.547	0.355	0.574
7.15	...	...	...	...	...	...	...	...	...	5.651	3.249	2.341	0.702	0.378	0.424
7.20	...	...	...	...	...	...	...	...	...	6.024	3.544	2.556	0.876	0.425	0.312
7.25	...	...	...	...	...	...	...	...	...	6.409	3.854	2.786	1.061	0.492	0.230
7.30	...	...	...	...	...	...	...	...	...	6.799	4.172	3.026	1.254	0.571	0.171
7.35	...	...	...	...	...	...	...	...	...	...	4.494	3.271	1.430	0.657	0.129
7.40	...	...	...	...	...	...	...	...	...	...	4.816	3.517	1.645	0.746	0.098
7.45	...	...	...	...	...	...	...	...	...	...	5.136	3.763	1.837	0.837	0.076
7.50	...	...	...	...	...	...	...	...	...	...	5.452	4.005	2.024	0.926	0.059
7.55	...	...	...	...	...	...	...	...	...	...	5.763	4.243	2.207	1.014	0.047
7.60	...	...	...	...	...	...	...	...	...	...	6.069	4.477	2.384	1.099	0.038
7.65	...	...	...	...	...	...	...	...	...	...	6.369	4.707	2.556	1.181	0.031
7.70	...	...	...	...	...	...	...	...	...	...	6.664	4.931	2.722	1.261	0.025
7.75	...	...	...	...	...	...	...	...	...	...	6.953	5.151	2.884	1.338	0.021
7.80	...	...	...	...	...	...	...	...	...	...	...	5.366	3.040	1.413	0.018
7.85	...	...	...	...	...	...	...	...	...	...	...	5.577	3.192	1.485	0.015
7.90	...	...	...	...	...	...	...	...	...	...	...	5.783	3.339	1.555	0.013
7.95	...	...	...	...	...	...	...	...	...	...	...	5.985	3.482	1.623	0.011
8.00	...	...	...	...	...	...	...	...	...	...	...	6.182	3.621	1.688	0.009
8.05	...	...	...	...	...	...	...	...	...	...	...	6.376	3.757	1.752	0.008
8.10	...	...	...	...	...	...	...	...	...	...	...	6.566	3.889	1.814	0.007
8.15	...	...	...	...	...	...	...	...	...	...	...	6.752	4.018	1.875	0.006
8.20	...	...	...	...	...	...	...	...	...	...	...	6.934	4.143	1.935	0.005
8.25	...	...	...	...	...	...	...	...	...	...	...	...	4.266	1.992	0.005
8.30	...	...	...	...	...	...	...	...	...	...	...	...	4.385	2.049	0.004
8.35	...	...	...	...	...	...	...	...	...	...	...	...	4.502	2.105	0.003
8.40	...	...	...	...	...	...	...	...	...	...	...	...	4.616	2.159	0.003
8.45	...	...	...	...	...	...	...	...	...	...	...	...	4.727	2.211	0.003
8.50	...	...	...	...	...	...	...	...	...	...	...	...	4.835	2.263	0.002

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. *CONTINUED.*

SULFUR IONIZATION BALANCE																		
Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	
4.00	2.949	0.000	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.05	3.291	0.000	6.415	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.10	3.365	0.000	5.105	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.15	3.328	0.000	4.009	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.20	3.220	0.001	3.051	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.25	3.071	0.003	2.214	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.30	2.919	0.014	1.509	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.35	2.809	0.051	0.964	6.406	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.40	2.776	0.130	0.590	5.007	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.45	2.823	0.250	0.360	3.884	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.50	2.666	0.395	0.226	2.971	...	...	...	...	...	...	...	...	...	...	...	...	...	
4.55	2.919	0.551	0.147	2.270	6.915	...	...	...	...	...	...	...	...	...	...	...	...	
4.60	3.179	0.714	0.102	1.782	5.777	...	...	...	...	...	...	...	...	...	...	...	...	
4.65	3.442	0.882	0.081	1.424	4.853	...	...	...	...	...	...	...	...	...	...	...	...	
4.70	3.714	1.054	0.077	1.127	4.049	...	...	...	...	...	...	...	...	...	...	...	...	
4.75	3.994	1.234	0.094	0.869	3.333	...	...	...	...	...	...	...	...	...	...	...	...	
4.80	4.286	1.427	0.132	0.651	2.697	...	...	...	...	...	...	...	...	...	...	...	...	
4.85	4.596	1.638	0.197	0.475	2.140	5.899	...	...	...	...	...	...	...	...	...	...	...	
4.90	4.928	1.870	0.292	0.343	1.658	4.853	...	...	...	...	...	...	...	...	...	...	...	
4.95	5.286	2.128	0.418	0.256	1.250	3.933	6.386	...	...	...	...	...	...	...	...	...	...	
5.00	5.669	2.412	0.578	0.215	0.913	3.130	4.980	...	...	...	...	...	...	...	...	...	...	
5.05	6.084	2.729	0.773	0.222	0.647	2.440	3.746	...	...	...	...	...	...	...	...	...	...	
5.10	6.529	3.075	1.005	0.277	0.450	1.857	2.671	...	...	...	...	...	...	...	...	...	...	
5.15	...	3.456	1.275	0.384	0.324	1.378	1.747	...	...	...	...	...	...	...	...	...	...	
5.20	...	3.907	1.619	0.570	0.293	1.023	0.990	...	...	...	...	...	...	...	...	...	...	
5.25	...	4.488	2.097	0.901	0.423	0.855	0.457	6.216	...	...	...	...	...	...	...	...	...	
5.30	...	5.242	2.751	1.415	0.751	0.909	0.181	5.098	...	...	...	...	...	...	...	...	...	
5.35	...	6.087	3.499	2.031	1.193	1.097	0.072	4.240	...	...	...	...	...	...	...	...	...	
5.40	...	6.930	4.248	2.655	1.650	1.321	0.033	3.529	...	...	...	...	...	...	...	...	...	
5.45	...	...	4.949	3.237	2.077	1.533	0.018	2.912	...	...	...	...	...	...	...	...	...	
5.50	...	...	5.598	3.771	2.466	1.717	0.012	2.363	6.029	...	...	...	...	...	...	...	...	
5.55	...	...	6.190	4.253	2.810	1.872	0.013	1.872	4.953	...	...	...	...	...	...	...	...	
5.60	...	...	6.737	4.695	3.121	2.006	0.021	1.434	3.986	...	...	...	...	...	...	...	...	
5.65	...	...	...	5.111	3.413	2.132	0.045	1.052	3.123	6.159	...	...	...	...	...	...	...	
5.70	...	...	...	5.522	3.706	2.268	0.094	0.752	2.365	4.892	...	...	...	...	...	...	...	
5.75	...	...	...	5.953	4.024	2.436	0.186	0.487	1.721	3.785	6.881	...	...	...	...	...	...	
5.80	...	...	...	6.425	4.387	2.657	0.335	0.327	1.198	2.841	5.461	...	...	...	...	...	...	
5.85	...	...	...	6.950	4.807	2.942	0.550	0.260	0.798	2.058	4.246	...	...	...	...	...	...	
5.90	...	...	...	...	5.293	3.298	0.836	0.288	0.522	1.432	3.228	5.668	...	...	...	...	...	
5.95	...	...	...	...	5.847	3.726	1.194	0.409	0.365	0.957	2.396	4.429	...	...	...	...	...	
6.00	...	...	...	...	6.467	4.226	1.622	0.619	0.321	0.621	1.735	3.399	5.645	...	...	...	...	
6.05	...	...	...	...	...	4.788	2.111	0.909	0.377	0.412	1.229	2.555	4.419	6.390	...	...	...	
6.10	...	...	...	...	...	5.406	2.656	1.266	0.519	0.311	0.856	1.874	3.389	4.970	6.670	...	...	
6.15	...	...	...	...	...	6.068	3.242	1.680	0.736	0.305	0.601	1.335	2.532	3.757	5.091	...	...	
6.20	...	...	...	...	...	6.772	3.871	2.148	1.021	0.387	0.453	0.927	1.833	2.732	3.735	...	...	
6.25	...	...	...	...	...	...	4.550	2.676	1.380	0.557	0.413	0.647	1.288	1.888	2.589	...	...	
6.30	...	...	...	...	...	...	5.301	3.286	1.831	0.833	0.493	0.507	0.904	1.231	1.658	...	...	
6.35	...	...	...	...	...	...	6.162	4.014	2.412	1.252	0.729	0.538	0.713	0.789	0.967	...	...	
6.40	...	...	...	...	...	...	...	4.891	3.151	1.839	1.147	0.765	0.736	0.579	0.530	6.591	...	
6.45	...	...	...	...	...	...	...	5.873	4.001	2.549	1.697	1.138	0.921	0.551	0.298	5.592	...	
6.50	...	...	...	...	...	...	...	6.883	4.888	3.302	2.302	1.577	1.188	0.619	0.179	4.783	...	
6.55	...	...	...	...	...	...	...	...	5.755	4.044	2.903	2.023	1.476	0.723	0.116	4.100	...	
6.60	...	...	...	...	...	...	...	...	6.581	4.751	3.477	2.451	1.756	0.833	0.080	3.510	...	
6.65	...	...	...	...	...	...	...	...	...	5.413	4.013	2.849	2.018	0.936	0.059	2.993	6.963	
6.70	...	...	...	...	...	...	...	...	...	6.028	4.509	3.215	2.256	1.025	0.047	2.538	6.022	
6.75	...	...	...	...	...	...	...	...	...	6.599	4.966	3.548	2.470	1.100	0.041	2.140	5.183	
6.80	...	...	...	...	...	...	...	...	...	...	5.388	3.853	2.662	1.162	0.040	1.792	4.437	
6.85	...	...	...	...	...	...	...	...	...	...	5.783	4.137	2.838	1.216	0.043	1.489	3.773	
6.90	...	...	...	...	...	...	...	...	...	...	6.157	4.404	3.004	1.266	0.053	1.229	3.184	
6.95	...	...	...	...	...	...	...	...	...	...	6.517	4.662	3.165	1.319	0.070	1.006	2.663	
7.00	...	...	...	...	...	...	...	...	...	...	6.870	4.918	3.327	1.379	0.097	0.818	2.203	
7.05	...	...	...	...	...	...	...	...	...	...	...	5.177	3.496	1.451	0.136	0.663	1.799	
7.10	...	...	...	...	...	...	...	...	...	...	...	5.441	3.674	1.537	0.188	0.542	1.451	
7.15	...	...	...	...	...	...	...	...	...	...	...	5.719	3.869	1.644	0.260	0.448	1.150	
7.20	...	...	...	...	...	...	...	...	...	...	...	6.013	4.081	1.773	0.350	0.388	0.896	
7.25	...	...	...	...	...	...	...	...	...	...	...	6.323	4.313	1.926	0.462	0.358	0.689	
7.30	...	...	...	...	...	...	...	...	...	...	...	6.650	4.565	2.102	0.594	0.358	0.525	
7.35	...	...	...	...	...	...	...	...	...	...	...	6.992	4.833	2.298	0.744	0.383	0.398	
7.40	...	...	...	...	...	...	...	...	...	...	...	...	5.115	2.510	0.908	0.427	0.302	
7.45	...	...	...	...	...	...	...	...	...	...	...	...	5.404	2.734	1.081	0.487	0.230	
7.50	...	...	...	...	...	...	...	...	...	...	...	...	5.698	2.964	1.258	0.556	0.177	
7.55	...	...	...	...	...	...	...	...	...	...	...	...	5.992	3.197	1.438	0.632	0.137	
7.60	...	...	...	...	...	...	...	...	...	...	...	...	6.285	3.431	1.617	0.710	0.108	
7.65	...	...	...	...	...	...	...	...	...	...	...	...	6.573	3.663	1.793	0.790	0.085	
7.70	...	...	...	...	...	...	...	...	...	...	...	...	6.857	3.893	1.966	0.870	0.069	
7.75	...	...	...	...	...	...	...	...	...	...	...	...	...	4.118	2.134	0.948	0.056	
7.80	...	...	...	...	...	...	...	...	...	...	...	...	...	4.340	2.298	1.025	0.045	
7.85	...	...	...	...	...	...	...	...	...	...	...	...	...	4.556	2.458	1.100	0.038	
7.90	...	...	...	...	...	...	...	...	...	...	...	...	...	4.769	2.612	1.173	0.031	
7.95	...	...	...	...	...	...	...	...	...	...	...	...	...	4.977	2.763	1.243	0.026	
8.00	...	...	...	...	...	...	...	...	...	...	...	...	...	5.180	2.908	1.312	0.022	
8.05	...	...	...	...	...	...	...	...	...	...	...	...	...	5.379	3.050	1.379	0.019	
8.10	...	...	...	...	...	...	...	...	...	...	...	...	...	5.573	3.188	1.445	0.016	
8.15	...	...	...	...	...	...	...	...	...	...	...	...	...	5.763	3.322	1.508	0.014	
8																		

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. *CONTINUED.*

CHLORINE IONIZATION BALANCE

Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII
4.00	0.000	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.05	0.000	5.817	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.10	0.000	4.564	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.15	0.000	3.445	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.20	0.001	2.453	5.893	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.25	0.011	1.594	4.205	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.30	0.058	0.906	2.846	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.35	0.198	0.452	1.873	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.40	0.446	0.232	1.252	5.597	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.45	0.752	0.164	0.859	4.478	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.50	1.077	0.179	0.595	3.623	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.55	1.409	0.243	0.411	2.942	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.60	1.745	0.340	0.283	2.380	6.768	...	...	...	...	...	...	...	...	...	...	...	...	...
4.65	2.084	0.462	0.198	1.907	5.717	...	...	...	...	...	...	...	...	...	...	...	...	...
4.70	2.423	0.604	0.145	1.505	4.793	...	...	...	...	...	...	...	...	...	...	...	...	...
4.75	2.765	0.761	0.122	1.162	3.976	...	...	...	...	...	...	...	...	...	...	...	...	...
4.80	3.110	0.936	0.126	0.873	3.257	...	...	...	...	...	...	...	...	...	...	...	...	...
4.85	3.465	1.131	0.159	0.637	2.628	6.047	...	...	...	...	...	...	...	...	...	...	...	...
4.90	3.833	1.349	0.225	0.455	2.085	5.010	...	...	...	...	...	...	...	...	...	...	...	...
4.95	4.218	1.593	0.323	0.323	1.623	4.099	...	...	...	...	...	...	...	...	...	...	...	...
5.00	4.613	1.859	0.454	0.239	1.237	3.302	...	...	...	...	...	...	...	...	...	...	...	...
5.05	5.039	2.156	0.615	0.202	0.921	2.609	5.807	...	...	...	...	...	...	...	...	...	...	...
5.10	5.480	2.476	0.808	0.209	0.670	2.015	4.715	6.901	...	...	...	...	...	...	...	...	...	...
5.15	5.942	2.824	1.034	0.262	0.485	1.513	3.761	5.388	...	...	...	...	...	...	...	...	...	...
5.20	6.428	3.201	1.292	0.361	0.364	1.102	2.937	4.059	...	...	...	...	...	...	...	...	...	...
5.25	6.952	3.620	1.597	0.510	0.308	0.779	2.236	2.901	...	...	...	...	...	...	...	...	...	...
5.30	...	4.080	1.946	0.715	0.322	0.546	1.659	1.904	...	...	...	...	...	...	...	...	...	...
5.35	...	4.606	2.364	0.996	0.427	0.423	1.219	1.082	6.952	...	...	...	...	...	...	...	...	...
5.40	...	5.272	2.926	1.428	0.693	0.478	0.983	0.492	5.531	...	...	...	...	...	...	...	...	...
5.45	...	6.136	3.688	2.067	1.174	0.764	1.001	0.186	4.481	...	...	...	...	...	...	...	...	...
5.50	...	...	4.565	2.826	1.785	1.192	1.182	0.070	3.697	...	...	...	...	...	...	...	...	...
5.55	...	...	5.448	3.596	2.416	1.650	1.410	0.030	3.055	...	...	...	...	...	...	...	...	...
5.60	...	...	6.283	4.323	3.012	2.085	1.633	0.016	2.497	6.154	...	...	...	...	...	...	...	...
5.65	...	...	...	4.999	3.562	2.485	1.833	0.012	2.001	5.082	...	...	...	...	...	...	...	...
5.70	...	...	...	5.627	4.071	2.852	2.013	0.017	1.558	4.118	...	...	...	...	...	...	...	...
5.75	...	...	...	6.216	4.546	3.192	2.179	0.034	1.168	3.254	6.187	...	...	...	...	...	...	...
5.80	...	...	...	6.783	5.004	3.522	2.344	0.073	0.835	2.490	4.930	...	...	...	...	...	...	...
5.85	...	...	...	...	5.467	3.864	2.530	0.147	0.571	1.833	3.824	6.737	...	...	...	...	...	...
5.90	...	...	...	...	5.956	4.237	2.755	0.271	0.387	1.291	2.874	5.330	...	...	...	...	...	...
5.95	...	...	...	...	6.490	4.660	3.036	0.459	0.293	0.871	2.083	4.124	6.874	...	...	...	...	...
6.00	...	...	...	...	...	5.142	3.383	0.720	0.295	0.575	1.449	3.114	5.440	...	...	...	...	...
6.05	...	...	...	...	...	5.691	3.801	1.055	0.395	0.402	0.968	2.292	4.232	6.651	...	...	...	...
6.10	...	...	...	...	...	6.305	4.290	1.464	0.588	0.346	0.632	1.644	3.234	5.261	...	...	...	...
6.15	...	...	...	...	...	6.980	4.843	1.939	0.866	0.396	0.425	1.153	2.423	4.095	5.809	...	...	...
6.20	...	...	...	...	...	...	5.451	2.471	1.213	0.535	0.330	0.798	1.776	3.125	4.475	5.995	...	...
6.25	...	...	...	...	...	...	6.104	3.049	1.622	0.751	0.333	0.562	1.271	2.326	3.343	4.527	...	...
6.30	...	...	...	...	...	...	6.802	3.674	2.089	1.039	0.423	0.895	1.681	2.394	3.271	...	...	...
6.35	...	...	...	...	...	...	...	4.350	2.618	1.403	0.603	0.411	0.647	1.187	1.620	2.219	...	...
6.40	...	...	...	...	...	...	...	5.107	3.237	1.868	0.899	0.518	0.545	0.860	1.037	1.382	...	...
6.45	...	...	...	...	...	...	...	5.991	3.992	2.478	1.352	0.796	0.627	0.736	0.676	0.790	...	...
6.50	...	...	...	...	...	...	...	...	4.888	3.239	1.967	1.247	0.897	0.814	0.536	0.443	5.924	...
6.55	...	...	...	...	...	...	...	...	5.864	4.087	2.677	1.804	1.285	1.026	0.544	0.259	5.043	...
6.60	...	...	...	...	...	...	...	...	6.845	4.947	3.407	2.390	1.712	1.289	0.620	0.164	4.322	...
6.65	...	...	...	...	...	...	...	...	...	5.780	4.117	2.964	2.138	1.562	0.718	0.112	3.708	...
6.70	...	...	...	...	...	...	...	...	...	6.570	4.790	3.509	2.543	1.824	0.818	0.081	3.174	...
6.75	...	...	...	...	...	...	...	...	...	...	5.422	4.019	2.920	2.067	0.909	0.063	2.707	6.324
6.80	...	...	...	...	...	...	...	...	...	...	6.010	4.492	3.267	2.288	0.988	0.052	2.297	5.472
6.85	...	...	...	...	...	...	...	...	...	...	6.560	4.931	3.587	2.488	1.055	0.047	1.939	4.713
6.90	...	...	...	...	...	...	...	...	...	...	...	5.342	3.884	2.671	1.113	0.047	1.626	4.036
6.95	...	...	...	...	...	...	...	...	...	...	...	5.729	4.164	2.842	1.167	0.053	1.354	3.434
7.00	...	...	...	...	...	...	...	...	...	...	...	6.101	4.432	3.007	1.221	0.065	1.119	2.900
7.05	...	...	...	...	...	...	...	...	...	...	...	6.462	4.694	3.171	1.279	0.085	0.918	2.425
7.10	...	...	...	...	...	...	...	...	...	...	...	6.819	4.956	3.337	1.347	0.115	0.749	2.006
7.15	...	...	...	...	...	...	...	...	...	...	...	...	5.221	3.512	1.427	0.138	0.611	1.639
7.20	...	...	...	...	...	...	...	...	...	...	...	...	5.495	3.698	1.523	0.216	0.503	1.324
7.25	...	...	...	...	...	...	...	...	...	...	...	...	5.781	3.900	1.640	0.292	0.424	1.050
7.30	...	...	...	...	...	...	...	...	...	...	...	...	6.082	4.120	1.778	0.387	0.374	0.822
7.35	...	...	...	...	...	...	...	...	...	...	...	...	6.398	4.357	1.937	0.501	0.354	0.637
7.40	...	...	...	...	...	...	...	...	...	...	...	...	6.729	4.612	2.118	0.634	0.360	0.490
7.45	...	...	...	...	...	...	...	...	...	...	...	...	...	4.881	2.315	0.783	0.387	0.377
7.50	...	...	...	...	...	...	...	...	...	...	...	...	...	5.161	2.526	0.943	0.432	0.290
7.55	...	...	...	...	...	...	...	...	...	...	...	...	...	5.447	2.746	1.110	0.490	0.224
7.60	...	...	...	...	...	...	...	...	...	...	...	...	...	5.736	2.972	1.282	0.556	0.175
7.65	...	...	...	...	...	...	...	...	...	...	...	...	...	6.024	3.199	1.454	0.627	0.138
7.70	...	...	...	...	...	...	...	...	...	...	...	...	...	6.310	3.426	1.625	0.701	0.110
7.75	...	...	...	...	...	...	...	...	...	...	...	...	...	6.592	3.652	1.794	0.776	0.088
7.80	...	...	...	...	...	...	...	...	...	...	...	...	...	6.869	3.874	1.960	0.851	0.072
7.85	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.093	2.121	0.926	0.059
7.90	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.308	2.279	0.998	0.048
7.95	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.518	2.432	1.070	0.040
8.00	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.724	2.580	1.139	0.034
8.05	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.926	2.725	1.207	0.029
8.10	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.123	2.866	1.273	0.024
8.15	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.316	3.003	1.338	0.021
8.20	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.504	3.136	1.401	0.018
8.25	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.689	3.265	1.462	0.015
8.30	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.869	3.391	1.523	0.013
8.35	...	...	...	...	...	...	...	...	...	...	...	...	...	...	6.046	3.514	1.582	0.012
8.40	...	...	...	...	...	...	...	...	...	...	...	...	...	...	6.218	3.634	1.639	0.010
8.45	...	...	...	...	...	...	...	...	...	...	...	...	...	...	6.387	3.751	1.696	0.009
8.50</																		

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. CONTINUED.

ARGON IONIZATION BALANCE

Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX
4.00	0.000	3.346	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.05	0.002	2.419	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.10	0.011	1.594	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.15	0.060	0.891	6.968	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.20	0.231	0.385	5.290	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.25	0.587	0.130	3.997	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.30	1.050	0.041	2.990	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.35	1.526	0.016	2.145	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.40	1.984	0.022	1.407	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.45	2.451	0.081	0.780	5.326	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.50	3.009	0.275	0.330	3.822	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.55	3.683	0.635	0.115	2.780	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.60	4.295	0.991	0.051	2.108	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.65	4.736	1.240	0.037	1.636	6.443	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.70	5.050	1.422	0.042	1.266	5.259	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.75	5.297	1.584	0.063	0.961	4.290	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.80	5.502	1.748	0.104	0.709	3.485	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.85	5.741	1.927	0.170	0.507	2.813	6.613	...	...	...	...	...	...	...	...	...	...	...	...	...
4.90	5.988	2.127	0.264	0.355	2.250	5.537	...	...	...	...	...	...	...	...	...	...	...	...	...
4.95	6.255	2.350	0.384	0.248	1.777	4.598	...	...	...	...	...	...	...	...	...	...	...	...	...
5.00	6.546	2.595	0.529	0.182	1.364	3.759	...	...	...	...	...	...	...	...	...	...	...	...	...
5.05	6.855	2.855	0.696	0.152	1.038	3.045	6.085	...	...	...	...	...	...	...	...	...	...	...	...
5.10	...	3.140	0.885	0.158	0.770	2.423	5.009	...	...	...	...	...	...	...	...	...	...	...	...
5.15	...	3.446	1.098	0.200	0.561	1.888	4.059	...	...	...	...	...	...	...	...	...	...	...	...
5.20	...	3.771	1.333	0.280	0.408	1.436	3.229	6.226	...	...	...	...	...	...	...	...	...	...	...
5.25	...	4.135	1.609	0.399	0.312	1.065	2.512	5.038	6.817	...	...	...	...	...	...	...	...	...	...
5.30	...	4.528	1.916	0.561	0.274	0.774	1.902	4.000	5.271	...	...	...	...	...	...	...	...	...	...
5.35	...	4.955	2.259	0.768	0.295	0.560	1.397	3.102	3.912	...	...	...	...	...	...	...	...	...	...
5.40	...	5.422	2.642	1.022	0.377	0.426	0.994	2.340	2.727	...	...	...	...	...	...	...	...	...	...
5.45	...	5.944	3.082	1.329	0.530	0.377	0.699	1.713	1.713	...	...	...	...	...	...	...	...	...	...
5.50	...	6.559	3.616	1.755	0.792	0.453	0.945	1.253	0.896	5.917	...	...	...	...	...	...	...	...	...
5.55	...	...	4.339	2.365	1.257	0.742	0.626	1.050	0.363	4.656	...	...	...	...	...	...	...	...	...
5.60	...	...	5.282	3.200	1.954	1.273	0.956	1.113	0.127	3.764	...	...	...	...	...	...	...	...	...
5.65	...	...	6.301	4.114	2.738	1.900	1.398	1.306	0.048	3.092	...	...	...	...	...	...	...	...	...
5.70	...	...	...	5.010	3.509	2.524	1.846	1.521	0.023	2.530	6.086	...	...	...	...	...	...	...	...
5.75	...	...	...	5.859	4.238	3.112	2.269	1.721	0.015	2.036	5.033	...	...	...	...	...	...	...	...
5.80	...	...	...	6.658	4.923	3.662	2.662	1.904	0.018	1.597	4.086	...	...	...	...	...	...	...	...
5.85	...	...	...	...	5.568	4.179	3.031	2.072	0.032	1.209	3.237	6.011	...	...	...	...	...	...	...
5.90	...	...	...	...	6.192	4.679	3.388	2.240	0.067	0.877	2.486	4.786	...	...	...	...	...	...	...
5.95	...	...	...	...	6.812	5.180	3.752	2.424	0.133	0.610	1.837	3.707	6.398	...	...	...	...	...	...
6.00	...	...	...	...	...	5.702	4.143	2.644	0.248	0.420	1.300	2.779	5.037	...	...	...	...	...	...
6.05	...	...	...	...	...	6.265	4.579	2.918	0.424	0.318	0.882	2.006	3.871	6.318	...	...	...	...	...
6.10	...	...	...	...	...	6.880	5.073	3.257	0.671	0.313	0.589	1.389	2.899	4.950	...	...	...	...	...
6.15	...	...	...	...	...	...	5.632	3.669	0.996	0.407	0.420	0.926	2.112	3.804	5.994	...	...	...	...
6.20	...	...	...	...	...	...	6.256	4.153	1.397	0.597	0.369	0.608	1.499	2.864	4.695	6.513	...	...	...
6.25	...	...	...	...	...	...	6.940	4.704	1.867	0.874	0.427	0.421	1.042	2.110	3.613	5.061	6.723	...	...
6.30	...	...	...	...	...	...	...	5.312	2.396	1.225	0.577	0.347	0.722	1.518	2.722	3.832	5.153	...	...
6.35	...	...	...	...	...	...	...	5.972	2.978	1.643	0.808	0.374	0.522	1.069	1.999	2.799	3.811	...	...
6.40	...	...	...	...	...	...	...	6.681	3.613	2.124	1.117	0.493	0.434	0.753	1.432	1.947	2.678	...	...
6.45	...	...	...	...	...	...	...	...	4.315	2.684	1.517	0.717	0.464	0.574	1.021	1.275	1.750	...	...
6.50	...	...	...	...	...	...	...	...	5.122	3.357	2.041	1.079	0.646	0.560	0.794	0.808	1.049	...	...
6.55	...	...	...	...	...	...	...	...	6.067	4.177	2.721	1.607	1.007	0.740	0.775	0.567	0.595	6.197	...
6.60	...	...	...	...	...	...	...	...	...	5.109	3.522	2.266	1.509	1.074	0.924	0.509	0.346	5.248	...
6.65	...	...	...	...	...	...	...	...	...	6.078	4.366	2.976	2.072	1.481	1.159	0.552	0.216	4.490	...
6.70	...	...	...	...	...	...	...	...	...	...	5.199	3.683	2.641	1.902	1.419	0.635	0.146	3.855	...
6.75	...	...	...	...	...	...	...	...	...	...	5.997	4.361	3.189	2.311	1.677	0.728	0.105	3.308	...
6.80	...	...	...	...	...	...	...	...	...	...	6.751	5.001	3.705	2.696	1.920	0.816	0.080	2.832	6.548
6.85	...	...	...	...	...	...	...	...	...	...	...	5.600	4.188	3.054	2.144	0.896	0.065	2.415	5.689
6.90	...	...	...	...	...	...	...	...	...	...	...	6.161	4.637	3.385	2.349	0.965	0.057	2.050	4.923
6.95	...	...	...	...	...	...	...	...	...	...	...	6.688	5.058	3.693	2.537	1.025	0.054	1.731	4.241
7.00	...	...	...	...	...	...	...	...	...	...	...	...	5.455	3.983	2.713	1.081	0.056	1.452	3.632
7.05	...	...	...	...	...	...	...	...	...	...	...	...	5.834	4.259	2.881	1.136	0.064	1.210	3.090
7.10	...	...	...	...	...	...	...	...	...	...	...	...	6.201	4.527	3.046	1.194	0.080	1.001	2.608
7.15	...	...	...	...	...	...	...	...	...	...	...	...	6.562	4.793	3.213	1.259	0.104	0.823	2.180
7.20	...	...	...	...	...	...	...	...	...	...	...	...	6.921	5.059	3.386	1.334	0.139	0.673	1.802
7.25	...	...	...	...	...	...	...	...	...	...	...	...	...	5.332	3.568	1.424	0.188	0.554	1.475
7.30	...	...	...	...	...	...	...	...	...	...	...	...	...	5.614	3.763	1.532	0.252	0.461	1.187
7.35	...	...	...	...	...	...	...	...	...	...	...	...	...	5.907	3.974	1.658	0.334	0.396	0.945
7.40	...	...	...	...	...	...	...	...	...	...	...	...	...	6.215	4.201	1.805	0.435	0.360	0.744
7.45	...	...	...	...	...	...	...	...	...	...	...	...	...	6.535	4.446	1.972	0.553	0.350	0.581
7.50	...	...	...	...	...	...	...	...	...	...	...	...	...	6.868	4.704	2.157	0.688	0.362	0.452
7.55	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.975	2.357	0.836	0.393	0.351
7.60	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.254	2.567	0.993	0.439	0.274
7.65	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.536	2.784	1.155	0.496	0.215
7.70	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.821	3.005	1.320	0.559	0.170
7.75	...	...	...	...	...	...	...	...	...	...	...	...	...	...	6.103	3.226	1.486	0.627	0.136
7.80	...	...	...	...	...	...	...	...	...	...	...	...	...	...	6.384	3.447	1.650	0.697	0.110
7.85	...	...	...	...	...	...	...	...	...	...	...	...	...	...	6.659	3.666	1.812	0.768	0.089
7.90	...	...	...	...	...	...	...	...	...	...	...	...	...	...	6.931	3.882	1.971	0.839	0.073
7.95	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.094	2.126	0.910	0.061
8.00	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.302	2.277	0.979	0.051
8.05	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.507	2.424	1.047	0.043
8.10	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.706	2.568	1.113	0.036
8.15	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.902	2.707	1.179	0.031
8.20	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.093	2.843	1.242	0.026
8.25	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5.280	2.975	1.305	0.023

TABLE A.5: COLLISIONAL IONIZATION EQUILIBRIUM: IONIZATION BALANCE, CONTINUED.

CALCIUM IONIZATION BALANCE, CONT.												
Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
4.00	0.871	0.068	1.972	...	...	...	...	...	...	...	5.579	...
4.05	1.132	0.061	1.246	...	...	...	...	...	...	...	4.100	...
4.10	1.447	0.064	0.664	...	...	...	...	...	...	...	2.809	...
4.15	1.883	0.331	0.284	...	...	...	...	...	...	...	1.705	...
4.20	2.443	0.675	0.105	...	...	...	...	...	...	...	0.829	...
4.25	3.052	1.080	0.038	...	...	...	...	...	...	...	0.304	...
4.30	3.646	1.484	0.015	...	...	...	...	...	...	...	0.105	...
4.35	4.204	1.862	0.006	...	...	...	...	...	...	...	0.046	...
4.40	4.719	2.207	0.003	6.770	...	...	...	...	...	...	0.029	...
4.45	5.183	2.511	0.001	5.595	...	...	...	...	...	...	0.032	...
4.50	5.572	2.746	0.001	4.590	...	...	...	...	...	...	0.051	...
4.55	5.840	2.867	0.001	3.655	...	...	...	...	...	...	0.076	...
4.60	5.971	2.859	0.001	2.868	6.859	...	...	...	...	...	0.119	...
4.65	6.018	2.770	0.003	2.266	...	...	...	...	...	...	0.313	...
4.70	6.037	2.660	0.008	1.815	...	...	...	...	...	...	0.366	...
4.75	6.077	2.363	0.016	1.103	4.115	...	...	...	...	...	0.381	...
4.80	6.116	2.493	0.029	0.959	3.148	...	...	...	...	...	0.366	...
4.85	6.190	2.449	0.032	0.959	2.918	5.561	...	...	...	...	0.313	...
4.90	6.220	2.433	0.132	0.584	2.411	5.578	...	...	...	...	0.313	...
4.95	6.279	2.503	0.196	0.458	1.962	4.696	...	...	...	...	0.313	...
5.00	6.379	2.585	0.278	0.353	1.569	3.906	...	...	...	...	0.313	...
5.05	6.767	2.699	0.383	0.280	1.229	3.202	6.499	...	...	...	0.313	...
5.10	6.986	2.848	0.512	0.241	0.941	2.580	5.619	...	...	...	0.313	...
5.15	...	...	...	...	...	...	...	...	...	...	0.313	...
5.20	...	3.031	0.668	0.238	0.706	2.036	4.456	6.492	...	...	0.313	...
5.25	...	3.252	0.855	0.273	0.525	1.569	3.606	5.336	...	...	0.313	...
5.30	...	3.510	1.073	0.349	0.398	1.177	2.863	5.336	...	...	0.313	...
5.35	...	3.818	1.337	0.469	0.327	0.861	2.224	4.318	...	...	0.313	...
5.40	...	4.169	1.639	0.636	0.315	0.619	1.684	3.432	5.880	...	0.313	...
5.45	4.565	1.982	0.850	0.361	0.452	1.242	2.670	4.738	...	...	0.313	...
5.50	5.012	2.374	1.117	0.466	0.357	0.893	2.026	3.746	5.924	...	0.313	...
5.55	5.507	2.811	1.433	0.630	0.335	0.635	1.497	2.895	4.685	...	0.313	...
5.60	6.056	3.299	1.805	0.858	0.385	0.466	1.075	2.178	3.610	...	0.313	...
5.65	6.659	3.840	2.233	1.148	0.509	0.386	0.761	1.590	2.691	...	0.313	...
5.70	...	4.448	2.731	1.515	0.718	0.403	0.560	1.135	1.927	...	0.313	...
5.75	...	5.175	3.352	2.011	1.065	0.568	0.919	0.857	1.361	...	0.313	...
5.80	...	5.817	4.024	2.762	1.674	1.007	0.764	0.879	1.112	...	0.313	...
5.85	...	6.537	3.750	2.526	1.698	1.272	1.177	1.156	...	...	0.313	...
5.90	...	6.483	...	4.794	3.441	2.460	1.860	1.566	1.305	...	0.313	...
5.95	...	...	...	5.907	4.749	3.202	2.438	1.956	1.467	...	0.313	...
6.00	...	...	...	6.172	5.174	3.587	2.816	2.281	1.714	...	0.313	...
6.05	...	...	...	...	5.982	3.582	3.511	2.681	1.774	...	0.313	...
6.10	...	...	...	...	6.769	...	...	...	...	...	0.313	...
6.15	...	...	...	...	...	...	...	...	...	...	0.313	...
6.20	...	...	...	...	...	...	...	...	...	...	0.313	...
6.25	...	...	...	...	6.583	...	...	...	...	...	0.313	...
6.30	...	...	...	...	...	...	...	6.339	4.773	...	0.313	...
6.35	...	...	...	...	...	...	...	...	5.348	...	0.313	...
6.40	...	...	...	...	...	...	...	...	5.985	...	0.313	...
6.45	...	...	...	...	...	...	...	...	6.681	...	0.313	...
6.50	...	...	...	...	...	...	...	...	...	...	0.313	...
6.55	...	...	...	...	...	...	...	...	5.137	...	0.313	...
6.60	...	...	...	...	...	...	...	...	5.843	...	0.313	...
6.65	...	...	...	...	...	...	...	...	6.646	...	0.313	...
6.70	...	...	...	...	...	...	...	...	...	...	0.313	...
6.75	...	...	...	...	...	...	...	...	...	...	0.313	...
6.80	...	...	...	...	...	...	...	...	...	...	0.313	...
6.85	...	...	...	...	...	...	...	...	...	...	0.313	...
6.90	...	...	...	...	...	...	...	...	...	...	0.313	...
6.95	...	...	...	...	...	...	...	...	...	...	0.313	...
7.00	...	...	...	...	...	...	...	...	...	...	0.313	...
7.05	...	...	...	...	...	...	...	...	...	...	0.313	...
7.10	...	...	...	...	...	...	...	...	...	...	0.313	...
7.15	...	...	...	...	...	...	...	...	...	...	0.313	...
7.20	...	...	...	...	...	...	...	...	...	...	0.313	...
7.25	...	...	...	...	...	...	...	...	...	...	0.313	...
7.30	...	...	...	...	...	...	...	...	...	...	0.313	...
7.35	...	...	...	...	...	...	...	...	...	...	0.313	...
7.40	...	...	...	...	...	...	...	...	...	...	0.313	...
7.45	...	...	...	...	...	...	...	...	...	...	0.313	...
7.50	...	...	...	...	...	...	...	...	...	...	0.313	...
7.55	...	...	...	...	...	...	...	...	...	...	0.313	...
7.60	...	...	...	...	...	...	...	...	...	...	0.313	...
7.65	...	...	...	...	...	...	...	...	...	...	0.313	...
7.70	...	...	...	...	...	...	...	...	...	...	0.313	...
7.75	...	...	...	...	...	...	...	...	...	...	0.313	...
7.80	...	...	...	...	...	...	...	...	...	...	0.313	...
7.85	...	...	...	...	...	...	...	...	...	...	0.313	...
7.90	...	...	...	...	...	...	...	...	...	...	0.313	...
7.95	...	...	...	...	...	...	...	...	...	...	0.313	...
8.00	...	...	...	...	...	...	...	...	...	...	0.313	...
8.05	...	...	...	...	...	...	...	...	...	...	0.313	...
8.10	...	...	...	...	...	...	...	...	...	...	0.313	...
8.15	...	...	...	...	...	...	...	...	...	...	0.313	...
8.20	...	...	...	...	...	...	...	...	...	...	0.313	...
8.25	...	...	...	...	...	...	...	...	...	...	0.313	...
8.30	...	...	...	...	...	...	...	...	...	...	0.313	...
8.35	...	...	...	...	...	...	...	...	...	...	0.313	...
8.40	...	...	...	...	...	...	...	...	...	...	0.313	...
8.45	...	...	...	...	...	...	...	...	...	...	0.313	...
8.50	...	...	...	...	...	...	...	...	...	...	0.313	...
8.55	...	...	...	...	...	...	...	...	...	...	0.313	...
8.60	...	...	...	...	...	...	...	...	...	...	0.313	...
8.65	...	...	...	...	...	...	...	...	...	...	0.313	...
8.70	...	...	...	...	...	...	...	...	...	...	0.313	...
8.75	...	...	...	...	...	...	...	...	...	...	0.313	...
8.80	...	...	...	...	...	...	...	...	...	...	0.313	...
8.85	...	...	...	...	...	...	...	...	...	...	0.313	...
8.90	...	...	...	...	...	...	...	...	...	...	0.313	...
8.95	...	...	...	...	...	...	...	...	...	...	0.313	...
9.00	...	...	...	...	...	...	...	...	...	...	0.313	...
9.05	...	...	...	...	...	...	...	...	...	...	0.313	...
9.10	...	...	...	...	...	...	...	...	...	...	0.313	...
9.15	...	...	...	...	...	...	...	...	...	...	0.313	...
9.20	...	...	...	...	...	...	...	...	...	...	0.313	...
9.25	...	...	...	...	...	...	...	...	...	...	0.313	...
9.30	...	...	...	...	...	...	...	...	...	...	0.313	...
9.35	...	...	...	...	...	...	...	...	...	...	0.313	...
9.40	...	...	...	...	...	...	...	...	...	...	0.313	...
9.45	...	...	...	...	...	...	...	...	...	...	0.313	...
9.50	...	...	...	...	...	...	...	...	...	...	0.313	...
9.55	...	...	...	...	...	...	...	...	...	...	0.313	...
9.60	...	...	...	...	...	...	...	...	...	...	0.313	...
9.65	...	...	...	...	...	...	...	...	...	...	0.313	...
9.70	...	...	...	...	...	...	...	...	...	...	0.313	...
9.75	...	...	...	...	...	...	...	...	...	...	0.313	...
9.80	...	...	...	...	...	...	...	...	...	...	0.313	...
9.85	...	...	...	...	...	...	...	...	...	...	0.313	...
9.90	...	...	...	...	...	...	...	...	...	...	0.313	...
9.95	...	...	...	...	...	...	...	...	...	...	0.313	...
10.00	...	...	...	...	...	...	...	...	...	...	0.313	...

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. *CONTINUED.*

IRON IONIZATION BALANCE.													
Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
4.00	0.244	0.366	4.545	...	...	...	...	...	...	...	...	...	...
4.05	0.381	0.234	3.435	...	...	...	...	...	...	...	...	...	...
4.10	0.544	0.148	2.470	...	...	...	...	...	...	...	...	...	...
4.15	0.728	0.102	1.634	...	...	...	...	...	...	...	...	...	...
4.20	0.952	0.111	0.944	6.946	...	...	...	...	...	...	...	...	...
4.25	1.269	0.227	0.452	5.333	...	...	...	...	...	...	...	...	...
4.30	1.699	0.469	0.194	4.071	...	...	...	...	...	...	...	...	...
4.35	2.147	0.741	0.091	3.069	...	...	...	...	...	...	...	...	...
4.40	2.534	0.962	0.055	2.225	...	...	...	...	...	...	...	...	...
4.45	2.862	1.134	0.049	1.499	...	...	...	...	...	...	...	...	...
4.50	3.178	1.303	0.084	0.898	6.036	...	...	...	...	...	...	...	...
4.55	3.544	1.532	0.201	0.468	4.581	...	...	...	...	...	...	...	...
4.60	3.982	1.838	0.406	0.227	3.430	...	...	...	...	...	...	...	...
4.65	4.435	2.167	0.640	0.119	2.521	...	...	...	...	...	...	...	...
4.70	4.855	2.469	0.851	0.076	1.794	5.647	...	...	...	...	...	...	...
4.75	5.243	2.746	1.038	0.072	1.226	4.263	...	...	...	...	...	...	...
4.80	5.603	3.000	1.225	0.106	0.809	3.132	...	...	...	...	...	...	...
4.85	6.013	3.307	1.430	0.181	0.526	2.242	6.711	...	...	...	...	...	...
4.90	6.434	3.631	1.664	0.297	0.350	1.571	5.259	...	...	...	...	...	...
4.95	6.878	3.981	1.926	0.451	0.257	1.094	4.125	...	...	...	...	...	...
5.00	...	4.355	2.215	0.638	0.227	0.767	3.270	...	...	...	...	...	...
5.05	...	4.748	2.523	0.848	0.245	0.548	2.632	6.262	...	...	...	...	...
5.10	...	5.150	2.841	1.073	0.294	0.399	2.145	5.288	...	...	...	...	...
5.15	...	5.559	3.166	1.306	0.367	0.298	1.760	4.494	...	...	...	...	...
5.20	...	5.971	3.494	1.545	0.457	0.232	1.445	3.824	...	...	...	...	...
5.25	...	6.384	3.822	1.788	0.561	0.192	1.182	3.245	...	...	...	...	...
5.30	...	6.799	4.152	2.034	0.678	0.174	0.960	2.737	6.382	...	...	...	...
5.35	...	...	4.486	2.285	0.807	0.177	0.773	2.287	5.477	...	...	...	...
5.40	...	...	4.825	2.543	0.950	0.200	0.617	1.889	4.660	...	...	...	...
5.45	...	...	5.174	2.812	1.108	0.244	0.493	1.537	3.924	...	...	...	...
5.50	...	...	5.534	3.093	1.284	0.311	0.399	1.231	3.264	6.377	...	...	...
5.55	...	...	5.911	3.391	1.481	0.401	0.337	0.967	2.677	5.333	...	...	...
5.60	...	...	6.307	3.709	1.701	0.518	0.309	0.748	2.160	4.404	6.980	...	...
5.65	...	...	6.727	4.051	1.948	0.666	0.314	0.572	1.712	3.585	5.758	...	...
5.70	...	...	...	4.419	2.224	0.844	0.355	0.442	1.333	2.870	4.683	...	...
5.75	...	...	...	4.817	2.532	1.055	0.435	0.356	1.020	2.253	3.743	5.780	...
5.80	...	...	...	5.247	2.872	1.303	0.555	0.317	0.773	1.732	2.930	4.625	6.474
5.85	...	...	...	5.712	3.251	1.588	0.717	0.328	0.592	1.301	2.237	3.619	5.154
5.90	...	...	...	6.218	3.671	1.918	0.926	0.393	0.479	0.961	1.658	2.755	4.001
5.95	...	...	...	6.775	4.144	2.301	1.192	0.520	0.442	0.715	1.194	2.029	3.009
6.00	...	...	...	...	4.680	2.749	1.526	0.721	0.488	0.570	0.850	1.444	2.178
6.05	...	...	...	...	5.295	3.277	1.944	1.010	0.633	0.536	0.632	1.006	1.510
6.10	...	...	...	...	6.006	3.901	2.461	1.404	0.890	0.627	0.551	0.717	1.008
6.15	...	...	...	...	6.824	4.635	3.090	1.914	1.271	0.853	0.616	0.588	0.680
6.20	...	...	...	...	...	5.493	3.846	2.556	1.789	1.225	0.838	0.629	0.532
6.25	...	...	...	...	...	6.517	4.771	3.371	2.486	1.784	1.256	0.876	0.601
6.30	...	...	...	...	...	...	5.926	4.419	3.421	2.589	1.926	1.386	0.942
6.35	...	...	...	...	...	...	...	5.641	4.535	3.578	2.788	2.095	1.492
6.40	...	...	...	...	...	...	...	6.905	5.694	4.619	3.707	2.870	2.116
6.45	...	...	...	...	...	...	...	...	6.833	5.644	4.616	3.642	2.744
6.50	...	...	...	...	...	...	...	...	...	6.640	5.500	4.395	3.361
6.55	...	...	...	...	...	...	...	...	...	...	6.362	5.133	3.969
6.60	...	...	...	...	...	...	...	...	...	...	...	5.864	4.576
6.65	...	...	...	...	...	...	...	...	...	...	...	6.599	5.194
6.70	...	...	...	...	...	...	...	...	...	...	...	...	5.831
6.75	...	...	...	...	...	...	...	...	...	...	...	...	6.498

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. CONTINUED.

IRON IONIZATION BALANCE, CONT.														
Log(T)	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII
5.90	5.881	...	...	...	...	...	...	...	...	...	...	...	...	...
5.95	4.570	6.391	...	...	...	...	...	...	...	...	...	...	...	...
6.00	3.444	4.939	6.784	...	...	...	...	...	...	...	...	...	...	...
6.05	2.504	3.695	5.193	5.998	...	...	...	...	...	...	...	...	...	...
6.10	1.747	2.657	3.832	4.315	...	...	...	...	...	...	...	...	...	...
6.15	1.184	1.830	2.706	2.902	6.496	...	...	...	...	...	...	...	...	...
6.20	0.814	1.214	1.814	1.758	4.812	...	...	...	...	...	...	...	...	...
6.25	0.675	0.845	1.188	0.917	3.483	6.628	...	...	...	...	...	...	...	...
6.30	0.821	0.776	0.879	0.424	2.549	5.219	...	...	...	...	...	...	...	...
6.35	1.188	0.941	0.823	0.210	1.938	4.180	6.892	...	...	...	...	...	...	...
6.40	1.638	1.204	0.879	0.130	1.502	3.359	5.657	...	...	...	...	...	...	...
6.45	2.104	1.493	0.976	0.107	1.160	2.672	4.599	...	...	...	...	...	...	...
6.50	2.567	1.791	1.095	0.118	0.887	2.088	3.682	5.800	...	...	...	...	...	...
6.55	3.029	2.098	1.235	0.159	0.673	1.597	2.893	4.679	6.717	...	...	...	...	...
6.60	3.499	2.423	1.403	0.233	0.520	1.196	2.223	3.710	5.442	...	...	...	...	...
6.65	3.986	2.774	1.606	0.348	0.431	0.883	1.668	2.886	4.341	5.947	...	...	...	...
6.70	4.500	3.158	1.852	0.509	0.409	0.659	1.226	2.200	3.403	4.724	6.393	...	...	...
6.75	5.051	3.587	2.150	0.724	0.455	0.523	0.892	1.644	2.618	3.679	5.083	6.490	...	...
6.80	5.643	4.064	2.503	0.996	0.574	0.472	0.660	1.213	1.977	2.800	3.964	5.115	...	...
6.85	6.281	4.592	2.915	1.328	0.763	0.507	0.527	0.895	1.466	2.071	3.016	3.933	...	...
6.90	6.969	5.177	3.388	1.724	1.026	0.626	0.492	0.689	1.080	1.485	2.231	2.937	...	...
6.95	...	5.827	3.932	2.192	1.370	0.835	0.557	0.597	0.821	1.042	1.602	2.113	...	...
7.00	...	6.558	4.561	2.745	1.806	1.145	0.733	0.626	0.695	0.744	1.135	1.470	6.208	...
7.05	...	...	5.281	3.390	2.340	1.560	1.020	0.777	0.700	0.591	0.825	1.002	5.195	...
7.10	...	...	6.076	4.112	2.956	2.062	1.403	1.031	0.817	0.561	0.650	0.685	4.389	...
7.15	...	...	6.916	4.880	3.622	2.620	1.847	1.353	1.011	0.616	0.571	0.480	3.745	...
7.20	...	...	...	5.661	4.306	3.201	2.319	1.710	1.245	0.722	0.552	0.349	3.219	6.891
7.25	...	...	...	6.435	4.986	3.782	2.797	2.078	1.497	0.853	0.565	0.264	2.779	6.073
7.30	...	...	...	...	5.651	4.351	3.266	2.443	1.751	0.993	0.597	0.208	2.404	5.354
7.35	...	...	...	...	6.294	4.903	3.723	2.799	2.001	1.136	0.637	0.170	2.079	4.717
7.40	...	...	...	...	6.916	5.436	4.163	3.144	2.245	1.279	0.683	0.144	1.794	4.148
7.45	...	...	...	...	...	5.951	4.590	3.477	2.482	1.419	0.733	0.128	1.544	3.638
7.50	...	...	...	...	...	6.450	5.003	3.801	2.714	1.560	0.788	0.120	1.322	3.178
7.55	...	...	...	...	...	6.935	5.405	4.117	2.941	1.700	0.847	0.119	1.128	2.767
7.60	...	...	...	...	...	...	5.799	4.428	3.166	1.843	0.913	0.126	0.954	2.395
7.65	...	...	...	...	...	...	6.188	4.736	3.391	1.990	0.987	0.142	0.803	2.059
7.70	...	...	...	...	...	...	6.573	5.043	3.619	2.142	1.071	0.168	0.675	1.761
7.75	...	...	...	...	...	...	6.957	5.352	3.850	2.302	1.165	0.205	0.567	1.496
7.80	...	...	...	...	...	...	...	5.662	4.086	2.471	1.271	0.253	0.481	1.264
7.85	...	...	...	...	...	...	...	5.977	4.329	2.648	1.389	0.314	0.415	1.062
7.90	...	...	...	...	...	...	...	6.296	4.579	2.835	1.519	0.386	0.368	0.889
7.95	...	...	...	...	...	...	...	6.620	4.835	3.032	1.661	0.471	0.339	0.742
8.00	...	...	...	...	...	...	...	6.946	5.097	3.236	1.813	0.566	0.327	0.618
8.05	...	...	...	...	...	...	...	...	5.362	3.446	1.974	0.669	0.328	0.515
8.10	...	...	...	...	...	...	...	...	5.631	3.662	2.142	0.780	0.342	0.430
8.15	...	...	...	...	...	...	...	...	5.899	3.880	2.315	0.896	0.365	0.360
8.20	...	...	...	...	...	...	...	...	6.168	4.099	2.491	1.016	0.396	0.302
8.25	...	...	...	...	...	...	...	...	6.434	4.319	2.669	1.138	0.433	0.255
8.30	...	...	...	...	...	...	...	...	6.697	4.537	2.847	1.261	0.475	0.216
8.35	...	...	...	...	...	...	...	...	6.957	4.753	3.024	1.384	0.520	0.183
8.40	...	...	...	...	...	...	...	...	...	4.966	3.200	1.506	0.567	0.157
8.45	...	...	...	...	...	...	...	...	...	5.175	3.374	1.627	0.617	0.134
8.50	...	...	...	...	...	...	...	...	...	5.381	3.545	1.747	0.667	0.115

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. CONTINUED.

NICKEL IONIZATION BALANCE.														
Log(T)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
4.00	0.438	0.197	4.892	...	...	...	...	...	...	...	...	...	...	...
4.05	0.773	0.080	3.722	...	...	...	...	...	...	...	...	...	...	...
4.10	1.067	0.040	2.737	...	...	...	...	...	...	...	...	...	...	...
4.15	1.300	0.028	1.880	...	...	...	...	...	...	...	...	...	...	...
4.20	1.506	0.047	1.142	...	...	...	...	...	...	...	...	...	...	...
4.25	1.760	0.146	0.571	6.345	...	...	...	...	...	...	...	...	...	...
4.30	2.139	0.389	0.233	4.868	...	...	...	...	...	...	...	...	...	...
4.35	2.600	0.723	0.093	3.706	...	...	...	...	...	...	...	...	...	...
4.40	3.032	1.037	0.043	2.748	...	...	...	...	...	...	...	...	...	...
4.45	3.392	1.284	0.029	1.936	...	...	...	...	...	...	...	...	...	...
4.50	3.701	1.487	0.039	1.271	5.917	...	...	...	...	...	...	...	...	...
4.55	4.004	1.686	0.090	0.780	4.431	...	...	...	...	...	...	...	...	...
4.60	4.329	1.913	0.190	0.467	3.250	...	...	...	...	...	...	...	...	...
4.65	4.674	2.161	0.325	0.288	2.342	...	...	...	...	...	...	...	...	...
4.70	5.027	2.422	0.481	0.191	1.665	5.565	...	...	...	...	...	...	...	...
4.75	5.389	2.694	0.654	0.149	1.175	4.232	...	...	...	...	...	...	...	...
4.80	5.763	2.982	0.847	0.151	0.823	3.174	...	...	...	...	...	...	...	...
4.85	6.153	3.289	1.063	0.194	0.570	2.356	6.921	...	...	...	...	...	...	...
4.90	6.568	3.621	1.306	0.276	0.395	1.736	5.475	...	...	...	...	...	...	...
4.95	...	3.979	1.577	0.397	0.285	1.267	4.319	...	...	...	...	...	...	...
5.00	...	4.362	1.876	0.555	0.233	0.913	3.402	...	...	...	...	...	...	...
5.05	...	4.770	2.203	0.748	0.231	0.647	2.673	6.040	...	...	...	...	...	...
5.10	...	5.202	2.554	0.973	0.275	0.454	2.088	4.912	...	...	...	...	...	...
5.15	...	5.653	2.926	1.227	0.359	0.321	1.614	3.984	...	...	...	...	...	...
5.20	...	6.123	3.320	1.505	0.478	0.240	1.229	3.209	6.485	...	...	...	...	...
5.25	...	6.609	3.731	1.805	0.628	0.204	0.918	2.556	5.409	...	...	...	...	...
5.30	...	...	4.159	2.129	0.809	0.211	0.674	2.005	4.483	...	...	...	...	...
5.35	...	...	4.607	2.475	1.022	0.260	0.491	1.544	3.684	6.520	...	...	...	...
5.40	...	...	5.079	2.849	1.268	0.351	0.367	1.164	2.996	5.442	...	...	...	...
5.45	...	...	5.577	3.251	1.547	0.484	0.300	0.861	2.410	4.511	...	...	...	...
5.50	...	...	6.098	3.681	1.858	0.657	0.286	0.627	1.914	3.708	...	...	...	...
5.55	...	...	6.647	4.138	2.203	0.869	0.321	0.458	1.501	3.016	6.087	...	...	...
5.60	...	...	...	4.622	2.578	1.116	0.402	0.345	1.160	2.420	5.132	...	...	...
5.65	...	...	...	5.129	2.979	1.395	0.524	0.286	0.887	1.911	4.287	...	...	...
5.70	...	...	...	5.662	3.410	1.708	0.686	0.276	0.675	1.480	3.545	6.374	...	...
5.75	...	...	...	6.221	3.869	2.053	0.888	0.315	0.523	1.122	2.896	5.349	...	...
5.80	...	...	...	6.809	4.359	2.432	1.129	0.400	0.429	0.834	2.338	4.445	6.889	...
5.85	...	...	...	...	4.881	2.846	1.412	0.534	0.389	0.611	1.862	3.652	5.751	...
5.90	...	...	...	...	5.431	3.292	1.732	0.710	0.401	0.451	1.466	2.964	4.745	6.798
5.95	...	...	...	...	6.009	3.768	2.084	0.927	0.461	0.347	1.140	2.369	3.857	5.589
6.00	...	...	...	...	6.610	4.269	2.468	1.178	0.563	0.293	0.879	1.857	3.076	4.511
6.05	...	...	...	...	...	4.797	2.881	1.465	0.706	0.287	0.678	1.426	2.395	3.556
6.10	...	...	...	...	...	5.354	3.327	1.789	0.893	0.332	0.540	1.075	1.814	2.719
6.15	...	...	...	...	...	5.950	3.817	2.161	1.133	0.436	0.471	0.804	1.330	1.996
6.20	...	...	...	...	...	6.603	4.366	2.596	1.442	0.615	0.487	0.631	0.955	1.401
6.25	...	...	...	...	...	...	5.000	3.121	1.846	0.893	0.611	0.579	0.715	0.952
6.30	...	...	...	...	...	...	5.757	3.771	2.378	1.305	0.877	0.681	0.641	0.681
6.35	...	...	...	...	...	...	6.700	4.612	3.106	1.918	1.351	0.998	0.793	0.649
6.40	...	...	...	...	...	...	...	5.781	4.167	2.867	2.168	1.668	1.307	0.989
6.45	...	...	...	...	...	...	...	...	5.543	4.135	3.309	2.670	2.162	1.679
6.50	...	...	...	...	...	...	...	...	...	5.494	4.548	3.776	3.129	2.490
6.55	...	...	...	...	...	...	...	...	...	6.831	5.768	4.869	4.090	3.304
6.60	...	...	...	...	...	...	...	...	...	...	6.948	5.928	5.023	4.097
6.65	...	...	...	...	...	...	...	...	...	...	...	6.956	5.930	4.871
6.70	...	...	...	...	...	...	...	...	...	...	...	...	6.822	5.637
6.75	...	...	...	...	...	...	...	...	...	...	...	...	...	6.409

TABLE A.5 : COLLISIONAL IONIZATION EQUILIBRIUM : IONIZATION BALANCE. *CONTINUED.*

NICKEL IONIZATION BALANCE, <i>CONT.</i>															
Log(T)	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII	XXVIII	XXIX
6.00	6.328	...	...	...	...	...	...	...	...	...	...	...	...	...	...
6.05	5.071	6.827	...	...	...	...	...	...	...	...	...	...	...	...	...
6.10	3.954	5.406	...	...	...	...	...	...	...	...	...	...	...	...	...
6.15	2.971	4.139	5.513	6.814	...	...	...	...	...	...	...	...	...	...	...
6.20	2.131	3.036	4.112	5.082	5.694	...	...	...	...	...	...	...	...	...	...
6.25	1.456	2.113	2.912	3.575	3.907	...	...	...	...	...	...	...	...	...	...
6.30	0.970	1.396	1.938	2.316	2.401	5.376	...	...	...	...	...	...	...	...	...
6.35	0.736	0.944	1.246	1.361	1.231	3.728	6.761	...	...	...	...	...	...	...	...
6.40	0.886	0.890	0.968	0.836	0.518	2.587	5.159	...	...	...	...	...	...	...	...
6.45	1.398	1.211	1.080	0.720	0.235	1.920	4.077	6.645	...	...	...	...	...	...	...
6.50	2.040	1.673	1.347	0.776	0.143	1.484	3.268	5.441	...	...	...	...	...	...	...
6.55	2.694	2.159	1.651	0.884	0.117	1.150	2.599	4.416	6.753	...	...	...	...	...	...
6.60	3.337	2.642	1.965	1.015	0.126	0.882	2.028	3.526	5.515	...	...	...	...	...	...
6.65	3.969	3.125	2.288	1.168	0.165	0.673	1.546	2.755	4.429	6.430	...	...	...	...	...
6.70	4.600	3.614	2.630	1.350	0.241	0.523	1.149	2.098	3.485	5.176	...	...	...	...	...
6.75	5.243	4.125	3.000	1.572	0.363	0.439	0.841	1.552	2.677	4.085	5.731	...	...	...	...
6.80	5.912	4.667	3.411	1.844	0.539	0.429	0.625	1.120	2.005	3.154	4.519	6.033	...	...	...
6.85	6.620	5.255	3.876	2.177	0.780	0.497	0.505	0.803	1.468	2.378	3.486	4.744	6.171	...	...
6.90	...	5.896	4.400	2.578	1.092	0.648	0.481	0.596	1.059	1.751	2.622	3.646	4.831	...	...
6.95	...	6.591	4.985	3.047	1.476	0.882	0.554	0.498	0.773	1.262	1.915	2.729	3.693	...	...
7.00	...	...	5.636	3.589	1.934	1.201	0.722	0.509	0.609	0.910	1.360	1.977	2.742	...	...
7.05	...	...	6.362	4.211	2.474	1.610	0.990	0.629	0.567	0.693	0.957	1.394	1.976	...	...
7.10	...	...	...	4.920	3.103	2.115	1.363	0.864	0.650	0.613	0.704	0.977	1.393	5.894	...
7.15	...	...	...	5.709	3.815	2.710	1.833	1.204	0.847	0.659	0.588	0.710	0.977	4.971	...
7.20	...	...	...	6.555	4.585	3.369	2.374	1.622	1.131	0.800	0.579	0.563	0.695	4.234	...
7.25	...	...	...	...	5.382	4.060	2.953	2.084	1.466	1.003	0.642	0.497	0.509	3.638	...
7.30	...	...	...	...	6.180	4.756	3.542	2.563	1.826	1.236	0.744	0.480	0.385	3.146	6.683
7.35	...	...	...	...	6.961	5.441	4.125	3.040	2.189	1.481	0.866	0.493	0.301	2.731	5.914
7.40	...	...	...	...	...	6.105	4.691	3.507	2.548	1.727	0.997	0.521	0.243	2.374	5.235
7.45	...	...	...	...	...	6.745	5.238	3.957	2.895	1.968	1.130	0.559	0.201	2.063	4.632
7.50	...	...	...	...	...	...	5.765	4.391	3.232	2.203	1.263	0.603	0.172	1.789	4.091
7.55	...	...	...	...	...	...	6.271	4.809	3.556	2.431	1.396	0.653	0.152	1.546	3.604
7.60	...	...	...	...	...	...	6.760	5.213	3.870	2.654	1.527	0.706	0.140	1.335	3.170
7.65	...	...	...	...	...	...	...	5.605	4.176	2.872	1.660	0.766	0.136	1.141	2.773
7.70	...	...	...	...	...	...	...	5.987	4.475	3.088	1.795	0.831	0.140	0.972	2.413
7.75	...	...	...	...	...	...	...	6.361	4.770	3.303	1.933	0.904	0.152	0.824	2.091
7.80	...	...	...	...	...	...	...	6.729	5.063	3.519	2.077	0.986	0.173	0.697	1.803
7.85	...	...	...	...	...	...	...	...	5.355	3.738	2.226	1.077	0.205	0.589	1.546
7.90	...	...	...	...	...	...	...	...	5.648	3.962	2.383	1.178	0.247	0.501	1.320
7.95	...	...	...	...	...	...	...	...	5.944	4.190	2.549	1.290	0.300	0.433	1.122
8.00	...	...	...	...	...	...	...	...	6.242	4.423	2.722	1.413	0.365	0.381	0.950
8.05	...	...	...	...	...	...	...	...	6.542	4.662	2.903	1.546	0.440	0.347	0.802
8.10	...	...	...	...	...	...	...	...	6.845	4.905	3.091	1.688	0.525	0.328	0.677
8.15	...	...	...	...	...	...	...	...	...	5.151	3.286	1.838	0.618	0.323	0.571
8.20	...	...	...	...	...	...	...	...	...	5.400	3.484	1.994	0.718	0.329	0.482
8.25	...	...	...	...	...	...	...	...	...	5.649	3.685	2.155	0.823	0.345	0.408
8.30	...	...	...	...	...	...	...	...	...	5.898	3.888	2.319	0.933	0.369	0.346
8.35	...	...	...	...	...	...	...	...	...	6.146	4.092	2.485	1.045	0.399	0.294
8.40	...	...	...	...	...	...	...	...	...	6.391	4.294	2.651	1.158	0.435	0.251
8.45	...	...	...	...	...	...	...	...	...	6.633	4.495	2.818	1.272	0.474	0.215
8.50	...	...	...	...	...	...	...	...	...	6.871	4.693	2.983	1.386	0.516	0.185

TABLE A.6 : CIE ABUNDANCE SERIES.

CIE COOLING CURVE : SOLAR ABUNDANCES
 $\text{Log}(T) = 4.00 \text{ TO } 8.50$

Log(T)	Number Densities			Cooling Properties				General Plasma Properties ^a			
	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
4.00	0.0023	1.000	1.099	-25.65	-23.06	-11.64	11.37	1.532	2.386	8.012	2.166
4.05	0.0142	1.000	1.099	-24.27	-22.46	-11.59	10.83	1.737	2.386	8.533	2.143
4.10	0.0704	1.000	1.099	-23.28	-22.17	-11.52	10.58	2.048	2.386	9.264	2.040
4.15	0.2534	1.000	1.099	-22.47	-21.92	-11.40	10.38	2.657	2.386	10.55	1.764
4.20	0.5678	1.000	1.099	-21.99	-21.79	-11.26	10.30	3.674	2.387	12.41	1.431
4.25	0.8177	1.000	1.099	-21.84	-21.80	-11.15	10.36	4.740	2.387	14.09	1.245
4.30	0.9324	1.000	1.099	-21.85	-21.86	-11.08	10.48	5.637	2.387	15.37	1.175
4.35	0.9780	1.000	1.099	-21.87	-21.90	-11.02	10.57	6.467	2.387	16.46	1.149
4.40	1.004	1.000	1.099	-21.84	-21.88	-10.96	10.60	7.347	2.387	17.54	1.135
4.45	1.035	1.000	1.099	-21.77	-21.82	-10.90	10.59	8.366	2.387	18.72	1.118
4.50	1.067	1.000	1.099	-21.66	-21.73	-10.85	10.55	9.528	2.387	19.98	1.102
4.55	1.086	1.000	1.099	-21.56	-21.63	-10.79	10.50	10.78	2.387	21.25	1.092
4.60	1.094	1.000	1.099	-21.45	-21.53	-10.74	10.45	12.14	2.387	22.56	1.088
4.65	1.098	1.000	1.099	-21.34	-21.42	-10.69	10.39	13.65	2.387	23.91	1.087
4.70	1.100	1.000	1.099	-21.24	-21.32	-10.64	10.34	15.32	2.387	25.34	1.086
4.75	1.102	1.000	1.099	-21.14	-21.22	-10.59	10.29	17.22	2.387	26.86	1.084
4.80	1.110	1.000	1.099	-21.05	-21.14	-10.54	10.25	19.38	2.387	28.50	1.080
4.85	1.128	1.000	1.099	-20.97	-21.07	-10.49	10.23	21.92	2.387	30.31	1.072
4.90	1.154	1.000	1.099	-20.91	-21.01	-10.43	10.23	24.89	2.387	32.29	1.059
4.95	1.176	1.000	1.099	-20.87	-20.98	-10.38	10.25	28.19	2.387	34.37	1.049
5.00	1.188	1.000	1.099	-20.87	-20.99	-10.32	10.30	31.81	2.387	36.50	1.043
5.05	1.195	1.000	1.099	-20.90	-21.02	-10.27	10.38	35.79	2.387	38.72	1.041
5.10	1.198	1.000	1.099	-20.91	-21.03	-10.22	10.45	40.21	2.387	41.04	1.039
5.15	1.199	1.000	1.099	-20.89	-21.01	-10.17	10.48	45.14	2.387	43.49	1.039
5.20	1.200	1.000	1.099	-20.86	-20.98	-10.12	10.50	50.67	2.387	46.07	1.038
5.25	1.201	1.000	1.099	-20.85	-20.97	-10.07	10.54	56.87	2.387	48.81	1.038
5.30	1.201	1.000	1.099	-20.84	-20.96	-10.02	10.58	63.82	2.387	51.71	1.038
5.35	1.201	1.000	1.099	-20.84	-20.96	-9.972	10.63	71.62	2.387	54.78	1.038
5.40	1.202	1.000	1.099	-20.87	-20.99	-9.922	10.71	80.38	2.387	58.03	1.037
5.45	1.203	1.000	1.099	-21.01	-21.13	-9.872	10.90	90.22	2.387	61.48	1.037
5.50	1.203	1.000	1.099	-21.23	-21.35	-9.822	11.17	101.2	2.387	65.13	1.037
5.55	1.204	1.000	1.099	-21.43	-21.55	-9.772	11.42	113.6	2.387	68.99	1.037
5.60	1.204	1.000	1.099	-21.54	-21.66	-9.722	11.58	127.5	2.387	73.08	1.036
5.65	1.204	1.000	1.099	-21.58	-21.71	-9.672	11.67	143.1	2.387	77.41	1.036
5.70	1.204	1.000	1.099	-21.59	-21.71	-9.622	11.73	160.5	2.387	82.00	1.036
5.75	1.204	1.000	1.099	-21.59	-21.71	-9.572	11.78	180.1	2.387	86.87	1.036
5.80	1.204	1.000	1.099	-21.64	-21.76	-9.522	11.88	202.1	2.387	92.02	1.036
5.85	1.205	1.000	1.099	-21.74	-21.86	-9.471	12.03	226.8	2.387	97.47	1.036
5.90	1.205	1.000	1.099	-21.81	-21.93	-9.421	12.15	254.5	2.387	103.3	1.036
5.95	1.205	1.000	1.099	-21.83	-21.95	-9.371	12.22	285.6	2.387	109.4	1.036
6.00	1.205	1.000	1.099	-21.84	-21.96	-9.321	12.28	320.4	2.387	115.9	1.036
6.05	1.205	1.000	1.099	-21.84	-21.96	-9.271	12.33	359.6	2.387	122.7	1.036
6.10	1.206	1.000	1.099	-21.83	-21.96	-9.221	12.37	403.5	2.387	130.0	1.036
6.15	1.206	1.000	1.099	-21.82	-21.95	-9.171	12.41	452.8	2.387	137.7	1.036
6.20	1.206	1.000	1.099	-21.82	-21.94	-9.121	12.46	508.1	2.387	145.9	1.035
6.25	1.206	1.000	1.099	-21.85	-21.97	-9.071	12.54	570.1	2.387	154.5	1.035
6.30	1.207	1.000	1.099	-21.95	-22.07	-9.021	12.69	639.8	2.387	163.7	1.035
6.35	1.207	1.000	1.099	-22.08	-22.20	-8.971	12.87	717.9	2.387	173.4	1.035
6.40	1.207	1.000	1.099	-22.19	-22.31	-8.921	13.03	805.6	2.387	183.7	1.035
6.45	1.208	1.000	1.099	-22.27	-22.39	-8.871	13.16	904.0	2.387	194.6	1.035
6.50	1.208	1.000	1.099	-22.32	-22.44	-8.821	13.26	1014.5	2.387	206.1	1.035
6.55	1.208	1.000	1.099	-22.35	-22.48	-8.771	13.34	1138.3	2.387	218.4	1.035
6.60	1.208	1.000	1.099	-22.38	-22.50	-8.721	13.42	1277.3	2.387	231.3	1.035
6.65	1.208	1.000	1.099	-22.41	-22.53	-8.671	13.50	1433.2	2.387	245.0	1.034
6.70	1.208	1.000	1.099	-22.44	-22.56	-8.621	13.58	1608.2	2.387	259.6	1.034
6.75	1.208	1.000	1.099	-22.46	-22.59	-8.571	13.65	1804.4	2.387	274.9	1.034
6.80	1.208	1.000	1.099	-22.48	-22.60	-8.521	13.72	2024.7	2.387	291.2	1.034
6.85	1.209	1.000	1.099	-22.48	-22.60	-8.471	13.77	2271.8	2.387	308.5	1.034
6.90	1.209	1.000	1.099	-22.46	-22.59	-8.421	13.80	2549.1	2.387	326.8	1.034
6.95	1.209	1.000	1.099	-22.45	-22.57	-8.371	13.84	2860.2	2.387	346.1	1.034
7.00	1.209	1.000	1.099	-22.45	-22.57	-8.321	13.89	3209.2	2.387	366.7	1.034
7.05	1.209	1.000	1.099	-22.46	-22.59	-8.271	13.95	3600.9	2.387	388.4	1.034

a. $P_{12} = P \times 10^{12}$, $\rho_{24} = \rho \times 10^{24}$, $\mu_{24} = \mu \times 10^{24}$

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.CIE COOLING CURVE : SOLAR ABUNDANCES, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.10	1.209	1.000	1.099	-22.49	-22.62	-8.221	14.03	4040.4	2.387	411.4	1.034
7.15	1.209	1.000	1.099	-22.53	-22.65	-8.171	14.12	4533.5	2.387	435.8	1.034
7.20	1.209	1.000	1.099	-22.56	-22.68	-8.121	14.20	5086.8	2.387	461.6	1.034
7.25	1.209	1.000	1.099	-22.58	-22.70	-8.071	14.27	5707.5	2.387	489.0	1.034
7.30	1.209	1.000	1.099	-22.60	-22.72	-8.021	14.34	6404.0	2.387	518.0	1.034
7.35	1.209	1.000	1.099	-22.61	-22.73	-7.971	14.40	7185.4	2.387	548.6	1.034
7.40	1.209	1.000	1.099	-22.61	-22.73	-7.921	14.45	8062.2	2.387	581.2	1.034
7.45	1.209	1.000	1.099	-22.61	-22.73	-7.871	14.50	9046.0	2.387	615.6	1.034
7.50	1.209	1.000	1.099	-22.60	-22.73	-7.821	14.54	10149.8	2.387	652.1	1.034
7.55	1.209	1.000	1.099	-22.60	-22.72	-7.771	14.59	11388.3	2.387	690.7	1.034
7.60	1.209	1.000	1.099	-22.59	-22.71	-7.721	14.63	12777.9	2.387	731.6	1.034
7.65	1.209	1.000	1.099	-22.57	-22.70	-7.671	14.66	14337.1	2.387	775.0	1.034
7.70	1.209	1.000	1.099	-22.56	-22.68	-7.621	14.70	16086.6	2.387	820.9	1.034
7.75	1.209	1.000	1.099	-22.54	-22.67	-7.571	14.73	18049.5	2.387	869.6	1.034
7.80	1.209	1.000	1.099	-22.53	-22.65	-7.521	14.77	20251.9	2.387	921.1	1.034
7.85	1.209	1.000	1.099	-22.51	-22.64	-7.471	14.80	22723.1	2.387	975.7	1.034
7.90	1.209	1.000	1.099	-22.49	-22.62	-7.421	14.83	25495.8	2.387	1033.5	1.034
7.95	1.209	1.000	1.099	-22.48	-22.60	-7.371	14.87	28606.9	2.387	1094.7	1.034
8.00	1.209	1.000	1.099	-22.46	-22.58	-7.321	14.90	32097.6	2.387	1159.6	1.034
8.05	1.209	1.000	1.099	-22.44	-22.56	-7.271	14.93	36014.2	2.387	1228.3	1.034
8.10	1.209	1.000	1.099	-22.42	-22.54	-7.221	14.96	40408.7	2.387	1301.1	1.034
8.15	1.209	1.000	1.099	-22.40	-22.53	-7.171	14.99	45339.4	2.387	1378.2	1.034
8.20	1.209	1.000	1.099	-22.38	-22.51	-7.121	15.02	50871.7	2.387	1459.8	1.034
8.25	1.209	1.000	1.099	-22.36	-22.49	-7.071	15.05	57079.1	2.387	1546.3	1.034
8.30	1.209	1.000	1.099	-22.34	-22.47	-7.021	15.08	64044.0	2.387	1638.0	1.034
8.35	1.209	1.000	1.099	-22.32	-22.45	-6.971	15.11	71858.6	2.387	1735.0	1.034
8.40	1.209	1.000	1.099	-22.30	-22.43	-6.921	15.14	80626.8	2.387	1837.8	1.034
8.45	1.209	1.000	1.099	-22.28	-22.40	-6.871	15.17	90464.8	2.387	1946.7	1.034
8.50	1.209	1.000	1.099	-22.26	-22.38	-6.821	15.20	101503	2.387	2062.1	1.034

CIE COOLING CURVE : [Fe/H] = -0.5

Log(T) = 4.00 TO 8.50

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
4.00	0.0023	1.000	1.080	-25.83	-23.22	-11.65	11.54	1.505	2.239	8.198	2.069
4.05	0.0141	1.000	1.080	-24.49	-22.68	-11.59	11.04	1.707	2.239	8.732	2.046
4.10	0.0703	1.000	1.080	-23.42	-22.30	-11.52	10.72	2.014	2.239	9.483	1.947
4.15	0.2530	1.000	1.080	-22.56	-22.00	-11.41	10.46	2.619	2.240	10.81	1.680
4.20	0.5673	1.000	1.080	-22.07	-21.85	-11.27	10.37	3.631	2.240	12.73	1.360
4.25	0.8162	1.000	1.080	-21.92	-21.86	-11.16	10.43	4.689	2.240	14.47	1.181
4.30	0.9317	1.000	1.080	-21.94	-21.94	-11.08	10.56	5.582	2.240	15.78	1.113
4.35	0.9767	1.000	1.080	-22.00	-22.02	-11.02	10.69	6.403	2.240	16.91	1.089
4.40	1.001	1.000	1.080	-22.02	-22.06	-10.97	10.77	7.269	2.240	18.01	1.076
4.45	1.027	1.000	1.080	-22.00	-22.05	-10.91	10.81	8.259	2.240	19.20	1.063
4.50	1.054	1.000	1.080	-21.94	-22.00	-10.85	10.81	9.383	2.240	20.47	1.050
4.55	1.069	1.000	1.080	-21.87	-21.93	-10.80	10.80	10.61	2.240	21.76	1.042
4.60	1.076	1.000	1.080	-21.78	-21.85	-10.75	10.76	11.94	2.240	23.08	1.039
4.65	1.079	1.000	1.080	-21.69	-21.75	-10.70	10.72	13.41	2.240	24.46	1.038
4.70	1.080	1.000	1.080	-21.59	-21.66	-10.65	10.67	15.05	2.240	25.92	1.037
4.75	1.082	1.000	1.080	-21.50	-21.57	-10.60	10.63	16.91	2.240	27.47	1.036
4.80	1.088	1.000	1.080	-21.41	-21.48	-10.55	10.60	19.03	2.240	29.14	1.033
4.85	1.103	1.000	1.080	-21.33	-21.41	-10.49	10.57	21.49	2.240	30.97	1.026
4.90	1.124	1.000	1.080	-21.27	-21.35	-10.44	10.57	24.34	2.240	32.96	1.016
4.95	1.142	1.000	1.080	-21.23	-21.32	-10.39	10.59	27.53	2.240	35.06	1.008
5.00	1.152	1.000	1.080	-21.22	-21.32	-10.34	10.63	31.04	2.240	37.22	1.004
5.05	1.157	1.000	1.080	-21.23	-21.33	-10.28	10.69	34.90	2.240	39.47	1.002
5.10	1.159	1.000	1.080	-21.22	-21.32	-10.23	10.73	39.20	2.240	41.83	1.001
5.15	1.160	1.000	1.080	-21.19	-21.29	-10.18	10.75	44.00	2.240	44.32	1.000
5.20	1.161	1.000	1.080	-21.16	-21.26	-10.13	10.77	49.38	2.240	46.95	1.000
5.25	1.161	1.000	1.080	-21.14	-21.23	-10.08	10.80	55.42	2.240	49.74	1.000
5.30	1.161	1.000	1.080	-21.12	-21.21	-10.03	10.83	62.19	2.240	52.69	0.999
5.35	1.162	1.000	1.080	-21.10	-21.20	-9.983	10.86	69.79	2.240	55.81	0.999
5.40	1.162	1.000	1.080	-21.14	-21.23	-9.933	10.95	78.31	2.240	59.12	0.999
5.45	1.162	1.000	1.080	-21.27	-21.37	-9.883	11.13	87.88	2.240	62.63	0.999

TABLE A.6 : CIE ABUNDANCE SERIES, CONTINUED.

CIE COOLING CURVE : [Fe/H] = -0.5, CONT.

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	p_{24}	C_1	$\bar{\mu}_{24}$
5.50	1.163	1.000	1.080	-21.50	-21.60	-9.833	11.42	98.62	2.240	66.35	0.999
5.55	1.163	1.000	1.080	-21.70	-21.79	-9.783	11.67	110.7	2.240	70.28	0.999
5.60	1.163	1.000	1.080	-21.81	-21.91	-9.733	11.83	124.2	2.240	74.45	0.999
5.65	1.163	1.000	1.080	-21.85	-21.95	-9.683	11.92	139.3	2.240	78.86	0.999
5.70	1.163	1.000	1.080	-21.86	-21.96	-9.633	11.98	156.3	2.240	83.53	0.999
5.75	1.163	1.000	1.080	-21.87	-21.97	-9.583	12.04	175.4	2.240	88.48	0.999
5.80	1.163	1.000	1.080	-21.93	-22.03	-9.533	12.15	196.8	2.240	93.73	0.999
5.85	1.163	1.000	1.080	-22.05	-22.15	-9.483	12.32	220.9	2.240	99.29	0.999
5.90	1.163	1.000	1.080	-22.15	-22.24	-9.433	12.47	247.8	2.240	105.2	0.999
5.95	1.164	1.000	1.080	-22.19	-22.29	-9.383	12.56	278.1	2.240	111.4	0.999
6.00	1.164	1.000	1.080	-22.22	-22.32	-9.333	12.64	312.0	2.240	118.0	0.999
6.05	1.164	1.000	1.080	-22.24	-22.34	-9.283	12.71	350.1	2.240	125.0	0.998
6.10	1.164	1.000	1.080	-22.24	-22.34	-9.233	12.76	392.8	2.240	132.4	0.998
6.15	1.164	1.000	1.080	-22.24	-22.34	-9.183	12.81	440.8	2.240	140.3	0.998
6.20	1.164	1.000	1.080	-22.23	-22.33	-9.133	12.85	494.6	2.240	148.6	0.998
6.25	1.164	1.000	1.080	-22.26	-22.36	-9.083	12.93	554.9	2.240	157.4	0.998
6.30	1.164	1.000	1.080	-22.34	-22.44	-9.033	13.06	622.7	2.240	166.7	0.998
6.35	1.164	1.000	1.080	-22.44	-22.54	-8.983	13.21	698.7	2.240	176.6	0.998
6.40	1.164	1.000	1.080	-22.53	-22.63	-8.933	13.35	784.0	2.240	187.1	0.998
6.45	1.165	1.000	1.080	-22.59	-22.69	-8.883	13.46	879.7	2.240	198.2	0.998
6.50	1.165	1.000	1.080	-22.64	-22.74	-8.833	13.56	987.1	2.240	209.9	0.998
6.55	1.165	1.000	1.080	-22.66	-22.76	-8.783	13.63	1107.6	2.240	222.3	0.998
6.60	1.165	1.000	1.080	-22.69	-22.79	-8.733	13.71	1242.8	2.240	235.5	0.998
6.65	1.165	1.000	1.080	-22.71	-22.81	-8.683	13.78	1394.5	2.240	249.5	0.998
6.70	1.165	1.000	1.080	-22.73	-22.83	-8.633	13.85	1564.7	2.240	264.3	0.998
6.75	1.165	1.000	1.080	-22.75	-22.85	-8.583	13.92	1755.6	2.240	279.9	0.998
6.80	1.165	1.000	1.080	-22.76	-22.86	-8.533	13.98	1969.9	2.240	296.5	0.998
6.85	1.165	1.000	1.080	-22.75	-22.85	-8.483	14.02	2210.3	2.240	314.1	0.998
6.90	1.165	1.000	1.080	-22.74	-22.84	-8.433	14.06	2480.0	2.240	332.7	0.998
6.95	1.165	1.000	1.080	-22.74	-22.84	-8.383	14.11	2782.6	2.240	352.4	0.998
7.00	1.165	1.000	1.080	-22.73	-22.83	-8.333	14.15	3122.2	2.240	373.3	0.998
7.05	1.165	1.000	1.080	-22.73	-22.83	-8.283	14.20	3503.2	2.240	395.4	0.998
7.10	1.165	1.000	1.080	-22.75	-22.85	-8.233	14.27	3930.7	2.240	418.9	0.998
7.15	1.165	1.000	1.080	-22.76	-22.86	-8.183	14.33	4410.4	2.240	443.7	0.998
7.20	1.165	1.000	1.080	-22.77	-22.87	-8.133	14.39	4948.5	2.240	470.0	0.998
7.25	1.165	1.000	1.080	-22.77	-22.87	-8.083	14.44	5552.4	2.240	497.8	0.998
7.30	1.165	1.000	1.080	-22.77	-22.87	-8.033	14.49	6229.9	2.240	527.3	0.998
7.35	1.165	1.000	1.080	-22.76	-22.86	-7.983	14.53	6990.0	2.240	558.6	0.998
7.40	1.165	1.000	1.080	-22.75	-22.85	-7.933	14.57	7843.0	2.240	591.7	0.998
7.45	1.165	1.000	1.080	-22.74	-22.84	-7.883	14.61	8800.0	2.240	626.7	0.998
7.50	1.165	1.000	1.080	-22.73	-22.83	-7.833	14.65	9873.8	2.240	663.9	0.998
7.55	1.165	1.000	1.080	-22.72	-22.82	-7.783	14.69	11078.6	2.240	703.2	0.998
7.60	1.165	1.000	1.080	-22.70	-22.80	-7.733	14.72	12430.4	2.240	744.9	0.998
7.65	1.165	1.000	1.080	-22.68	-22.78	-7.683	14.75	13947.1	2.240	789.0	0.998
7.70	1.165	1.000	1.080	-22.66	-22.76	-7.633	14.78	15648.9	2.240	835.8	0.998
7.75	1.165	1.000	1.080	-22.65	-22.75	-7.583	14.82	17558.4	2.240	885.3	0.998
7.80	1.165	1.000	1.080	-22.63	-22.73	-7.533	14.85	19700.9	2.240	937.7	0.998
7.85	1.165	1.000	1.080	-22.61	-22.71	-7.483	14.88	22104.8	2.240	993.3	0.998
7.90	1.165	1.000	1.080	-22.59	-22.69	-7.433	14.91	24802.0	2.240	1052.2	0.998
7.95	1.165	1.000	1.080	-22.57	-22.67	-7.383	14.94	27828.3	2.240	1114.5	0.998
8.00	1.165	1.000	1.080	-22.55	-22.65	-7.333	14.97	31223.9	2.240	1180.5	0.998
8.05	1.165	1.000	1.080	-22.53	-22.63	-7.283	15.00	35033.9	2.240	1250.5	0.998
8.10	1.165	1.000	1.080	-22.50	-22.60	-7.233	15.02	39308.7	2.240	1324.6	0.998
8.15	1.165	1.000	1.080	-22.48	-22.58	-7.183	15.05	44105.1	2.240	1403.1	0.998
8.20	1.165	1.000	1.080	-22.46	-22.56	-7.133	15.08	49486.8	2.240	1486.2	0.998
8.25	1.165	1.000	1.080	-22.44	-22.54	-7.083	15.11	55525.1	2.240	1574.3	0.998
8.30	1.165	1.000	1.080	-22.42	-22.52	-7.033	15.14	62300.2	2.240	1667.6	0.998
8.35	1.165	1.000	1.080	-22.40	-22.50	-6.983	15.17	69902.0	2.240	1766.4	0.998
8.40	1.165	1.000	1.080	-22.38	-22.48	-6.933	15.20	78431.4	2.240	1871.0	0.998
8.45	1.165	1.000	1.080	-22.35	-22.45	-6.883	15.22	88001.5	2.240	1981.9	0.998
8.50	1.165	1.000	1.080	-22.33	-22.43	-6.833	15.25	98739.4	2.240	2099.3	0.998

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.

CIE COOLING CURVE : [Fe/H] = -1.0
 Log(T) = 4.00 TO 8.50

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_1	$\bar{\mu}_{24}$
4.00	0.0022	1.000	1.064	-25.94	-23.31	-11.66	11.63	1.483	2.125	8.354	1.992
4.05	0.0141	1.000	1.064	-24.61	-22.78	-11.60	11.15	1.683	2.125	8.898	1.971
4.10	0.0702	1.000	1.064	-23.49	-22.36	-11.53	10.78	1.986	2.125	9.667	1.873
4.15	0.2529	1.000	1.064	-22.60	-22.03	-11.41	10.50	2.587	2.125	11.03	1.613
4.20	0.5667	1.000	1.064	-22.10	-21.88	-11.27	10.40	3.595	2.126	13.00	1.303
4.25	0.8163	1.000	1.064	-21.95	-21.89	-11.16	10.45	4.650	2.126	14.79	1.130
4.30	0.9312	1.000	1.064	-21.99	-21.98	-11.08	10.60	5.537	2.126	16.14	1.065
4.35	0.9758	1.000	1.064	-22.07	-22.08	-11.02	10.75	6.351	2.126	17.28	1.042
4.40	0.9984	1.000	1.064	-22.13	-22.16	-10.97	10.87	7.205	2.126	18.41	1.031
4.45	1.021	1.000	1.064	-22.15	-22.19	-10.91	10.95	8.172	2.126	19.61	1.020
4.50	1.043	1.000	1.064	-22.15	-22.19	-10.86	11.01	9.265	2.126	20.88	1.009
4.55	1.055	1.000	1.064	-22.11	-22.16	-10.81	11.03	10.46	2.126	22.18	1.003
4.60	1.061	1.000	1.064	-22.06	-22.11	-10.76	11.03	11.76	2.126	23.52	1.000
4.65	1.063	1.000	1.064	-21.98	-22.04	-10.71	11.00	13.21	2.126	24.93	0.999
4.70	1.064	1.000	1.064	-21.90	-21.95	-10.66	10.97	14.83	2.126	26.41	0.999
4.75	1.066	1.000	1.064	-21.81	-21.86	-10.61	10.93	16.66	2.126	27.99	0.998
4.80	1.071	1.000	1.064	-21.72	-21.77	-10.55	10.89	18.73	2.126	29.68	0.996
4.85	1.082	1.000	1.064	-21.63	-21.69	-10.50	10.86	21.13	2.126	31.53	0.990
4.90	1.099	1.000	1.064	-21.57	-21.64	-10.45	10.85	23.90	2.126	33.53	0.983
4.95	1.114	1.000	1.064	-21.54	-21.61	-10.40	10.88	26.99	2.126	35.63	0.976
5.00	1.122	1.000	1.064	-21.53	-21.60	-10.34	10.92	30.40	2.126	37.81	0.973
5.05	1.126	1.000	1.064	-21.52	-21.60	-10.29	10.96	34.17	2.126	40.09	0.971
5.10	1.127	1.000	1.064	-21.50	-21.58	-10.24	11.00	38.37	2.126	42.48	0.970
5.15	1.128	1.000	1.064	-21.47	-21.55	-10.19	11.02	43.07	2.126	45.01	0.970
5.20	1.129	1.000	1.064	-21.44	-21.52	-10.14	11.04	48.33	2.126	47.68	0.969
5.25	1.129	1.000	1.064	-21.41	-21.49	-10.09	11.06	54.23	2.126	50.51	0.969
5.30	1.129	1.000	1.064	-21.38	-21.46	-10.04	11.08	60.86	2.126	53.50	0.969
5.35	1.129	1.000	1.064	-21.36	-21.44	-9.993	11.11	68.29	2.126	56.67	0.969
5.40	1.129	1.000	1.064	-21.40	-21.48	-9.943	11.20	76.63	2.126	60.03	0.969
5.45	1.130	1.000	1.064	-21.53	-21.61	-9.893	11.38	85.99	2.126	63.59	0.969
5.50	1.130	1.000	1.064	-21.75	-21.84	-9.843	11.65	96.49	2.126	67.37	0.969
5.55	1.130	1.000	1.064	-21.95	-22.03	-9.793	11.90	108.3	2.126	71.36	0.969
5.60	1.130	1.000	1.064	-22.07	-22.15	-9.743	12.07	121.5	2.126	75.59	0.969
5.65	1.130	1.000	1.064	-22.11	-22.19	-9.693	12.16	136.3	2.126	80.07	0.969
5.70	1.130	1.000	1.064	-22.12	-22.20	-9.643	12.22	152.9	2.126	84.81	0.969
5.75	1.130	1.000	1.064	-22.14	-22.22	-9.593	12.29	171.6	2.126	89.84	0.969
5.80	1.130	1.000	1.064	-22.20	-22.28	-9.543	12.40	192.5	2.126	95.16	0.969
5.85	1.130	1.000	1.064	-22.33	-22.41	-9.493	12.58	216.0	2.126	100.8	0.969
5.90	1.130	1.000	1.064	-22.45	-22.53	-9.443	12.75	242.4	2.126	106.8	0.969
5.95	1.130	1.000	1.064	-22.51	-22.59	-9.393	12.86	272.0	2.126	113.1	0.969
6.00	1.130	1.000	1.064	-22.55	-22.63	-9.343	12.95	305.2	2.126	119.8	0.969
6.05	1.130	1.000	1.064	-22.58	-22.66	-9.293	13.03	342.4	2.126	126.9	0.969
6.10	1.131	1.000	1.064	-22.60	-22.68	-9.242	13.10	384.2	2.126	134.4	0.969
6.15	1.131	1.000	1.064	-22.59	-22.67	-9.192	13.14	431.1	2.126	142.4	0.969
6.20	1.131	1.000	1.064	-22.59	-22.67	-9.142	13.19	483.7	2.126	150.8	0.969
6.25	1.131	1.000	1.064	-22.61	-22.69	-9.092	13.26	542.8	2.126	159.8	0.969
6.30	1.131	1.000	1.064	-22.67	-22.75	-9.042	13.37	609.0	2.126	169.2	0.969
6.35	1.131	1.000	1.064	-22.74	-22.82	-8.992	13.49	683.3	2.126	179.3	0.969
6.40	1.131	1.000	1.064	-22.80	-22.88	-8.942	13.60	766.7	2.126	189.9	0.969
6.45	1.131	1.000	1.064	-22.84	-22.92	-8.892	13.69	860.3	2.126	201.2	0.969
6.50	1.131	1.000	1.064	-22.87	-22.95	-8.842	13.77	965.3	2.126	213.1	0.968
6.55	1.131	1.000	1.064	-22.89	-22.98	-8.792	13.84	1083.1	2.126	225.7	0.968
6.60	1.131	1.000	1.064	-22.91	-22.99	-8.742	13.91	1215.3	2.126	239.1	0.968
6.65	1.131	1.000	1.064	-22.92	-23.00	-8.692	13.97	1363.6	2.126	253.2	0.968
6.70	1.131	1.000	1.064	-22.93	-23.01	-8.642	14.03	1530.0	2.126	268.3	0.968
6.75	1.131	1.000	1.064	-22.94	-23.02	-8.592	14.09	1716.7	2.126	284.2	0.968
6.80	1.131	1.000	1.064	-22.94	-23.02	-8.542	14.14	1926.2	2.126	301.0	0.968
6.85	1.131	1.000	1.064	-22.94	-23.02	-8.492	14.19	2161.3	2.126	318.8	0.968
6.90	1.131	1.000	1.064	-22.93	-23.01	-8.442	14.23	2425.0	2.126	337.7	0.968
6.95	1.131	1.000	1.064	-22.92	-23.00	-8.392	14.27	2720.9	2.126	357.7	0.968
7.00	1.131	1.000	1.064	-22.91	-22.99	-8.342	14.31	3052.9	2.126	378.9	0.968
7.05	1.131	1.000	1.064	-22.90	-22.98	-8.292	14.35	3425.5	2.126	401.4	0.968
7.10	1.131	1.000	1.064	-22.90	-22.98	-8.242	14.40	3843.4	2.126	425.2	0.968
7.15	1.131	1.000	1.064	-22.90	-22.98	-8.192	14.45	4312.4	2.126	450.4	0.968

TABLE A.6 : CIE ABUNDANCE SERIES, CONTINUED.

CIE COOLING CURVE : [Fe/H] = -1.0, CONT.

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.20	1.131	1.000	1.064	-22.89	-22.97	-8.142	14.49	4838.6	2.126	477.0	0.968
7.25	1.131	1.000	1.064	-22.88	-22.96	-8.092	14.53	5429.1	2.126	505.3	0.968
7.30	1.131	1.000	1.064	-22.87	-22.95	-8.042	14.57	6091.5	2.126	535.3	0.968
7.35	1.131	1.000	1.064	-22.85	-22.94	-7.992	14.60	6834.8	2.126	567.0	0.968
7.40	1.131	1.000	1.064	-22.84	-22.92	-7.942	14.64	7668.8	2.126	600.6	0.968
7.45	1.131	1.000	1.064	-22.82	-22.90	-7.892	14.67	8604.5	2.126	636.2	0.968
7.50	1.131	1.000	1.064	-22.81	-22.89	-7.842	14.71	9654.4	2.126	673.9	0.968
7.55	1.131	1.000	1.064	-22.79	-22.87	-7.792	14.74	10832.4	2.126	713.8	0.968
7.60	1.131	1.000	1.064	-22.77	-22.85	-7.742	14.77	12154.2	2.126	756.1	0.968
7.65	1.131	1.000	1.064	-22.75	-22.83	-7.692	14.80	13637.2	2.126	800.9	0.968
7.70	1.131	1.000	1.064	-22.73	-22.81	-7.642	14.83	15301.2	2.126	848.3	0.968
7.75	1.131	1.000	1.064	-22.71	-22.79	-7.592	14.86	17168.3	2.126	898.6	0.968
7.80	1.131	1.000	1.064	-22.69	-22.77	-7.542	14.89	19263.1	2.126	951.8	0.968
7.85	1.131	1.000	1.064	-22.67	-22.75	-7.492	14.92	21613.6	2.126	1008.2	0.968
7.90	1.131	1.000	1.064	-22.65	-22.73	-7.442	14.95	24250.9	2.126	1068.0	0.968
7.95	1.131	1.000	1.064	-22.62	-22.70	-7.392	14.97	27209.9	2.126	1131.3	0.968
8.00	1.131	1.000	1.064	-22.60	-22.68	-7.342	15.00	30530.1	2.126	1198.3	0.968
8.05	1.131	1.000	1.064	-22.58	-22.66	-7.292	15.03	34255.3	2.126	1269.3	0.968
8.10	1.131	1.000	1.064	-22.56	-22.64	-7.242	15.06	38435.1	2.126	1344.5	0.968
8.15	1.131	1.000	1.064	-22.54	-22.62	-7.192	15.09	43124.9	2.126	1424.2	0.968
8.20	1.131	1.000	1.064	-22.51	-22.60	-7.142	15.11	48387.0	2.126	1508.6	0.968
8.25	1.131	1.000	1.064	-22.49	-22.57	-7.092	15.14	54291.1	2.126	1598.0	0.968
8.30	1.131	1.000	1.064	-22.47	-22.55	-7.042	15.17	60915.6	2.126	1692.7	0.968
8.35	1.131	1.000	1.064	-22.45	-22.53	-6.992	15.20	68348.4	2.126	1792.9	0.968
8.40	1.131	1.000	1.064	-22.42	-22.51	-6.942	15.22	76688.2	2.126	1899.2	0.968
8.45	1.131	1.000	1.064	-22.40	-22.48	-6.892	15.25	86045.6	2.126	2011.7	0.968
8.50	1.131	1.000	1.064	-22.38	-22.46	-6.842	15.28	96544.8	2.126	2130.9	0.968

CIE COOLING CURVE : [Fe/H] = -1.5

Log(T) = 4.00 TO 8.50

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
4.00	0.0022	1.000	1.064	-26.00	-23.38	-11.66	11.69	1.483	2.118	8.368	1.986
4.05	0.0141	1.000	1.064	-24.66	-22.84	-11.60	11.20	1.682	2.118	8.913	1.964
4.10	0.0702	1.000	1.064	-23.52	-22.39	-11.53	10.81	1.986	2.118	9.683	1.867
4.15	0.2525	1.000	1.064	-22.62	-22.05	-11.41	10.52	2.586	2.118	11.05	1.609
4.20	0.5666	1.000	1.064	-22.11	-21.89	-11.27	10.41	3.594	2.118	13.03	1.299
4.25	0.8163	1.000	1.064	-21.97	-21.91	-11.16	10.47	4.650	2.118	14.82	1.127
4.30	0.9311	1.000	1.064	-22.01	-22.01	-11.08	10.62	5.535	2.118	16.16	1.062
4.35	0.9756	1.000	1.064	-22.11	-22.12	-11.02	10.79	6.349	2.118	17.31	1.039
4.40	0.9981	1.000	1.064	-22.20	-22.23	-10.97	10.94	7.203	2.119	18.44	1.027
4.45	1.021	1.000	1.064	-22.27	-22.30	-10.91	11.07	8.170	2.119	19.64	1.016
4.50	1.042	1.000	1.064	-22.31	-22.35	-10.86	11.17	9.263	2.119	20.91	1.006
4.55	1.055	1.000	1.064	-22.33	-22.38	-10.81	11.25	10.46	2.119	22.22	1.000
4.60	1.060	1.000	1.064	-22.34	-22.39	-10.76	11.31	11.76	2.119	23.56	0.997
4.65	1.063	1.000	1.064	-22.32	-22.37	-10.71	11.34	13.21	2.119	24.97	0.996
4.70	1.064	1.000	1.064	-22.26	-22.31	-10.66	11.33	14.83	2.119	26.46	0.996
4.75	1.066	1.000	1.064	-22.17	-22.23	-10.61	11.29	16.65	2.119	28.04	0.995
4.80	1.070	1.000	1.064	-22.06	-22.12	-10.55	11.23	18.73	2.119	29.73	0.992
4.85	1.082	1.000	1.064	-21.95	-22.01	-10.50	11.18	21.13	2.119	31.58	0.987
4.90	1.099	1.000	1.064	-21.88	-21.95	-10.45	11.16	23.89	2.119	33.58	0.979
4.95	1.113	1.000	1.064	-21.86	-21.94	-10.40	11.20	26.98	2.119	35.69	0.973
5.00	1.121	1.000	1.064	-21.88	-21.96	-10.34	11.27	30.39	2.119	37.87	0.970
5.05	1.125	1.000	1.064	-21.90	-21.98	-10.29	11.34	34.15	2.119	40.15	0.968
5.10	1.127	1.000	1.064	-21.91	-21.99	-10.24	11.41	38.35	2.119	42.55	0.967
5.15	1.128	1.000	1.064	-21.90	-21.98	-10.19	11.45	43.05	2.119	45.08	0.967
5.20	1.128	1.000	1.064	-21.88	-21.96	-10.14	11.48	48.31	2.119	47.75	0.967
5.25	1.128	1.000	1.064	-21.86	-21.94	-10.09	11.51	54.21	2.119	50.58	0.966
5.30	1.128	1.000	1.064	-21.85	-21.93	-10.04	11.55	60.83	2.119	53.58	0.966
5.35	1.128	1.000	1.064	-21.84	-21.92	-9.993	11.59	68.25	2.119	56.76	0.966
5.40	1.128	1.000	1.064	-21.87	-21.95	-9.943	11.67	76.58	2.119	60.12	0.966
5.45	1.128	1.000	1.064	-22.00	-22.08	-9.893	11.85	85.93	2.119	63.69	0.966
5.50	1.129	1.000	1.064	-22.21	-22.29	-9.843	12.11	96.42	2.119	67.46	0.966
5.55	1.129	1.000	1.064	-22.39	-22.47	-9.793	12.34	108.2	2.119	71.46	0.966

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.CIE COOLING CURVE : $[\text{Fe}/\text{H}] = -1.5$, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
5.60	1.129	1.000	1.064	-22.49	-22.57	-9.743	12.49	121.4	2.119	75.69	0.966
5.65	1.129	1.000	1.064	-22.54	-22.62	-9.693	12.59	136.2	2.119	80.18	0.966
5.70	1.129	1.000	1.064	-22.55	-22.63	-9.643	12.65	152.8	2.119	84.93	0.966
5.75	1.129	1.000	1.064	-22.56	-22.64	-9.593	12.71	171.5	2.119	89.96	0.966
5.80	1.129	1.000	1.064	-22.62	-22.70	-9.543	12.82	192.4	2.119	95.29	0.966
5.85	1.129	1.000	1.064	-22.73	-22.81	-9.493	12.98	215.9	2.119	100.9	0.966
5.90	1.129	1.000	1.064	-22.82	-22.90	-9.443	13.12	242.2	2.119	106.9	0.966
5.95	1.129	1.000	1.064	-22.86	-22.94	-9.393	13.21	271.8	2.119	113.3	0.966
6.00	1.129	1.000	1.064	-22.89	-22.97	-9.343	13.29	304.9	2.119	120.0	0.966
6.05	1.129	1.000	1.064	-22.92	-23.00	-9.293	13.37	342.1	2.119	127.1	0.966
6.10	1.129	1.000	1.064	-22.93	-23.01	-9.243	13.43	383.9	2.119	134.6	0.966
6.15	1.129	1.000	1.064	-22.93	-23.00	-9.193	13.48	430.7	2.119	142.6	0.966
6.20	1.129	1.000	1.064	-22.92	-23.00	-9.143	13.52	483.3	2.119	151.0	0.966
6.25	1.129	1.000	1.064	-22.93	-23.01	-9.093	13.58	542.2	2.119	160.0	0.966
6.30	1.129	1.000	1.064	-22.97	-23.04	-9.043	13.67	608.4	2.119	169.5	0.966
6.35	1.129	1.000	1.064	-23.01	-23.09	-8.993	13.76	682.7	2.119	179.5	0.966
6.40	1.129	1.000	1.064	-23.04	-23.12	-8.943	13.84	766.0	2.119	190.1	0.966
6.45	1.129	1.000	1.064	-23.06	-23.14	-8.893	13.91	859.4	2.119	201.4	0.966
6.50	1.129	1.000	1.064	-23.07	-23.15	-8.843	13.97	964.3	2.119	213.3	0.966
6.55	1.129	1.000	1.064	-23.07	-23.15	-8.793	14.02	1082.0	2.119	226.0	0.966
6.60	1.129	1.000	1.064	-23.07	-23.15	-8.743	14.07	1214.0	2.119	239.4	0.966
6.65	1.129	1.000	1.064	-23.07	-23.15	-8.693	14.12	1362.2	2.119	253.6	0.966
6.70	1.129	1.000	1.064	-23.07	-23.15	-8.643	14.17	1528.4	2.119	268.6	0.966
6.75	1.129	1.000	1.064	-23.06	-23.14	-8.593	14.21	1714.8	2.119	284.5	0.966
6.80	1.129	1.000	1.064	-23.05	-23.13	-8.543	14.25	1924.1	2.119	301.4	0.966
6.85	1.129	1.000	1.064	-23.04	-23.12	-8.493	14.29	2158.9	2.119	319.2	0.966
6.90	1.129	1.000	1.064	-23.02	-23.10	-8.443	14.32	2422.3	2.119	338.1	0.966
6.95	1.129	1.000	1.064	-23.01	-23.09	-8.393	14.36	2717.9	2.119	358.2	0.966
7.00	1.129	1.000	1.064	-23.00	-23.08	-8.343	14.40	3049.5	2.119	379.4	0.966
7.05	1.129	1.000	1.064	-22.98	-23.06	-8.293	14.43	3421.6	2.119	401.9	0.966
7.10	1.129	1.000	1.064	-22.97	-23.05	-8.243	14.47	3839.1	2.119	425.7	0.966
7.15	1.129	1.000	1.064	-22.96	-23.04	-8.193	14.51	4307.6	2.119	450.9	0.966
7.20	1.129	1.000	1.064	-22.94	-23.02	-8.143	14.54	4833.2	2.119	477.6	0.966
7.25	1.129	1.000	1.064	-22.93	-23.00	-8.093	14.58	5422.9	2.119	505.9	0.966
7.30	1.129	1.000	1.064	-22.91	-22.99	-8.043	14.61	6084.6	2.119	535.9	0.966
7.35	1.129	1.000	1.064	-22.89	-22.97	-7.993	14.64	6827.1	2.119	567.7	0.966
7.40	1.129	1.000	1.064	-22.87	-22.95	-7.943	14.67	7660.1	2.119	601.3	0.966
7.45	1.129	1.000	1.064	-22.85	-22.93	-7.893	14.70	8594.8	2.119	636.9	0.966
7.50	1.129	1.000	1.064	-22.83	-22.91	-7.843	14.73	9643.5	2.119	674.7	0.966
7.55	1.129	1.000	1.064	-22.81	-22.89	-7.793	14.76	10820.2	2.119	714.6	0.966
7.60	1.129	1.000	1.064	-22.79	-22.87	-7.743	14.79	12140.4	2.119	757.0	0.966
7.65	1.129	1.000	1.064	-22.77	-22.85	-7.693	14.82	13621.8	2.119	801.8	0.966
7.70	1.129	1.000	1.064	-22.75	-22.83	-7.643	14.85	15283.9	2.119	849.4	0.966
7.75	1.129	1.000	1.064	-22.73	-22.81	-7.593	14.88	17148.8	2.119	899.7	0.966
7.80	1.129	1.000	1.064	-22.70	-22.78	-7.543	14.90	19241.3	2.119	953.0	0.966
7.85	1.129	1.000	1.064	-22.68	-22.76	-7.493	14.93	21589.1	2.119	1009.5	0.966
7.90	1.129	1.000	1.064	-22.66	-22.74	-7.443	14.96	24223.4	2.119	1069.3	0.966
7.95	1.129	1.000	1.064	-22.64	-22.72	-7.393	14.99	27179.1	2.119	1132.6	0.966
8.00	1.129	1.000	1.064	-22.62	-22.70	-7.343	15.02	30495.4	2.119	1199.7	0.966
8.05	1.129	1.000	1.064	-22.59	-22.67	-7.293	15.04	34216.4	2.119	1270.8	0.966
8.10	1.129	1.000	1.064	-22.57	-22.65	-7.243	15.07	38391.5	2.119	1346.1	0.966
8.15	1.129	1.000	1.064	-22.55	-22.63	-7.193	15.10	43075.9	2.119	1425.9	0.966
8.20	1.129	1.000	1.064	-22.53	-22.61	-7.143	15.13	48332.0	2.119	1510.4	0.966
8.25	1.129	1.000	1.064	-22.50	-22.58	-7.093	15.15	54229.4	2.119	1599.9	0.966
8.30	1.129	1.000	1.064	-22.48	-22.56	-7.043	15.18	60846.4	2.119	1694.7	0.966
8.35	1.129	1.000	1.064	-22.46	-22.54	-6.993	15.21	68270.8	2.119	1795.1	0.966
8.40	1.129	1.000	1.064	-22.44	-22.52	-6.943	15.24	76601.1	2.119	1901.5	0.966
8.45	1.129	1.000	1.064	-22.41	-22.49	-6.893	15.26	85947.8	2.119	2014.1	0.966
8.50	1.129	1.000	1.064	-22.39	-22.47	-6.843	15.29	96435.1	2.119	2133.5	0.966

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.

CIE COOLING CURVE : [Fe/H] = -2.0
 Log(T) = 4.00 TO 8.50

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
4.00	0.0022	1.000	1.064	-26.03	-23.40	-11.66	11.72	1.483	2.115	8.372	1.984
4.05	0.0141	1.000	1.064	-24.68	-22.86	-11.60	11.22	1.682	2.115	8.917	1.962
4.10	0.0700	1.000	1.064	-23.53	-22.40	-11.53	10.82	1.985	2.115	9.687	1.865
4.15	0.2528	1.000	1.064	-22.63	-22.05	-11.41	10.53	2.586	2.115	11.06	1.607
4.20	0.5668	1.000	1.064	-22.12	-21.90	-11.27	10.42	3.594	2.116	13.03	1.297
4.25	0.8163	1.000	1.064	-21.98	-21.92	-11.16	10.48	4.649	2.116	14.82	1.125
4.30	0.9310	1.000	1.064	-22.02	-22.02	-11.08	10.63	5.535	2.116	16.17	1.061
4.35	0.9755	1.000	1.064	-22.12	-22.14	-11.02	10.80	6.349	2.116	17.32	1.038
4.40	0.9980	1.000	1.064	-22.23	-22.25	-10.97	10.97	7.202	2.116	18.45	1.026
4.45	1.020	1.000	1.064	-22.31	-22.34	-10.91	11.11	8.169	2.116	19.65	1.015
4.50	1.042	1.000	1.064	-22.37	-22.42	-10.86	11.23	9.262	2.116	20.92	1.005
4.55	1.055	1.000	1.064	-22.44	-22.49	-10.81	11.36	10.45	2.116	22.23	0.999
4.60	1.060	1.000	1.064	-22.49	-22.54	-10.76	11.46	11.76	2.116	23.57	0.996
4.65	1.062	1.000	1.064	-22.51	-22.56	-10.71	11.53	13.21	2.116	24.98	0.995
4.70	1.064	1.000	1.064	-22.49	-22.54	-10.66	11.56	14.83	2.116	26.47	0.995
4.75	1.065	1.000	1.064	-22.40	-22.46	-10.61	11.52	16.65	2.116	28.05	0.994
4.80	1.070	1.000	1.064	-22.27	-22.32	-10.55	11.44	18.73	2.116	29.75	0.991
4.85	1.082	1.000	1.064	-22.13	-22.19	-10.50	11.36	21.12	2.116	31.59	0.986
4.90	1.099	1.000	1.064	-22.05	-22.12	-10.45	11.33	23.89	2.116	33.60	0.978
4.95	1.113	1.000	1.064	-22.05	-22.12	-10.40	11.39	26.98	2.116	35.70	0.972
5.00	1.121	1.000	1.064	-22.10	-22.17	-10.34	11.49	30.38	2.116	37.89	0.969
5.05	1.125	1.000	1.064	-22.16	-22.24	-10.29	11.60	34.15	2.116	40.17	0.967
5.10	1.127	1.000	1.064	-22.21	-22.28	-10.24	11.71	38.35	2.116	42.57	0.966
5.15	1.127	1.000	1.064	-22.23	-22.31	-10.19	11.78	43.04	2.116	45.10	0.966
5.20	1.128	1.000	1.064	-22.25	-22.33	-10.14	11.85	48.30	2.116	47.77	0.966
5.25	1.128	1.000	1.064	-22.26	-22.33	-10.09	11.91	54.20	2.116	50.61	0.965
5.30	1.128	1.000	1.064	-22.26	-22.34	-10.04	11.96	60.81	2.116	53.61	0.965
5.35	1.128	1.000	1.064	-22.26	-22.34	-9.993	12.01	68.24	2.116	56.78	0.965
5.40	1.128	1.000	1.064	-22.30	-22.38	-9.943	12.10	76.57	2.116	60.15	0.965
5.45	1.128	1.000	1.064	-22.42	-22.50	-9.893	12.27	85.91	2.116	63.71	0.965
5.50	1.128	1.000	1.064	-22.59	-22.67	-9.843	12.49	96.39	2.116	67.49	0.965
5.55	1.128	1.000	1.064	-22.74	-22.81	-9.793	12.69	108.2	2.116	71.49	0.965
5.60	1.128	1.000	1.064	-22.82	-22.90	-9.743	12.82	121.4	2.116	75.73	0.965
5.65	1.128	1.000	1.064	-22.86	-22.94	-9.693	12.91	136.2	2.116	80.21	0.965
5.70	1.128	1.000	1.064	-22.87	-22.95	-9.643	12.97	152.8	2.116	84.97	0.965
5.75	1.128	1.000	1.064	-22.89	-22.97	-9.593	13.04	171.4	2.116	90.00	0.965
5.80	1.128	1.000	1.064	-22.93	-23.01	-9.543	13.13	192.3	2.116	95.33	0.965
5.85	1.128	1.000	1.064	-23.00	-23.08	-9.493	13.25	215.8	2.116	101.0	0.965
5.90	1.128	1.000	1.064	-23.06	-23.14	-9.443	13.36	242.1	2.116	107.0	0.965
5.95	1.128	1.000	1.064	-23.09	-23.17	-9.393	13.44	271.7	2.116	113.3	0.965
6.00	1.128	1.000	1.064	-23.10	-23.18	-9.343	13.50	304.8	2.116	120.0	0.965
6.05	1.128	1.000	1.064	-23.12	-23.20	-9.293	13.57	342.0	2.116	127.1	0.965
6.10	1.128	1.000	1.064	-23.12	-23.20	-9.243	13.62	383.8	2.116	134.7	0.965
6.15	1.128	1.000	1.064	-23.12	-23.20	-9.193	13.67	430.6	2.116	142.6	0.965
6.20	1.128	1.000	1.064	-23.12	-23.20	-9.143	13.72	483.1	2.116	151.1	0.965
6.25	1.128	1.000	1.064	-23.12	-23.20	-9.093	13.77	542.1	2.116	160.0	0.965
6.30	1.128	1.000	1.064	-23.13	-23.21	-9.043	13.83	608.2	2.116	169.5	0.965
6.35	1.128	1.000	1.064	-23.15	-23.23	-8.993	13.90	682.4	2.116	179.6	0.965
6.40	1.128	1.000	1.064	-23.16	-23.24	-8.943	13.96	765.7	2.116	190.2	0.965
6.45	1.128	1.000	1.064	-23.16	-23.24	-8.893	14.01	859.2	2.116	201.5	0.965
6.50	1.128	1.000	1.064	-23.16	-23.24	-8.843	14.06	964.0	2.116	213.4	0.965
6.55	1.128	1.000	1.064	-23.15	-23.23	-8.793	14.10	1081.6	2.116	226.1	0.965
6.60	1.128	1.000	1.064	-23.14	-23.22	-8.743	14.14	1213.6	2.116	239.5	0.965
6.65	1.128	1.000	1.064	-23.13	-23.21	-8.693	14.18	1361.7	2.116	253.7	0.965
6.70	1.128	1.000	1.064	-23.12	-23.20	-8.643	14.22	1527.8	2.116	268.7	0.965
6.75	1.128	1.000	1.064	-23.11	-23.19	-8.593	14.26	1714.3	2.116	284.6	0.965
6.80	1.128	1.000	1.064	-23.09	-23.17	-8.543	14.29	1923.4	2.116	301.5	0.965
6.85	1.128	1.000	1.064	-23.08	-23.16	-8.493	14.33	2158.1	2.116	319.3	0.965
6.90	1.128	1.000	1.064	-23.06	-23.14	-8.443	14.36	2421.5	2.116	338.3	0.965
6.95	1.128	1.000	1.064	-23.05	-23.13	-8.393	14.40	2716.9	2.116	358.3	0.965
7.00	1.128	1.000	1.064	-23.03	-23.11	-8.343	14.43	3048.4	2.116	379.5	0.965
7.05	1.128	1.000	1.064	-23.01	-23.09	-8.293	14.46	3420.4	2.116	402.0	0.965
7.10	1.128	1.000	1.064	-23.00	-23.07	-8.243	14.50	3837.8	2.116	425.8	0.965
7.15	1.128	1.000	1.064	-22.98	-23.06	-8.193	14.53	4306.0	2.116	451.1	0.965

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.CIE COOLING CURVE : $[\text{Fe}/\text{H}] = -2.0$, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
7.20	1.128	1.000	1.064	-22.96	-23.04	-8.143	14.56	4831.5	2.116	477.8	0.965
7.25	1.128	1.000	1.064	-22.94	-23.02	-8.093	14.59	5421.0	2.116	506.1	0.965
7.30	1.128	1.000	1.064	-22.92	-23.00	-8.043	14.62	6082.4	2.116	536.1	0.965
7.35	1.128	1.000	1.064	-22.90	-22.98	-7.993	14.65	6824.6	2.116	567.9	0.965
7.40	1.128	1.000	1.064	-22.88	-22.96	-7.943	14.68	7657.4	2.116	601.5	0.965
7.45	1.128	1.000	1.064	-22.86	-22.94	-7.893	14.71	8591.7	2.116	637.2	0.965
7.50	1.128	1.000	1.064	-22.84	-22.92	-7.843	14.74	9640.0	2.116	674.9	0.965
7.55	1.128	1.000	1.064	-22.82	-22.90	-7.793	14.77	10816.3	2.116	714.9	0.965
7.60	1.128	1.000	1.064	-22.80	-22.88	-7.743	14.80	12136.1	2.116	757.3	0.965
7.65	1.128	1.000	1.064	-22.78	-22.86	-7.693	14.83	13616.9	2.116	802.1	0.965
7.70	1.128	1.000	1.064	-22.75	-22.83	-7.643	14.85	15278.4	2.116	849.7	0.965
7.75	1.128	1.000	1.064	-22.73	-22.81	-7.593	14.88	17142.7	2.116	900.0	0.965
7.80	1.128	1.000	1.064	-22.71	-22.79	-7.543	14.91	19234.4	2.116	953.4	0.965
7.85	1.128	1.000	1.064	-22.69	-22.77	-7.493	14.94	21581.3	2.116	1009.8	0.965
7.90	1.128	1.000	1.064	-22.67	-22.75	-7.443	14.97	24214.7	2.116	1069.7	0.965
7.95	1.128	1.000	1.064	-22.64	-22.72	-7.393	14.99	27169.3	2.116	1133.1	0.965
8.00	1.128	1.000	1.064	-22.62	-22.70	-7.343	15.02	30484.5	2.116	1200.2	0.965
8.05	1.128	1.000	1.064	-22.60	-22.68	-7.293	15.05	34204.1	2.116	1271.3	0.965
8.10	1.128	1.000	1.064	-22.58	-22.66	-7.243	15.08	38377.7	2.116	1346.7	0.965
8.15	1.128	1.000	1.064	-22.55	-22.63	-7.193	15.10	43060.5	2.116	1426.4	0.965
8.20	1.128	1.000	1.064	-22.53	-22.61	-7.143	15.13	48314.6	2.116	1511.0	0.965
8.25	1.128	1.000	1.064	-22.51	-22.59	-7.093	15.16	54209.9	2.116	1600.5	0.965
8.30	1.128	1.000	1.064	-22.49	-22.56	-7.043	15.19	60824.5	2.116	1695.3	0.965
8.35	1.128	1.000	1.064	-22.46	-22.54	-6.993	15.21	68246.2	2.116	1795.8	0.965
8.40	1.128	1.000	1.064	-22.44	-22.52	-6.943	15.24	76573.5	2.116	1902.2	0.965
8.45	1.128	1.000	1.064	-22.42	-22.50	-6.893	15.27	85916.9	2.116	2014.9	0.965
8.50	1.128	1.000	1.064	-22.39	-22.47	-6.843	15.29	96400.4	2.116	2134.3	0.965

CIE COOLING CURVE : $[\text{Fe}/\text{H}] = -3.0$

Log(T) = 4.00 TO 8.50

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
4.00	0.0022	1.000	1.064	-26.04	-23.41	-11.66	11.73	1.479	2.114	8.365	1.987
4.05	0.0141	1.000	1.064	-24.69	-22.87	-11.60	11.23	1.682	2.114	8.919	1.961
4.10	0.0701	1.000	1.064	-23.53	-22.40	-11.53	10.82	1.985	2.114	9.690	1.864
4.15	0.2528	1.000	1.064	-22.63	-22.06	-11.41	10.53	2.586	2.114	11.06	1.606
4.20	0.5669	1.000	1.064	-22.12	-21.90	-11.27	10.42	3.594	2.115	13.04	1.297
4.25	0.8163	1.000	1.064	-21.98	-21.92	-11.16	10.48	4.649	2.115	14.83	1.125
4.30	0.9310	1.000	1.064	-22.03	-22.02	-11.08	10.64	5.535	2.115	16.18	1.060
4.35	0.9755	1.000	1.064	-22.13	-22.15	-11.02	10.81	6.349	2.115	17.32	1.037
4.40	0.9980	1.000	1.064	-22.24	-22.26	-10.97	10.98	7.202	2.115	18.45	1.026
4.45	1.020	1.000	1.064	-22.33	-22.36	-10.91	11.13	8.169	2.115	19.65	1.015
4.50	1.042	1.000	1.064	-22.40	-22.45	-10.86	11.26	9.261	2.115	20.92	1.004
4.55	1.055	1.000	1.064	-22.49	-22.54	-10.81	11.41	10.45	2.115	22.23	0.998
4.60	1.060	1.000	1.064	-22.57	-22.62	-10.76	11.54	11.76	2.115	23.58	0.996
4.65	1.062	1.000	1.064	-22.63	-22.68	-10.71	11.65	13.21	2.115	24.99	0.995
4.70	1.064	1.000	1.064	-22.63	-22.69	-10.66	11.70	14.83	2.115	26.48	0.994
4.75	1.065	1.000	1.064	-22.55	-22.61	-10.61	11.67	16.65	2.115	28.06	0.993
4.80	1.070	1.000	1.064	-22.39	-22.45	-10.55	11.56	18.73	2.115	29.75	0.991
4.85	1.082	1.000	1.064	-22.23	-22.29	-10.50	11.46	21.12	2.115	31.60	0.986
4.90	1.099	1.000	1.064	-22.15	-22.21	-10.45	11.43	23.89	2.115	33.60	0.978
4.95	1.113	1.000	1.064	-22.16	-22.23	-10.40	11.50	26.98	2.115	35.71	0.972
5.00	1.121	1.000	1.064	-22.24	-22.31	-10.34	11.63	30.38	2.115	37.90	0.968
5.05	1.125	1.000	1.064	-22.33	-22.41	-10.29	11.77	34.15	2.115	40.18	0.966
5.10	1.126	1.000	1.064	-22.43	-22.51	-10.24	11.92	38.34	2.115	42.58	0.966
5.15	1.127	1.000	1.064	-22.52	-22.60	-10.19	12.07	43.04	2.115	45.11	0.965
5.20	1.128	1.000	1.064	-22.60	-22.67	-10.14	12.20	48.30	2.115	47.78	0.965
5.25	1.128	1.000	1.064	-22.66	-22.74	-10.09	12.31	54.20	2.115	50.62	0.965
5.30	1.128	1.000	1.064	-22.72	-22.80	-10.04	12.42	60.81	2.115	53.62	0.965
5.35	1.128	1.000	1.064	-22.77	-22.85	-9.993	12.52	68.23	2.115	56.80	0.965
5.40	1.128	1.000	1.064	-22.82	-22.90	-9.943	12.62	76.56	2.115	60.16	0.965
5.45	1.128	1.000	1.064	-22.90	-22.98	-9.893	12.75	85.90	2.115	63.73	0.965
5.50	1.128	1.000	1.064	-22.98	-23.06	-9.843	12.88	96.38	2.115	67.50	0.965
5.55	1.128	1.000	1.064	-23.04	-23.12	-9.793	12.99	108.1	2.115	71.50	0.965

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.CIE COOLING CURVE : $[\text{Fe}/\text{H}] = -3.0$, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_1	$\bar{\mu}_{24}$
5.60	1.128	1.000	1.064	-23.08	-23.16	-9.743	13.08	121.3	2.115	75.74	0.965
5.65	1.128	1.000	1.064	-23.12	-23.20	-9.693	13.17	136.1	2.115	80.23	0.965
5.70	1.128	1.000	1.064	-23.14	-23.22	-9.643	13.24	152.8	2.115	84.98	0.965
5.75	1.128	1.000	1.064	-23.16	-23.24	-9.593	13.31	171.4	2.115	90.02	0.965
5.80	1.128	1.000	1.064	-23.18	-23.26	-9.543	13.38	192.3	2.115	95.35	0.965
5.85	1.128	1.000	1.064	-23.20	-23.28	-9.493	13.45	215.8	2.115	101.0	0.965
5.90	1.128	1.000	1.064	-23.22	-23.30	-9.443	13.52	242.1	2.115	107.0	0.965
5.95	1.128	1.000	1.064	-23.23	-23.31	-9.393	13.58	271.7	2.115	113.3	0.965
6.00	1.128	1.000	1.064	-23.23	-23.31	-9.343	13.63	304.8	2.115	120.0	0.965
6.05	1.128	1.000	1.064	-23.24	-23.32	-9.293	13.69	342.0	2.115	127.2	0.965
6.10	1.128	1.000	1.064	-23.24	-23.32	-9.243	13.74	383.7	2.115	134.7	0.965
6.15	1.128	1.000	1.064	-23.23	-23.31	-9.193	13.78	430.5	2.115	142.7	0.965
6.20	1.128	1.000	1.064	-23.23	-23.31	-9.143	13.83	483.1	2.115	151.1	0.965
6.25	1.128	1.000	1.064	-23.23	-23.31	-9.093	13.88	542.0	2.115	160.1	0.965
6.30	1.128	1.000	1.064	-23.22	-23.30	-9.043	13.92	608.2	2.115	169.6	0.965
6.35	1.128	1.000	1.064	-23.23	-23.30	-8.993	13.98	682.4	2.115	179.6	0.965
6.40	1.128	1.000	1.064	-23.22	-23.30	-8.943	14.02	765.6	2.115	190.2	0.965
6.45	1.128	1.000	1.064	-23.21	-23.29	-8.893	14.06	859.0	2.115	201.5	0.965
6.50	1.128	1.000	1.064	-23.20	-23.28	-8.843	14.10	963.9	2.115	213.5	0.965
6.55	1.128	1.000	1.064	-23.19	-23.26	-8.793	14.14	1081.5	2.115	226.1	0.965
6.60	1.128	1.000	1.064	-23.17	-23.25	-8.743	14.17	1213.4	2.115	239.5	0.965
6.65	1.128	1.000	1.064	-23.16	-23.24	-8.693	14.21	1361.5	2.115	253.7	0.965
6.70	1.128	1.000	1.064	-23.14	-23.22	-8.643	14.24	1527.6	2.115	268.7	0.965
6.75	1.128	1.000	1.064	-23.13	-23.21	-8.593	14.28	1714.0	2.115	284.7	0.965
6.80	1.128	1.000	1.064	-23.11	-23.19	-8.543	14.31	1923.2	2.115	301.5	0.965
6.85	1.128	1.000	1.064	-23.09	-23.17	-8.493	14.34	2157.8	2.115	319.4	0.965
6.90	1.128	1.000	1.064	-23.08	-23.16	-8.443	14.38	2421.1	2.115	338.3	0.965
6.95	1.128	1.000	1.064	-23.06	-23.14	-8.393	14.41	2716.5	2.115	358.4	0.965
7.00	1.128	1.000	1.064	-23.04	-23.12	-8.343	14.44	3048.0	2.115	379.6	0.965
7.05	1.128	1.000	1.064	-23.03	-23.10	-8.293	14.48	3419.9	2.115	402.1	0.965
7.10	1.128	1.000	1.064	-23.01	-23.09	-8.243	14.51	3837.2	2.115	425.9	0.965
7.15	1.128	1.000	1.064	-22.99	-23.07	-8.193	14.54	4305.4	2.115	451.2	0.965
7.20	1.128	1.000	1.064	-22.97	-23.05	-8.143	14.57	4830.7	2.115	477.9	0.965
7.25	1.128	1.000	1.064	-22.95	-23.03	-8.093	14.60	5420.2	2.115	506.2	0.965
7.30	1.128	1.000	1.064	-22.93	-23.01	-8.043	14.63	6081.5	2.115	536.2	0.965
7.35	1.128	1.000	1.064	-22.91	-22.99	-7.993	14.66	6823.6	2.115	568.0	0.965
7.40	1.128	1.000	1.064	-22.89	-22.96	-7.943	14.69	7656.2	2.115	601.6	0.965
7.45	1.128	1.000	1.064	-22.86	-22.94	-7.893	14.71	8590.4	2.115	637.3	0.965
7.50	1.128	1.000	1.064	-22.84	-22.92	-7.843	14.74	9638.6	2.115	675.0	0.965
7.55	1.128	1.000	1.064	-22.82	-22.90	-7.793	14.77	10814.7	2.115	715.0	0.965
7.60	1.128	1.000	1.064	-22.80	-22.88	-7.743	14.80	12134.3	2.115	757.4	0.965
7.65	1.128	1.000	1.064	-22.78	-22.86	-7.693	14.83	13614.9	2.115	802.3	0.965
7.70	1.128	1.000	1.064	-22.76	-22.84	-7.643	14.86	15276.1	2.115	849.8	0.965
7.75	1.128	1.000	1.064	-22.73	-22.81	-7.593	14.88	17140.1	2.115	900.2	0.965
7.80	1.128	1.000	1.064	-22.71	-22.79	-7.543	14.91	19231.5	2.115	953.5	0.965
7.85	1.128	1.000	1.064	-22.69	-22.77	-7.493	14.94	21578.1	2.115	1010.0	0.965
7.90	1.128	1.000	1.064	-22.67	-22.75	-7.443	14.97	24211.0	2.115	1069.8	0.965
7.95	1.128	1.000	1.064	-22.65	-22.73	-7.393	15.00	27165.2	2.115	1133.2	0.965
8.00	1.128	1.000	1.064	-22.62	-22.70	-7.343	15.02	30479.9	2.115	1200.4	0.965
8.05	1.128	1.000	1.064	-22.60	-22.68	-7.293	15.05	34199.0	2.115	1271.5	0.965
8.10	1.128	1.000	1.064	-22.58	-22.66	-7.243	15.08	38371.9	2.115	1346.9	0.965
8.15	1.128	1.000	1.064	-22.56	-22.63	-7.193	15.11	43054.0	2.115	1426.7	0.965
8.20	1.128	1.000	1.064	-22.53	-22.61	-7.143	15.13	48307.4	2.115	1511.2	0.965
8.25	1.128	1.000	1.064	-22.51	-22.59	-7.093	15.16	54201.8	2.115	1600.8	0.965
8.30	1.128	1.000	1.064	-22.49	-22.57	-7.043	15.19	60815.4	2.115	1695.6	0.965
8.35	1.128	1.000	1.064	-22.46	-22.54	-6.993	15.21	68236.0	2.115	1796.1	0.965
8.40	1.128	1.000	1.064	-22.44	-22.52	-6.943	15.24	76562.1	2.115	1902.5	0.965
8.45	1.128	1.000	1.064	-22.42	-22.50	-6.893	15.27	85904.0	2.115	2015.2	0.965
8.50	1.128	1.000	1.064	-22.39	-22.47	-6.843	15.29	96385.9	2.115	2134.6	0.965

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.

CIE COOLING CURVE : [Fe/H] = NIL, ZERO METALS.

LOG(T) = 4.00 TO 8.50

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
4.00	0.0022	1.000	1.064	-26.04	-23.41	-11.66	11.73	1.483	2.114	8.374	1.983
4.05	0.0141	1.000	1.064	-24.69	-22.87	-11.60	11.23	1.682	2.114	8.919	1.961
4.10	0.0701	1.000	1.064	-23.53	-22.40	-11.53	10.82	1.985	2.114	9.690	1.864
4.15	0.2528	1.000	1.064	-22.63	-22.06	-11.41	10.53	2.586	2.114	11.06	1.606
4.20	0.5669	1.000	1.064	-22.12	-21.90	-11.27	10.42	3.594	2.115	13.04	1.297
4.25	0.8163	1.000	1.064	-21.98	-21.92	-11.16	10.48	4.649	2.115	14.83	1.125
4.30	0.9310	1.000	1.064	-22.03	-22.02	-11.08	10.64	5.535	2.115	16.18	1.060
4.35	0.9755	1.000	1.064	-22.13	-22.15	-11.02	10.81	6.349	2.115	17.33	1.037
4.40	0.9980	1.000	1.064	-22.24	-22.26	-10.97	10.98	7.202	2.115	18.45	1.026
4.45	1.020	1.000	1.064	-22.33	-22.36	-10.91	11.13	8.169	2.115	19.65	1.015
4.50	1.042	1.000	1.064	-22.41	-22.45	-10.86	11.27	9.261	2.115	20.93	1.004
4.55	1.055	1.000	1.064	-22.49	-22.54	-10.81	11.41	10.45	2.115	22.23	0.998
4.60	1.060	1.000	1.064	-22.58	-22.63	-10.76	11.55	11.76	2.115	23.58	0.996
4.65	1.062	1.000	1.064	-22.64	-22.70	-10.71	11.66	13.21	2.115	24.99	0.995
4.70	1.064	1.000	1.064	-22.65	-22.71	-10.66	11.72	14.83	2.115	26.48	0.994
4.75	1.065	1.000	1.064	-22.57	-22.63	-10.61	11.69	16.65	2.115	28.06	0.993
4.80	1.070	1.000	1.064	-22.41	-22.47	-10.55	11.58	18.73	2.115	29.75	0.991
4.85	1.082	1.000	1.064	-22.24	-22.30	-10.50	11.47	21.12	2.115	31.60	0.986
4.90	1.099	1.000	1.064	-22.16	-22.23	-10.45	11.44	23.89	2.115	33.61	0.978
4.95	1.113	1.000	1.064	-22.17	-22.25	-10.40	11.51	26.98	2.115	35.71	0.972
5.00	1.121	1.000	1.064	-22.25	-22.33	-10.34	11.64	30.38	2.115	37.90	0.968
5.05	1.125	1.000	1.064	-22.36	-22.44	-10.29	11.80	34.15	2.115	40.18	0.966
5.10	1.126	1.000	1.064	-22.46	-22.54	-10.24	11.95	38.34	2.115	42.58	0.966
5.15	1.127	1.000	1.064	-22.56	-22.64	-10.19	12.11	43.04	2.115	45.11	0.965
5.20	1.128	1.000	1.064	-22.66	-22.74	-10.14	12.26	48.30	2.115	47.78	0.965
5.25	1.128	1.000	1.064	-22.74	-22.82	-10.09	12.39	54.19	2.115	50.62	0.965
5.30	1.128	1.000	1.064	-22.82	-22.90	-10.04	12.52	60.81	2.115	53.62	0.965
5.35	1.128	1.000	1.064	-22.89	-22.97	-9.993	12.64	68.23	2.115	56.80	0.965
5.40	1.128	1.000	1.064	-22.95	-23.03	-9.943	12.75	76.56	2.115	60.16	0.965
5.45	1.128	1.000	1.064	-23.01	-23.08	-9.893	12.86	85.90	2.115	63.73	0.965
5.50	1.128	1.000	1.064	-23.05	-23.13	-9.843	12.95	96.38	2.115	67.50	0.965
5.55	1.128	1.000	1.064	-23.09	-23.17	-9.793	13.04	108.1	2.115	71.50	0.965
5.60	1.128	1.000	1.064	-23.13	-23.21	-9.743	13.13	121.3	2.115	75.74	0.965
5.65	1.128	1.000	1.064	-23.16	-23.24	-9.693	13.21	136.1	2.115	80.23	0.965
5.70	1.128	1.000	1.064	-23.18	-23.26	-9.643	13.28	152.8	2.115	84.98	0.965
5.75	1.128	1.000	1.064	-23.20	-23.28	-9.593	13.35	171.4	2.115	90.02	0.965
5.80	1.128	1.000	1.064	-23.22	-23.30	-9.543	13.42	192.3	2.115	95.35	0.965
5.85	1.128	1.000	1.064	-23.23	-23.31	-9.493	13.48	215.8	2.115	101.0	0.965
5.90	1.128	1.000	1.064	-23.24	-23.32	-9.443	13.54	242.1	2.115	107.0	0.965
5.95	1.128	1.000	1.064	-23.25	-23.33	-9.393	13.60	271.6	2.115	113.3	0.965
6.00	1.128	1.000	1.064	-23.25	-23.33	-9.343	13.65	304.8	2.115	120.0	0.965
6.05	1.128	1.000	1.064	-23.25	-23.33	-9.293	13.70	342.0	2.115	127.2	0.965
6.10	1.128	1.000	1.064	-23.25	-23.33	-9.243	13.75	383.7	2.115	134.7	0.965
6.15	1.128	1.000	1.064	-23.25	-23.33	-9.193	13.80	430.5	2.115	142.7	0.965
6.20	1.128	1.000	1.064	-23.25	-23.32	-9.143	13.85	483.1	2.115	151.1	0.965
6.25	1.128	1.000	1.064	-23.24	-23.32	-9.093	13.89	542.0	2.115	160.1	0.965
6.30	1.128	1.000	1.064	-23.23	-23.31	-9.043	13.93	608.1	2.115	169.6	0.965
6.35	1.128	1.000	1.064	-23.23	-23.31	-8.993	13.98	682.3	2.115	179.6	0.965
6.40	1.128	1.000	1.064	-23.23	-23.30	-8.943	14.03	765.6	2.115	190.3	0.965
6.45	1.128	1.000	1.064	-23.21	-23.29	-8.893	14.06	859.0	2.115	201.5	0.965
6.50	1.128	1.000	1.064	-23.20	-23.28	-8.843	14.10	963.8	2.115	213.5	0.965
6.55	1.128	1.000	1.064	-23.19	-23.27	-8.793	14.14	1081.4	2.115	226.1	0.965
6.60	1.128	1.000	1.064	-23.18	-23.25	-8.743	14.18	1213.4	2.115	239.5	0.965
6.65	1.128	1.000	1.064	-23.16	-23.24	-8.693	14.21	1361.5	2.115	253.7	0.965
6.70	1.128	1.000	1.064	-23.15	-23.22	-8.643	14.25	1527.6	2.115	268.7	0.965
6.75	1.128	1.000	1.064	-23.13	-23.21	-8.593	14.28	1714.0	2.115	284.7	0.965
6.80	1.128	1.000	1.064	-23.11	-23.19	-8.543	14.31	1923.1	2.115	301.5	0.965
6.85	1.128	1.000	1.064	-23.10	-23.17	-8.493	14.35	2157.8	2.115	319.4	0.965
6.90	1.128	1.000	1.064	-23.08	-23.16	-8.443	14.38	2421.1	2.115	338.3	0.965
6.95	1.128	1.000	1.064	-23.06	-23.14	-8.393	14.41	2716.5	2.115	358.4	0.965
7.00	1.128	1.000	1.064	-23.05	-23.12	-8.343	14.45	3047.9	2.115	379.6	0.965
7.05	1.128	1.000	1.064	-23.03	-23.11	-8.293	14.48	3419.8	2.115	402.1	0.965
7.10	1.128	1.000	1.064	-23.01	-23.09	-8.243	14.51	3837.1	2.115	425.9	0.965
7.15	1.128	1.000	1.064	-22.99	-23.07	-8.193	14.54	4305.3	2.115	451.2	0.965

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.

CIE COOLING CURVE : $[\text{Fe}/\text{H}] = \text{ZERO METALS}$, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	p_{24}	C_i	$\bar{\mu}_{24}$
7.20	1.128	1.000	1.064	-22.97	-23.05	-8.143	14.57	4830.7	2.115	477.9	0.965
7.25	1.128	1.000	1.064	-22.95	-23.03	-8.093	14.60	5420.1	2.115	506.2	0.965
7.30	1.128	1.000	1.064	-22.93	-23.01	-8.043	14.63	6081.4	2.115	536.2	0.965
7.35	1.128	1.000	1.064	-22.91	-22.99	-7.993	14.66	6823.5	2.115	568.0	0.965
7.40	1.128	1.000	1.064	-22.89	-22.96	-7.943	14.69	7656.1	2.115	601.6	0.965
7.45	1.128	1.000	1.064	-22.86	-22.94	-7.893	14.71	8590.3	2.115	637.3	0.965
7.50	1.128	1.000	1.064	-22.84	-22.92	-7.843	14.74	9638.4	2.115	675.0	0.965
7.55	1.128	1.000	1.064	-22.82	-22.90	-7.793	14.77	10814.5	2.115	715.0	0.965
7.60	1.128	1.000	1.064	-22.80	-22.88	-7.743	14.80	12134.1	2.115	757.4	0.965
7.65	1.128	1.000	1.064	-22.78	-22.86	-7.693	14.83	13614.6	2.115	802.3	0.965
7.70	1.128	1.000	1.064	-22.76	-22.84	-7.643	14.86	15275.9	2.115	849.8	0.965
7.75	1.128	1.000	1.064	-22.74	-22.81	-7.593	14.89	17139.8	2.115	900.2	0.965
7.80	1.128	1.000	1.064	-22.71	-22.79	-7.543	14.91	19231.2	2.115	953.5	0.965
7.85	1.128	1.000	1.064	-22.69	-22.77	-7.493	14.94	21577.8	2.115	1010.0	0.965
7.90	1.128	1.000	1.064	-22.67	-22.75	-7.443	14.97	24210.6	2.115	1069.9	0.965
7.95	1.128	1.000	1.064	-22.65	-22.73	-7.393	15.00	27164.8	2.115	1133.3	0.965
8.00	1.128	1.000	1.064	-22.62	-22.70	-7.343	15.02	30479.4	2.115	1200.4	0.965
8.05	1.128	1.000	1.064	-22.60	-22.68	-7.293	15.05	34198.4	2.115	1271.5	0.965
8.10	1.128	1.000	1.064	-22.58	-22.66	-7.243	15.08	38371.3	2.115	1346.9	0.965
8.15	1.128	1.000	1.064	-22.56	-22.63	-7.193	15.11	43053.3	2.115	1426.7	0.965
8.20	1.128	1.000	1.064	-22.53	-22.61	-7.143	15.13	48306.6	2.115	1511.2	0.965
8.25	1.128	1.000	1.064	-22.51	-22.59	-7.093	15.16	54200.9	2.115	1600.8	0.965
8.30	1.128	1.000	1.064	-22.49	-22.57	-7.043	15.19	60814.4	2.115	1695.6	0.965
8.35	1.128	1.000	1.064	-22.46	-22.54	-6.993	15.21	68234.9	2.115	1796.1	0.965
8.40	1.128	1.000	1.064	-22.44	-22.52	-6.943	15.24	76560.8	2.115	1902.5	0.965
8.45	1.128	1.000	1.064	-22.42	-22.50	-6.893	15.27	85902.6	2.115	2015.3	0.965
8.50	1.128	1.000	1.064	-22.39	-22.47	-6.843	15.29	96384.3	2.115	2134.7	0.965

CIE COOLING CURVE : $[\text{Fe}/\text{H}] = +0.5$

Log(T) = 4.00 TO 8.50

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	p_{24}	C_i	$\bar{\mu}_{24}$
4.10	0.0711	1.000	1.103	-22.98	-21.88	-11.51	10.29	2.055	2.486	9.092	2.117
4.15	0.2547	1.000	1.103	-22.26	-21.71	-11.40	10.17	2.666	2.486	10.36	1.831
4.20	0.5700	1.000	1.103	-21.80	-21.60	-11.26	10.11	3.686	2.486	12.18	1.486
4.25	0.8202	1.000	1.103	-21.64	-21.60	-11.15	10.16	4.755	2.486	13.83	1.293
4.30	0.9356	1.000	1.103	-21.61	-21.62	-11.07	10.24	5.655	2.487	15.08	1.220
4.35	0.9812	1.000	1.103	-21.57	-21.60	-11.01	10.27	6.487	2.487	16.15	1.193
4.40	1.008	1.000	1.103	-21.48	-21.53	-10.96	10.24	7.371	2.487	17.22	1.178
4.45	1.039	1.000	1.103	-21.36	-21.42	-10.90	10.19	8.393	2.487	18.37	1.161
4.50	1.071	1.000	1.103	-21.22	-21.30	-10.85	10.11	9.559	2.487	19.61	1.144
4.55	1.090	1.000	1.103	-21.09	-21.17	-10.79	10.04	10.82	2.487	20.86	1.134
4.60	1.098	1.000	1.103	-20.97	-21.05	-10.74	9.969	12.19	2.487	22.14	1.130
4.65	1.102	1.000	1.103	-20.86	-20.94	-10.69	9.911	13.69	2.487	23.47	1.128
4.70	1.104	1.000	1.103	-20.75	-20.83	-10.64	9.852	15.38	2.487	24.87	1.127
4.75	1.107	1.000	1.103	-20.65	-20.74	-10.59	9.803	17.28	2.487	26.36	1.125
4.80	1.116	1.000	1.103	-20.57	-20.66	-10.54	9.776	19.46	2.487	27.98	1.121
4.85	1.134	1.000	1.103	-20.50	-20.59	-10.48	9.763	22.02	2.487	29.76	1.112
4.90	1.160	1.000	1.103	-20.43	-20.54	-10.43	9.753	25.00	2.487	31.71	1.099
4.95	1.183	1.000	1.103	-20.39	-20.50	-10.37	9.772	28.33	2.487	33.75	1.088
5.00	1.197	1.000	1.103	-20.39	-20.51	-10.32	9.827	31.97	2.487	35.86	1.082
5.05	1.204	1.000	1.103	-20.42	-20.54	-10.27	9.909	35.99	2.487	38.04	1.078
5.10	1.208	1.000	1.103	-20.42	-20.55	-10.22	9.961	40.44	2.487	40.33	1.076
5.15	1.210	1.000	1.103	-20.40	-20.52	-10.17	9.992	45.42	2.487	42.74	1.075
5.20	1.211	1.000	1.103	-20.37	-20.49	-10.12	10.01	50.99	2.487	45.28	1.075
5.25	1.212	1.000	1.103	-20.35	-20.48	-10.07	10.04	57.24	2.487	47.98	1.074
5.30	1.213	1.000	1.103	-20.34	-20.47	-10.02	10.08	64.26	2.487	50.83	1.074
5.35	1.215	1.000	1.103	-20.34	-20.46	-9.969	10.13	72.14	2.487	53.86	1.073
5.40	1.216	1.000	1.103	-20.37	-20.50	-9.919	10.21	81.00	2.487	57.07	1.072
5.45	1.219	1.000	1.103	-20.51	-20.63	-9.868	10.40	90.97	2.487	60.48	1.071
5.50	1.221	1.000	1.103	-20.73	-20.86	-9.818	10.68	102.20	2.487	64.09	1.070
5.55	1.221	1.000	1.103	-20.93	-21.06	-9.768	10.93	114.70	2.487	67.91	1.070
5.60	1.222	1.000	1.103	-21.05	-21.18	-9.717	11.10	128.70	2.487	71.94	1.070
5.65	1.222	1.000	1.103	-21.09	-21.22	-9.667	11.19	144.4	2.487	76.21	1.069

TABLE A.6 : CIE ABUNDANCE SERIES, *CONTINUED*.

CIE COOLING CURVE : $[\text{Fe}/\text{H}] = +0.5$, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
5.70	1.223	1.000	1.103	-21.09	-21.22	-9.617	11.24	162.1	2.487	80.73	1.069
5.75	1.223	1.000	1.103	-21.09	-21.22	-9.567	11.29	181.9	2.487	85.52	1.069
5.80	1.224	1.000	1.103	-21.14	-21.27	-9.517	11.39	204.1	2.487	90.60	1.069
5.85	1.224	1.000	1.103	-21.24	-21.38	-9.467	11.54	229.1	2.487	95.98	1.069
5.90	1.225	1.000	1.103	-21.32	-21.45	-9.417	11.67	257.1	2.487	101.70	1.068
5.95	1.226	1.000	1.103	-21.34	-21.47	-9.367	11.74	288.5	2.487	107.7	1.068
6.00	1.226	1.000	1.103	-21.35	-21.48	-9.317	11.80	323.8	2.487	114.1	1.068
6.05	1.227	1.000	1.103	-21.35	-21.48	-9.266	11.85	363.4	2.487	120.9	1.067
6.10	1.227	1.000	1.103	-21.34	-21.47	-9.216	11.89	407.9	2.487	128.1	1.067
6.15	1.228	1.000	1.103	-21.33	-21.46	-9.166	11.93	457.9	2.487	135.7	1.067
6.20	1.229	1.000	1.103	-21.32	-21.46	-9.116	11.97	513.9	2.487	143.8	1.066
6.25	1.230	1.000	1.103	-21.35	-21.49	-9.066	12.05	576.8	2.487	152.3	1.066
6.30	1.231	1.000	1.103	-21.46	-21.59	-9.016	12.21	647.5	2.487	161.4	1.066
6.35	1.232	1.000	1.103	-21.59	-21.73	-8.966	12.39	726.8	2.487	171.0	1.065
6.40	1.233	1.000	1.103	-21.71	-21.85	-8.915	12.56	815.8	2.487	181.1	1.065
6.45	1.234	1.000	1.103	-21.80	-21.94	-8.865	12.70	915.7	2.487	191.9	1.064
6.50	1.234	1.000	1.103	-21.86	-22.00	-8.815	12.81	1027.7	2.487	203.3	1.064
6.55	1.235	1.000	1.103	-21.90	-22.03	-8.765	12.90	1153.3	2.487	215.4	1.064
6.60	1.235	1.000	1.103	-21.93	-22.07	-8.715	12.98	1294.3	2.487	228.1	1.064
6.65	1.236	1.000	1.103	-21.96	-22.10	-8.665	13.06	1452.5	2.487	241.7	1.063
6.70	1.236	1.000	1.103	-22.00	-22.14	-8.615	13.15	1629.9	2.487	256.0	1.063
6.75	1.236	1.000	1.103	-22.04	-22.17	-8.565	13.24	1829.0	2.487	271.2	1.063
6.80	1.237	1.000	1.103	-22.06	-22.20	-8.515	13.31	2052.3	2.487	287.3	1.063
6.85	1.237	1.000	1.103	-22.06	-22.20	-8.465	13.36	2303.0	2.487	304.3	1.063
6.90	1.237	1.000	1.103	-22.05	-22.18	-8.415	13.40	2584.2	2.487	322.4	1.063
6.95	1.237	1.000	1.103	-22.04	-22.17	-8.365	13.44	2899.7	2.487	341.5	1.063
7.00	1.237	1.000	1.103	-22.04	-22.17	-8.315	13.49	3253.8	2.487	361.7	1.063
7.05	1.237	1.000	1.103	-22.06	-22.20	-8.265	13.56	3651.2	2.487	383.2	1.063
7.10	1.238	1.000	1.103	-22.11	-22.24	-8.214	13.66	4097.0	2.487	405.9	1.063
7.15	1.238	1.000	1.103	-22.16	-22.30	-8.164	13.76	4597.2	2.487	430.0	1.062
7.20	1.238	1.000	1.103	-22.21	-22.35	-8.114	13.86	5158.4	2.487	455.4	1.062
7.25	1.238	1.000	1.103	-22.26	-22.40	-8.064	13.96	5788.0	2.487	482.4	1.062
7.30	1.238	1.000	1.103	-22.30	-22.43	-8.014	14.05	6494.4	2.487	511.0	1.062
7.35	1.238	1.000	1.103	-22.32	-22.46	-7.964	14.12	7287.0	2.487	541.3	1.062
7.40	1.238	1.000	1.103	-22.35	-22.48	-7.914	14.20	8176.3	2.487	573.4	1.062
7.45	1.238	1.000	1.103	-22.36	-22.49	-7.864	14.26	9174.0	2.487	607.4	1.062
7.50	1.238	1.000	1.103	-22.37	-22.50	-7.814	14.32	10293.6	2.487	643.4	1.062
7.55	1.238	1.000	1.103	-22.37	-22.51	-7.764	14.37	11549.7	2.487	681.5	1.062
7.60	1.238	1.000	1.103	-22.37	-22.51	-7.714	14.42	12959.1	2.487	721.9	1.062
7.65	1.238	1.000	1.103	-22.37	-22.51	-7.664	14.47	14540.5	2.487	764.7	1.062
7.70	1.238	1.000	1.103	-22.37	-22.50	-7.614	14.52	16314.8	2.487	810.0	1.062
7.75	1.238	1.000	1.103	-22.36	-22.49	-7.564	14.56	18305.7	2.487	858.0	1.062
7.80	1.238	1.000	1.103	-22.35	-22.48	-7.514	14.60	20539.6	2.487	908.8	1.062
7.85	1.238	1.000	1.103	-22.34	-22.47	-7.464	14.64	23046.0	2.487	962.7	1.062
7.90	1.238	1.000	1.103	-22.33	-22.46	-7.414	14.68	25858.3	2.487	1019.7	1.062
7.95	1.238	1.000	1.103	-22.31	-22.45	-7.364	14.71	29013.8	2.487	1080.1	1.062
8.00	1.238	1.000	1.103	-22.30	-22.44	-7.314	14.75	32554.3	2.487	1144.2	1.062
8.05	1.238	1.000	1.103	-22.29	-22.42	-7.264	14.79	36526.9	2.487	1211.9	1.062
8.10	1.238	1.000	1.103	-22.27	-22.41	-7.214	14.82	40984.2	2.487	1283.8	1.062
8.15	1.238	1.000	1.103	-22.26	-22.40	-7.164	14.86	45985.4	2.487	1359.8	1.062
8.20	1.238	1.000	1.103	-22.25	-22.38	-7.114	14.90	51596.8	2.487	1440.4	1.062
8.25	1.238	1.000	1.103	-22.23	-22.37	-7.064	14.93	57892.9	2.487	1525.8	1.062
8.30	1.238	1.000	1.103	-22.21	-22.35	-7.014	14.96	64957.3	2.487	1616.2	1.062
8.35	1.239	1.000	1.103	-22.20	-22.33	-6.964	15.00	72883.6	2.487	1712.0	1.062
8.40	1.239	1.000	1.103	-22.18	-22.32	-6.914	15.03	81777.0	2.487	1813.4	1.062
8.45	1.239	1.000	1.103	-22.16	-22.30	-6.864	15.06	91755.6	2.487	1920.9	1.062
8.50	1.239	1.000	1.103	-22.14	-22.28	-6.814	15.09	102952	2.487	2034.7	1.062

TABLE A.7 : NEQ FULL FIELD, INITIAL TEMPERATURE SERIES.

NEQ COOLING CURVE : FULLFIELD, LOG(T₀) = 5.50, SOLAR ABUNDANCES
LOG(T) = 5.5 DOWN TO 4.0

Log(T)	Number Densities			Cooling Properties				General Plasma Properties ^a			
	n _e	n _H	n _t	log(Λ _{net})	log(Λ _N)	log(U)	log(τ _e)	P ₁₂	ρ ₂₄	C _i	μ ₂₄
5.500	3.503	2.911	3.200	-20.30	-21.35	-9.358	11.17	294.8	8.361	65.10	1.037
5.438	4.302	3.575	3.930	-20.11	-21.34	-9.330	11.09	311.5	8.535	60.41	1.037
5.390	4.982	4.141	4.553	-19.96	-21.31	-9.315	11.02	322.8	9.886	57.14	1.037
5.340	5.742	4.774	5.249	-19.82	-21.29	-9.303	10.96	332.2	11.40	53.99	1.037
5.290	6.599	5.488	6.033	-19.69	-21.29	-9.292	10.90	340.2	13.10	50.96	1.037
5.239	7.564	6.293	6.918	-19.58	-21.30	-9.284	10.85	347.0	15.02	48.07	1.037
5.188	8.653	7.200	7.916	-19.48	-21.31	-9.277	10.82	352.9	17.19	45.31	1.037
5.137	9.881	8.226	9.043	-19.39	-21.34	-9.270	10.79	357.9	19.64	42.69	1.038
5.085	11.27	9.384	10.32	-19.31	-21.37	-9.265	10.78	362.2	22.40	40.21	1.038
5.033	12.83	10.69	11.76	-19.23	-21.41	-9.260	10.76	366.0	25.53	37.86	1.038
4.980	14.59	12.17	13.38	-19.16	-21.46	-9.257	10.75	369.2	29.06	35.64	1.039
4.928	16.58	13.85	15.22	-19.10	-21.50	-9.253	10.75	371.9	33.06	33.54	1.039
4.875	18.82	15.74	17.31	-19.04	-21.55	-9.251	10.74	374.2	37.58	31.56	1.040
4.822	21.35	17.88	19.66	-18.98	-21.60	-9.249	10.74	376.1	42.69	29.68	1.041
4.770	24.21	20.30	22.32	-18.93	-21.66	-9.246	10.75	377.8	48.46	27.92	1.042
4.717	27.44	23.04	25.33	-18.88	-21.72	-9.244	10.76	379.3	55.00	26.26	1.042
4.665	30.96	26.04	28.63	-18.84	-21.79	-9.244	10.77	380.5	62.17	24.74	1.043
4.619	34.47	29.04	31.93	-18.80	-21.84	-9.243	10.78	381.4	69.32	23.45	1.044
4.578	37.96	32.03	35.21	-18.77	-21.89	-9.242	10.79	382.0	76.46	22.35	1.045
4.522	43.16	36.51	40.13	-18.72	-21.96	-9.241	10.80	382.6	87.14	20.95	1.046
4.473	48.30	40.96	45.03	-18.68	-22.01	-9.241	10.81	383.0	97.78	19.79	1.048
4.429	53.35	45.38	49.89	-18.64	-22.07	-9.241	10.81	383.1	108.3	18.80	1.049
4.378	59.91	51.20	56.28	-18.63	-22.16	-9.241	10.85	382.9	122.2	17.70	1.052
4.332	66.29	56.95	62.61	-18.63	-22.25	-9.242	10.90	382.4	135.9	16.77	1.055
4.291	72.49	62.67	68.89	-18.64	-22.34	-9.242	10.95	381.7	149.6	15.97	1.058
4.245	80.01	69.78	76.72	-18.67	-22.46	-9.244	11.02	380.4	166.6	15.11	1.063
4.203	87.27	76.91	84.55	-18.70	-22.57	-9.246	11.09	378.9	183.6	14.37	1.068
4.158	95.68	85.51	94.01	-18.74	-22.70	-9.248	11.17	376.5	204.1	13.58	1.076
4.116	103.8	94.25	103.6	-18.78	-22.81	-9.251	11.24	373.8	225.0	12.89	1.085
4.070	112.9	104.8	115.2	-18.82	-22.93	-9.256	11.32	370.3	250.0	12.17	1.096
4.027	122.0	115.8	127.3	-18.83	-23.02	-9.260	11.36	366.3	276.4	11.51	1.109

NEQ COOLING CURVE : FULL FIELD, LOG(T₀) = 6.50, SOLAR ABUNDANCES
LOG(T) = 6.5 DOWN TO 4.0

Log(T)	n _e	n _H	n _t	log(Λ _{net})	log(Λ _N)	log(U)	log(τ _e)	P ₁₂	ρ ₂₄	C _i	μ ₂₄
6.500	0.3613	0.2991	0.3288	-23.37	-22.44	-9.345	13.26	303.4	0.862	206.1	1.035
6.446	0.4321	0.3578	0.3933	-23.18	-22.42	-9.321	13.17	317.9	0.854	192.9	1.035
6.397	0.5004	0.4145	0.4556	-22.98	-22.34	-9.306	13.05	329.5	0.989	182.5	1.035
6.348	0.5771	0.4781	0.5255	-22.75	-22.24	-9.293	12.90	339.2	1.141	172.4	1.035
6.298	0.6632	0.5496	0.6042	-22.50	-22.11	-9.283	12.72	347.4	1.312	162.7	1.035
6.247	0.7603	0.6302	0.6928	-22.27	-21.99	-9.275	12.55	354.4	1.504	153.5	1.035
6.196	0.8699	0.7212	0.7928	-22.11	-21.95	-9.267	12.46	360.4	1.721	144.7	1.035
6.144	0.9936	0.8239	0.9057	-22.00	-21.95	-9.261	12.41	365.7	1.967	136.4	1.035
6.093	1.133	0.9399	1.033	-21.90	-21.97	-9.255	12.38	370.2	2.244	128.4	1.036
6.040	1.291	1.071	1.178	-21.80	-21.98	-9.251	12.34	374.1	2.557	121.0	1.036
5.988	1.470	1.219	1.341	-21.69	-21.98	-9.247	12.29	377.5	2.911	113.9	1.036
5.936	1.672	1.387	1.525	-21.57	-21.98	-9.243	12.23	380.5	3.311	107.2	1.036
5.883	1.900	1.577	1.733	-21.44	-21.96	-9.241	12.16	383.1	3.764	100.9	1.036
5.830	2.158	1.791	1.969	-21.28	-21.91	-9.238	12.05	385.4	4.275	94.94	1.036
5.777	2.450	2.033	2.235	-21.11	-21.85	-9.236	11.94	387.3	4.854	89.33	1.036
5.725	2.777	2.306	2.535	-20.96	-21.81	-9.234	11.85	389.1	5.504	84.08	1.036
5.672	3.150	2.616	2.876	-20.82	-21.78	-9.232	11.77	390.6	6.244	79.09	1.036
5.618	3.573	2.967	3.262	-20.68	-21.75	-9.231	11.68	392.0	7.083	74.39	1.036
5.565	4.050	3.364	3.698	-20.52	-21.69	-9.230	11.58	393.1	8.029	69.97	1.036
5.512	4.589	3.812	4.191	-20.33	-21.61	-9.228	11.44	394.2	9.100	65.81	1.036
5.459	5.195	4.316	4.744	-20.13	-21.52	-9.227	11.30	395.1	10.30	61.93	1.037
5.408	5.859	4.868	5.352	-19.96	-21.45	-9.226	11.18	395.8	11.62	58.36	1.037
5.356	6.611	5.494	6.040	-19.80	-21.41	-9.226	11.07	396.5	13.12	54.98	1.037
5.303	7.472	6.212	6.829	-19.67	-21.38	-9.225	11.00	397.1	14.83	51.75	1.037

a. P₁₂ = P × 10¹², ρ₂₄ = ρ × 10²⁴, μ₂₄ = μ × 10²⁴

TABLE A.7 : NEQ FULL FIELD, INITIAL TEMPERATURE SERIES. *CONTINUED.*NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(T_0) = 6.50$, *CONT.*

$\text{Log}(T)$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
5.250	8.457	7.033	7.731	-19.55	-21.37	-9.225	10.93	397.6	16.79	48.67	1.037
5.197	9.576	7.966	8.757	-19.45	-21.37	-9.224	10.89	398.0	19.01	45.75	1.037
5.143	10.84	9.021	9.917	-19.36	-21.39	-9.224	10.85	398.4	21.53	43.01	1.037
5.089	12.27	10.22	11.23	-19.28	-21.42	-9.224	10.82	398.7	24.39	40.43	1.038
5.036	13.88	11.57	12.72	-19.21	-21.45	-9.223	10.81	398.9	27.62	38.01	1.038
4.982	15.71	13.10	14.40	-19.14	-21.50	-9.223	10.79	399.0	31.27	35.72	1.039
4.929	17.76	14.83	16.30	-19.08	-21.54	-9.223	10.79	399.0	35.40	33.57	1.039
4.875	20.08	16.79	18.46	-19.03	-21.60	-9.223	10.79	399.0	40.08	31.55	1.040
4.821	22.70	19.01	20.89	-18.98	-21.65	-9.223	10.79	398.9	45.37	29.65	1.041
4.768	25.65	21.51	23.65	-18.93	-21.71	-9.223	10.80	398.8	51.34	27.87	1.042
4.714	29.00	24.35	26.77	-18.89	-21.78	-9.223	10.81	398.7	58.12	26.19	1.042
4.665	32.46	27.29	30.00	-18.85	-21.84	-9.223	10.82	398.5	65.15	24.73	1.043
4.620	35.91	30.24	33.24	-18.82	-21.90	-9.224	10.83	398.3	72.18	23.49	1.044
4.580	39.36	33.19	36.49	-18.79	-21.94	-9.224	10.84	398.1	79.23	22.41	1.045
4.525	44.52	37.64	41.38	-18.73	-22.00	-9.225	10.84	397.7	89.84	21.04	1.046
4.477	49.64	42.08	46.26	-18.69	-22.05	-9.225	10.84	397.2	100.5	19.89	1.047
4.434	54.70	46.50	51.12	-18.65	-22.09	-9.225	10.85	396.7	111.0	18.90	1.049
4.383	61.28	52.33	57.53	-18.62	-22.17	-9.226	10.87	395.9	124.9	17.80	1.051
4.337	67.69	58.11	63.88	-18.62	-22.25	-9.228	10.91	394.8	138.7	16.87	1.054
4.296	73.94	63.86	70.20	-18.62	-22.34	-9.229	10.95	393.7	152.4	16.07	1.058
4.250	81.54	71.05	78.10	-18.65	-22.45	-9.231	11.02	391.9	169.6	15.20	1.062
4.208	88.93	78.28	86.06	-18.68	-22.56	-9.233	11.09	389.9	186.9	14.45	1.068
4.162	97.55	87.12	95.77	-18.72	-22.69	-9.236	11.17	387.1	207.9	13.64	1.076
4.118	106.0	96.22	105.8	-18.76	-22.81	-9.240	11.24	383.9	229.7	12.93	1.085
4.077	114.2	105.8	116.3	-18.80	-22.92	-9.244	11.32	380.2	252.5	12.27	1.095
4.037	122.6	116.1	127.7	-18.83	-23.02	-9.248	11.38	376.0	277.2	11.65	1.108
3.995	131.4	127.8	140.5	-18.84	-23.11	-9.254	11.42	371.2	305.2	11.03	1.122

NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(T_0) = 7.50$, SOLAR ABUNDANCES. $\text{LOG}(T) = 7.5$ DOWN TO 4.0

$\text{Log}(T)$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0363	0.0300	0.0330	-25.65	-22.73	-9.343	14.54	304.4	0.087	652.1	1.034
7.445	0.0435	0.0360	0.0395	-25.50	-22.74	-9.320	14.50	319.1	0.086	609.7	1.034
7.396	0.0504	0.0417	0.0458	-25.37	-22.74	-9.305	14.45	330.7	0.099	576.7	1.034
7.347	0.0581	0.0480	0.0528	-25.25	-22.74	-9.292	14.40	340.4	0.115	544.8	1.034
7.297	0.0668	0.0552	0.0607	-25.12	-22.73	-9.281	14.34	348.6	0.132	514.2	1.034
7.246	0.0766	0.0633	0.0696	-24.99	-22.72	-9.273	14.28	355.7	0.151	485.1	1.034
7.195	0.0876	0.0725	0.0797	-24.85	-22.70	-9.265	14.21	361.7	0.173	457.3	1.034
7.143	0.1001	0.0828	0.0910	-24.71	-22.67	-9.260	14.13	367.0	0.198	431.0	1.034
7.091	0.1141	0.0944	0.1038	-24.56	-22.63	-9.255	14.04	371.5	0.225	406.0	1.034
7.039	0.1301	0.1076	0.1183	-24.41	-22.60	-9.250	13.95	375.4	0.257	382.3	1.034
6.987	0.1481	0.1225	0.1347	-24.28	-22.58	-9.245	13.88	378.9	0.292	359.9	1.034
6.934	0.1684	0.1394	0.1532	-24.18	-22.59	-9.243	13.84	381.9	0.333	338.8	1.034
6.882	0.1915	0.1584	0.1742	-24.08	-22.60	-9.239	13.80	384.5	0.378	318.9	1.034
6.829	0.2175	0.1800	0.1979	-23.99	-22.62	-9.236	13.77	386.8	0.430	300.0	1.034
6.776	0.2470	0.2044	0.2247	-23.88	-22.62	-9.234	13.72	388.8	0.488	282.3	1.034
6.723	0.2804	0.2320	0.2551	-23.75	-22.61	-9.232	13.64	390.5	0.554	265.5	1.034
6.670	0.3181	0.2633	0.2894	-23.62	-22.58	-9.230	13.57	392.1	0.628	249.8	1.034
6.617	0.3608	0.2986	0.3283	-23.48	-22.56	-9.229	13.49	393.4	0.713	234.9	1.034
6.563	0.4091	0.3386	0.3723	-23.35	-22.53	-9.228	13.41	394.6	0.808	221.0	1.035
6.510	0.4637	0.3839	0.4220	-23.22	-22.51	-9.227	13.34	395.7	0.916	207.8	1.035
6.457	0.5255	0.4351	0.4784	-23.06	-22.46	-9.225	13.23	396.6	1.039	195.4	1.035
6.403	0.5955	0.4931	0.5421	-22.88	-22.39	-9.225	13.11	397.3	1.177	183.7	1.035
6.350	0.6746	0.5587	0.6142	-22.65	-22.27	-9.224	12.93	398.0	1.334	172.7	1.035
6.296	0.7640	0.6330	0.6958	-22.40	-22.12	-9.224	12.74	398.6	1.511	162.4	1.035
6.243	0.8652	0.7169	0.7881	-22.17	-22.00	-9.222	12.56	399.1	1.711	152.7	1.035
6.189	0.9797	0.8120	0.8926	-22.02	-21.96	-9.222	12.47	399.6	1.938	143.6	1.035
6.136	1.109	0.9196	1.011	-21.91	-21.96	-9.221	12.41	400.0	2.195	135.0	1.035
6.082	1.256	1.041	1.145	-21.82	-21.98	-9.221	12.38	400.3	2.486	126.9	1.035
6.028	1.422	1.179	1.296	-21.72	-21.99	-9.222	12.33	400.6	2.815	119.3	1.036
5.975	1.61	1.335	1.468	-21.62	-21.99	-9.221	12.28	400.9	3.187	112.2	1.036
5.921	1.822	1.511	1.662	-21.51	-21.99	-9.221	12.23	401.1	3.608	105.4	1.036
5.868	2.062	1.711	1.881	-21.38	-21.96	-9.220	12.15	401.3	4.084	99.13	1.036

TABLE A.7 : NEQ FULL FIELD, INITIAL TEMPERATURE SERIES. *CONTINUED.*

NEQ COOLING CURVE : FULL FIELD, LOG(To) = 7.50, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	p_{24}	C_i	$\bar{\mu}_{24}$
5.814	2.333	1.936	2.129	-21.22	-21.91	-9.220	12.05	401.5	4.622	93.20	1.036
5.760	2.641	2.192	2.409	-21.05	-21.86	-9.221	11.93	401.7	5.232	87.62	1.036
5.707	2.985	2.477	2.724	-20.91	-21.82	-9.220	11.84	401.8	5.914	82.43	1.036
5.654	3.378	2.804	3.083	-20.77	-21.79	-9.220	11.76	401.9	6.694	77.48	1.036
5.600	3.823	3.174	3.489	-20.63	-21.76	-9.220	11.67	402.0	7.577	72.84	1.036
5.547	4.325	3.592	3.948	-20.46	-21.70	-9.219	11.56	402.1	8.574	68.48	1.036
5.493	4.894	4.065	4.468	-20.27	-21.61	-9.219	11.42	402.2	9.703	64.38	1.036
5.440	5.524	4.589	5.045	-20.09	-21.53	-9.220	11.29	402.2	10.95	60.59	1.036
5.389	6.223	5.17	5.684	-19.92	-21.47	-9.219	11.17	402.2	12.34	57.09	1.037
5.336	7.018	5.832	6.412	-19.77	-21.43	-9.220	11.08	402.3	13.92	53.75	1.037
5.283	7.929	6.591	7.245	-19.65	-21.41	-9.220	11.01	402.3	15.73	50.57	1.037
5.230	8.969	7.458	8.199	-19.53	-21.40	-9.219	10.94	402.3	17.80	47.53	1.037
5.176	10.15	8.441	9.279	-19.43	-21.41	-9.219	10.90	402.2	20.15	44.68	1.037
5.122	11.48	9.553	10.50	-19.35	-21.43	-9.220	10.87	402.2	22.80	41.99	1.037
5.069	12.98	10.81	11.89	-19.27	-21.46	-9.219	10.84	402.1	25.81	39.47	1.038
5.015	14.68	12.24	13.45	-19.20	-21.50	-9.220	10.83	401.9	29.21	37.09	1.038
4.961	16.60	13.85	15.23	-19.14	-21.54	-9.220	10.82	401.8	33.06	34.86	1.039
4.907	18.77	15.67	17.23	-19.08	-21.59	-9.221	10.81	401.5	37.41	32.76	1.039
4.854	21.21	17.74	19.50	-19.03	-21.65	-9.220	10.82	401.3	42.34	30.79	1.040
4.800	23.95	20.07	22.06	-18.98	-21.70	-9.221	10.82	400.9	47.90	28.93	1.041
4.746	27.07	22.71	24.96	-18.94	-21.77	-9.222	10.83	400.7	54.20	27.19	1.042
4.694	30.51	25.63	28.18	-18.90	-21.83	-9.221	10.84	400.4	61.19	25.58	1.043
4.647	33.97	28.58	31.42	-18.86	-21.89	-9.221	10.85	400.1	68.23	24.21	1.043
4.604	37.43	31.54	34.68	-18.82	-21.94	-9.222	10.85	399.7	75.30	23.04	1.044
4.546	42.62	36.01	39.58	-18.77	-22.00	-9.223	10.86	399.3	85.95	21.55	1.046
4.495	47.79	40.48	44.50	-18.72	-22.04	-9.224	10.86	398.7	96.63	20.31	1.047
4.450	52.90	44.94	49.40	-18.67	-22.09	-9.224	10.85	398.1	107.3	19.26	1.049
4.409	57.92	49.36	54.26	-18.64	-22.14	-9.225	10.86	397.5	117.8	18.37	1.050
4.361	64.44	55.19	60.67	-18.62	-22.21	-9.226	10.89	396.5	131.7	17.35	1.053
4.318	70.79	60.98	67.04	-18.62	-22.29	-9.226	10.93	395.3	145.6	16.48	1.056
4.269	78.49	68.19	74.97	-18.63	-22.40	-9.229	10.98	393.6	162.8	15.55	1.061
4.225	85.94	75.42	82.91	-18.66	-22.51	-9.231	11.05	391.6	180.0	14.75	1.066
4.185	93.17	82.71	90.93	-18.69	-22.62	-9.234	11.12	389.3	197.4	14.04	1.072
4.141	101.5	91.62	100.7	-18.73	-22.74	-9.237	11.20	386.1	218.7	13.29	1.081
4.099	109.7	100.8	110.8	-18.77	-22.86	-9.241	11.27	382.5	240.7	12.61	1.091
4.053	118.9	112.2	123.3	-18.81	-22.98	-9.247	11.35	377.6	267.8	11.87	1.106
4.007	128.2	124.8	137.2	-18.83	-23.08	-9.253	11.40	372.0	297.8	11.18	1.122

NEQ COOLING CURVE : FULL FIELD, LOG(To) = 8.50, SOLAR ABUNDANCES.

LOG(T) = 8.5 DOWN TO 4.0

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	p_{24}	C_i	$\bar{\mu}_{24}$
8.500	0.0036	0.0030	0.0033	-27.31	-22.38	-9.345	15.20	304.5	0.009	2062.1	1.034
8.444	0.0044	0.0036	0.0040	-27.17	-22.41	-9.316	15.18	319.4	0.009	1926.1	1.034
8.395	0.0051	0.0042	0.0046	-27.06	-22.43	-9.302	15.14	331.0	0.010	1821.8	1.034
8.346	0.0058	0.0048	0.0053	-26.96	-22.45	-9.293	15.11	340.6	0.011	1721.1	1.034
8.296	0.0067	0.0055	0.0061	-26.86	-22.47	-9.281	15.08	348.9	0.013	1624.6	1.034
8.245	0.0077	0.0063	0.0070	-26.76	-22.49	-9.272	15.05	355.9	0.015	1532.4	1.034
8.194	0.0088	0.0073	0.0080	-26.66	-22.51	-9.265	15.02	361.9	0.017	1444.7	1.034
8.142	0.0100	0.0083	0.0091	-26.57	-22.53	-9.261	14.99	367.2	0.020	1361.4	1.034
8.091	0.0114	0.0095	0.0104	-26.47	-22.55	-9.254	14.95	371.7	0.023	1282.5	1.034
8.038	0.0130	0.0108	0.0119	-26.38	-22.57	-9.250	14.92	375.6	0.026	1207.7	1.034
7.986	0.0148	0.0123	0.0135	-26.29	-22.59	-9.246	14.89	379.1	0.029	1137.1	1.034
7.934	0.0169	0.0140	0.0154	-26.19	-22.61	-9.241	14.86	382.1	0.033	1070.3	1.034
7.881	0.0192	0.0159	0.0175	-26.10	-22.63	-9.238	14.82	384.7	0.038	1007.3	1.034
7.828	0.0218	0.0180	0.0198	-26.01	-22.65	-9.237	14.79	387.0	0.043	947.9	1.034
7.775	0.0248	0.0205	0.0225	-25.92	-22.66	-9.234	14.76	389.0	0.049	891.8	1.034
7.722	0.0281	0.0233	0.0256	-25.82	-22.68	-9.232	14.72	390.7	0.056	839.0	1.034
7.669	0.0319	0.0264	0.0290	-25.73	-22.70	-9.230	14.68	392.3	0.063	789.2	1.034
7.603	0.0373	0.0308	0.0339	-25.61	-22.72	-9.228	14.63	394.0	0.074	731.5	1.034
7.550	0.0423	0.0350	0.0384	-25.52	-22.73	-9.227	14.60	395.1	0.083	687.9	1.034
7.496	0.0479	0.0396	0.0436	-25.42	-22.74	-9.226	14.55	396.2	0.095	647.0	1.034
7.443	0.0543	0.0449	0.0494	-25.32	-22.75	-9.225	14.51	397.1	0.107	608.4	1.034
7.389	0.0616	0.0509	0.0560	-25.21	-22.75	-9.224	14.45	397.9	0.122	572.1	1.034

TABLE A.7 : NEQ FULL FIELD, INITIAL TEMPERATURE SERIES, CONTINUED.

NEQ COOLING CURVE : FULL FIELD, LOG(T₀) = 8.50, CONT.

Log(T)	n _e	n _H	n _i	log(Λ_{net})	log(Λ_N)	log(U)	log(τ_c)	P ₁₂	ρ_{24}	C ₁	$\bar{\mu}_{24}$
7.336	0.0697	0.0577	0.0634	-25.11	-22.75	-9.224	14.41	398.6	0.138	538.0	1.034
7.282	0.0790	0.0654	0.0719	-24.99	-22.74	-9.223	14.34	399.2	0.156	505.8	1.034
7.229	0.0895	0.0740	0.0814	-24.87	-22.73	-9.222	14.28	399.7	0.177	475.6	1.034
7.175	0.1014	0.0839	0.0922	-24.73	-22.70	-9.222	14.19	400.2	0.200	447.1	1.034
7.122	0.1148	0.0950	0.1044	-24.59	-22.67	-9.221	14.11	400.6	0.227	420.4	1.034
7.068	0.1300	0.1075	0.1182	-24.45	-22.63	-9.221	14.02	401.0	0.257	395.2	1.034
7.015	0.1472	0.1218	0.1339	-24.31	-22.60	-9.220	13.94	401.3	0.291	371.6	1.034
6.961	0.1667	0.1379	0.1516	-24.19	-22.59	-9.220	13.87	401.6	0.329	349.3	1.034
6.907	0.1887	0.1561	0.1716	-24.09	-22.60	-9.220	13.82	401.8	0.373	328.4	1.034
6.854	0.2136	0.1767	0.1943	-24.01	-22.62	-9.219	13.80	402.0	0.422	308.7	1.034
6.800	0.2418	0.2001	0.2200	-23.91	-22.64	-9.219	13.75	402.2	0.478	290.2	1.034
6.746	0.2737	0.2265	0.2490	-23.80	-22.63	-9.220	13.70	402.4	0.541	272.8	1.034
6.693	0.3098	0.2564	0.2819	-23.67	-22.62	-9.219	13.62	402.5	0.612	256.4	1.034
6.639	0.3507	0.2903	0.3191	-23.54	-22.59	-9.219	13.54	402.7	0.693	241.1	1.034
6.585	0.3970	0.3286	0.3612	-23.41	-22.57	-9.219	13.47	402.8	0.784	226.6	1.034
6.532	0.4493	0.3719	0.4088	-23.28	-22.54	-9.218	13.39	402.9	0.888	213.0	1.035
6.478	0.5085	0.4210	0.4628	-23.13	-22.51	-9.218	13.30	402.9	1.005	200.2	1.035
6.424	0.5754	0.4765	0.5238	-22.96	-22.44	-9.219	13.18	403.0	1.137	188.2	1.035
6.370	0.6512	0.5393	0.5929	-22.75	-22.34	-9.219	13.02	403.0	1.287	176.9	1.035
6.317	0.7369	0.6104	0.6710	-22.50	-22.19	-9.218	12.83	403.0	1.457	166.3	1.035
6.263	0.8337	0.6908	0.7594	-22.24	-22.05	-9.219	12.62	403.0	1.649	156.3	1.035
6.209	0.9433	0.7818	0.8594	-22.06	-21.97	-9.219	12.49	403.0	1.866	147.0	1.035
6.156	1.067	0.8848	0.9727	-21.95	-21.96	-9.218	12.44	403.0	2.112	138.1	1.035
6.102	1.208	1.001	1.101	-21.85	-21.98	-9.218	12.39	403.1	2.390	129.9	1.035
6.048	1.367	1.133	1.246	-21.76	-21.99	-9.219	12.36	403.1	2.705	122.1	1.035
5.994	1.547	1.283	1.410	-21.66	-22.00	-9.219	12.31	403.0	3.062	114.7	1.036
5.941	1.750	1.452	1.596	-21.55	-22.00	-9.218	12.25	403.0	3.465	107.9	1.036
5.887	1.980	1.643	1.806	-21.43	-21.99	-9.219	12.19	403.0	3.921	101.4	1.036
5.833	2.240	1.858	2.043	-21.29	-21.95	-9.219	12.10	403.0	4.436	95.31	1.036
5.780	2.534	2.103	2.312	-21.12	-21.89	-9.218	11.98	403.0	5.020	89.60	1.036
5.727	2.864	2.377	2.613	-20.97	-21.84	-9.218	11.89	403.0	5.675	84.27	1.036
5.673	3.239	2.688	2.955	-20.83	-21.81	-9.219	11.80	403.0	6.417	79.24	1.036
5.620	3.665	3.042	3.345	-20.69	-21.78	-9.218	11.71	403.0	7.262	74.49	1.036
5.566	4.146	3.442	3.784	-20.54	-21.73	-9.219	11.62	402.9	8.217	70.03	1.036
5.512	4.690	3.895	4.282	-20.35	-21.65	-9.219	11.48	402.9	9.297	65.83	1.036
5.459	5.301	4.403	4.840	-20.16	-21.57	-9.219	11.34	402.9	10.51	61.91	1.036
5.407	5.972	4.961	5.454	-19.99	-21.50	-9.219	11.23	402.9	11.84	58.33	1.036
5.355	6.730	5.592	6.147	-19.83	-21.45	-9.219	11.12	402.8	13.35	54.94	1.037
5.302	7.597	6.314	6.941	-19.70	-21.42	-9.219	11.04	402.8	15.07	51.69	1.037
5.249	8.589	7.141	7.850	-19.58	-21.41	-9.219	10.97	402.7	17.05	48.61	1.037
5.195	9.718	8.081	8.884	-19.48	-21.41	-9.219	10.93	402.7	19.29	45.69	1.037
5.142	10.99	9.146	10.05	-19.38	-21.43	-9.219	10.88	402.6	21.83	42.94	1.037
5.088	12.43	10.35	11.38	-19.30	-21.45	-9.219	10.85	402.4	24.71	40.36	1.038
5.034	14.06	11.71	12.88	-19.23	-21.49	-9.219	10.84	402.3	27.96	37.93	1.038
4.980	15.90	13.26	14.57	-19.17	-21.53	-9.220	10.83	402.1	31.65	35.65	1.039
4.927	17.97	15.00	16.49	-19.11	-21.58	-9.220	10.82	401.9	35.81	33.50	1.039
4.873	20.31	16.98	18.66	-19.05	-21.63	-9.220	10.82	401.6	40.52	31.48	1.040
4.819	22.94	19.21	21.12	-19.00	-21.69	-9.221	10.82	401.2	45.86	29.58	1.041
4.766	25.91	21.73	23.89	-18.96	-21.75	-9.221	10.83	400.8	51.88	27.80	1.042
4.712	29.27	24.60	27.04	-18.91	-21.81	-9.221	10.84	400.5	58.71	26.12	1.043
4.663	32.73	27.55	30.28	-18.88	-21.87	-9.221	10.86	400.2	65.75	24.67	1.043
4.619	36.18	30.50	33.53	-18.84	-21.92	-9.222	10.86	399.9	72.80	23.44	1.044
4.578	39.63	33.46	36.79	-18.80	-21.97	-9.223	10.86	399.5	79.88	22.36	1.045
4.524	44.80	37.92	41.69	-18.75	-22.02	-9.223	10.86	399.0	90.53	21.00	1.047
4.476	49.93	42.39	46.60	-18.70	-22.06	-9.223	10.86	398.4	101.2	19.84	1.048
4.432	54.99	46.82	51.48	-18.65	-22.11	-9.225	10.85	397.8	111.8	18.86	1.050
4.381	61.56	52.66	57.89	-18.62	-22.18	-9.226	10.87	396.8	125.7	17.77	1.052
4.336	67.95	58.45	64.25	-18.61	-22.25	-9.227	10.90	395.7	139.5	16.84	1.055
4.295	74.16	64.19	70.56	-18.62	-22.34	-9.228	10.95	394.4	153.2	16.04	1.059
4.249	81.67	71.34	78.43	-18.64	-22.44	-9.230	11.01	392.6	170.3	15.18	1.064
4.208	88.91	78.50	86.30	-18.67	-22.55	-9.232	11.08	390.5	187.4	14.43	1.070
4.162	97.26	87.16	95.82	-18.70	-22.67	-9.236	11.15	387.5	208.1	13.65	1.078
4.121	105.2	95.95	105.5	-18.74	-22.79	-9.239	11.22	384.2	229.0	12.95	1.087
4.075	114.1	106.5	117.1	-18.78	-22.91	-9.245	11.30	379.8	254.2	12.22	1.100
4.032	122.7	117.6	129.3	-18.81	-23.01	-9.250	11.36	374.8	280.7	11.56	1.114

TABLE A.8 : NEQ ZERO FIELD, INITIAL TEMPERATURE SERIES.

NEQ COOLING CURVE : ZERO FIELD, LOG(T₀) = 5.50, SOLAR ABUNDANCES
 LOG(T) = 5.5 DOWN TO 4.0

Log(T)	Number Densities			Cooling Properties				General Plasma Properties ^a			
	n _e	n _H	n _i	log(Λ _{net})	log(Λ _N)	log(U)	log(τ _e)	P ₁₂	ρ ₂₄	C _i	μ ₂₄
5.500	3.503	2.911	3.200	-20.30	-21.35	-9.358	11.17	294.8	8.361	65.10	1.037
5.438	4.302	3.575	3.930	-20.11	-21.34	-9.330	11.09	311.5	8.535	60.41	1.037
5.390	4.982	4.141	4.553	-19.96	-21.31	-9.315	11.02	322.8	9.886	57.14	1.037
5.340	5.742	4.774	5.249	-19.82	-21.29	-9.303	10.96	332.2	11.40	53.99	1.037
5.290	6.599	5.488	6.033	-19.69	-21.29	-9.292	10.90	340.2	13.10	50.96	1.037
5.239	7.564	6.293	6.918	-19.58	-21.30	-9.284	10.85	347.0	15.02	48.07	1.037
5.188	8.653	7.200	7.915	-19.48	-21.31	-9.277	10.82	352.9	17.19	45.31	1.037
5.137	9.881	8.226	9.043	-19.39	-21.34	-9.270	10.79	357.9	19.64	42.69	1.038
5.085	11.27	9.384	10.32	-19.31	-21.37	-9.265	10.78	362.2	22.40	40.21	1.038
5.033	12.83	10.69	11.76	-19.23	-21.41	-9.260	10.76	366.0	25.53	37.86	1.038
4.980	14.59	12.17	13.38	-19.16	-21.46	-9.257	10.75	369.2	29.06	35.64	1.039
4.928	16.58	13.85	15.22	-19.10	-21.50	-9.253	10.75	371.9	33.06	33.54	1.039
4.875	18.82	15.74	17.31	-19.04	-21.55	-9.251	10.74	374.2	37.58	31.55	1.040
4.822	21.35	17.88	19.66	-18.98	-21.60	-9.249	10.74	376.1	42.69	29.68	1.041
4.770	24.21	20.30	22.32	-18.93	-21.66	-9.246	10.75	377.8	48.47	27.92	1.042
4.717	27.44	23.04	25.33	-18.88	-21.72	-9.244	10.76	379.3	55.01	26.26	1.042
4.665	30.97	26.05	28.63	-18.84	-21.78	-9.244	10.77	380.5	62.18	24.74	1.043
4.619	34.48	29.04	31.93	-18.80	-21.84	-9.243	10.78	381.3	69.33	23.45	1.044
4.578	37.97	32.04	35.22	-18.76	-21.89	-9.241	10.78	382.0	76.47	22.35	1.045
4.522	43.17	36.51	40.14	-18.71	-21.95	-9.241	10.79	382.6	87.16	20.95	1.046
4.473	48.31	40.97	45.04	-18.67	-22.01	-9.241	10.80	383.0	97.80	19.79	1.048
4.429	53.36	45.40	49.90	-18.64	-22.06	-9.241	10.81	383.0	108.4	18.80	1.049
4.378	59.90	51.20	56.29	-18.62	-22.14	-9.241	10.84	382.9	122.2	17.70	1.052
4.332	66.24	56.94	62.60	-18.61	-22.23	-9.242	10.88	382.3	135.9	16.77	1.055
4.292	72.38	62.63	68.85	-18.62	-22.32	-9.242	10.93	381.5	149.5	15.98	1.059
4.246	79.75	69.67	76.59	-18.65	-22.43	-9.244	11.00	380.1	166.3	15.12	1.064
4.205	86.78	76.66	84.27	-18.68	-22.54	-9.246	11.07	378.4	183.0	14.38	1.070
4.160	94.74	84.99	93.43	-18.71	-22.66	-9.249	11.13	375.8	202.9	13.61	1.078
4.114	103.3	94.63	104.0	-18.76	-22.79	-9.253	11.22	372.3	225.9	12.84	1.089
4.073	111.2	104.2	114.6	-18.79	-22.89	-9.257	11.28	368.4	248.7	12.17	1.102
4.030	119.3	115.1	126.5	-18.81	-22.99	-9.263	11.33	363.5	274.7	11.50	1.117

NEQ COOLING CURVE : ZERO FIELD, LOG(T₀) = 6.50, SOLAR ABUNDANCES
 LOG(T) = 6.5 DOWN TO 4.0

Log(T)	n _e	n _H	n _i	log(Λ _{net})	log(Λ _N)	log(U)	log(τ _e)	P ₁₂	ρ ₂₄	C _i	μ ₂₄
6.500	0.3613	0.2991	0.3288	-23.37	-22.44	-9.345	13.26	303.4	0.862	206.1	1.035
6.446	0.4321	0.3578	0.3933	-23.18	-22.41	-9.321	13.17	317.9	0.854	192.9	1.035
6.397	0.5004	0.4145	0.4556	-22.98	-22.34	-9.306	13.05	329.5	0.989	182.5	1.035
6.348	0.5771	0.4781	0.5255	-22.75	-22.23	-9.293	12.90	339.2	1.141	172.4	1.035
6.298	0.6632	0.5496	0.6042	-22.50	-22.10	-9.283	12.72	347.4	1.312	162.7	1.035
6.247	0.7603	0.6302	0.6928	-22.27	-21.99	-9.275	12.55	354.4	1.504	153.5	1.035
6.196	0.8699	0.7211	0.7928	-22.11	-21.95	-9.267	12.46	360.4	1.721	144.7	1.035
6.144	0.9936	0.8239	0.9057	-22.00	-21.95	-9.261	12.41	365.7	1.967	136.4	1.035
6.093	1.133	0.9399	1.033	-21.90	-21.97	-9.255	12.38	370.2	2.244	128.4	1.036
6.040	1.291	1.071	1.178	-21.79	-21.98	-9.251	12.33	374.1	2.557	121.0	1.036
5.988	1.470	1.219	1.341	-21.69	-21.98	-9.247	12.29	377.5	2.911	113.9	1.036
5.936	1.672	1.387	1.525	-21.57	-21.98	-9.243	12.23	380.5	3.311	107.2	1.036
5.883	1.900	1.577	1.733	-21.44	-21.96	-9.241	12.16	383.1	3.764	100.9	1.036
5.830	2.158	1.791	1.969	-21.28	-21.91	-9.238	12.05	385.3	4.275	94.94	1.036
5.777	2.449	2.033	2.235	-21.11	-21.85	-9.236	11.94	387.3	4.854	89.33	1.036
5.725	2.777	2.305	2.534	-20.96	-21.81	-9.234	11.85	389.1	5.503	84.08	1.036
5.672	3.150	2.615	2.875	-20.82	-21.78	-9.232	11.77	390.6	6.243	79.10	1.036
5.619	3.572	2.967	3.261	-20.68	-21.75	-9.230	11.68	392.0	7.081	74.40	1.036
5.565	4.049	3.363	3.697	-20.51	-21.69	-9.230	11.57	393.1	8.028	69.98	1.036
5.512	4.588	3.811	4.190	-20.32	-21.61	-9.228	11.43	394.2	9.098	65.82	1.036
5.459	5.193	4.315	4.743	-20.13	-21.52	-9.228	11.30	395.1	10.30	61.93	1.037
5.408	5.857	4.867	5.350	-19.95	-21.45	-9.226	11.17	395.8	11.62	58.37	1.037
5.356	6.609	5.493	6.039	-19.80	-21.40	-9.226	11.07	396.5	13.11	54.99	1.037
5.304	7.470	6.211	6.827	-19.67	-21.37	-9.225	11.00	397.1	14.83	51.75	1.037

a. P₁₂ = P x 10¹², ρ₂₄ = ρ x 10²⁴, μ₂₄ = μ x 10²⁴

TABLE A.8 : NEQ ZERO FIELD, INITIAL TEMPERATURE SERIES. *CONTINUED.*NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(T_0) = 6.50$, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
5.250	8.456	7.032	7.730	-19.55	-21.36	-9.225	10.93	397.6	16.79	48.67	1.037
5.197	9.574	7.965	8.756	-19.45	-21.37	-9.224	10.89	398.0	19.01	45.75	1.037
5.143	10.84	9.020	9.916	-19.35	-21.38	-9.224	10.84	398.4	21.53	43.01	1.037
5.089	12.27	10.22	11.23	-19.27	-21.41	-9.224	10.81	398.7	24.38	40.43	1.038
5.036	13.88	11.57	12.72	-19.20	-21.45	-9.223	10.80	398.8	27.61	38.01	1.038
4.982	15.70	13.10	14.40	-19.13	-21.49	-9.223	10.78	399.0	31.27	35.72	1.039
4.929	17.76	14.83	16.30	-19.07	-21.53	-9.223	10.78	399.0	35.40	33.57	1.039
4.875	20.08	16.79	18.46	-19.01	-21.58	-9.223	10.77	398.9	40.08	31.55	1.040
4.821	22.69	19.01	20.90	-18.96	-21.63	-9.223	10.77	398.8	45.37	29.65	1.041
4.768	25.65	21.52	23.65	-18.91	-21.69	-9.223	10.78	398.7	51.36	27.86	1.042
4.714	28.99	24.36	26.77	-18.86	-21.75	-9.224	10.78	398.5	58.14	26.18	1.043
4.665	32.45	27.30	30.02	-18.82	-21.81	-9.223	10.79	398.4	65.18	24.72	1.043
4.620	35.89	30.25	33.25	-18.79	-21.86	-9.224	10.80	398.2	72.20	23.48	1.044
4.580	39.32	33.19	36.48	-18.75	-21.91	-9.224	10.80	397.9	79.22	22.41	1.045
4.526	44.44	37.60	41.34	-18.70	-21.97	-9.224	10.81	397.5	89.76	21.04	1.046
4.478	49.52	42.01	46.19	-18.66	-22.02	-9.225	10.81	397.0	100.3	19.90	1.048
4.435	54.53	46.40	51.01	-18.62	-22.07	-9.225	10.82	396.5	110.8	18.92	1.050
4.384	61.02	52.17	57.35	-18.60	-22.14	-9.227	10.84	395.6	124.5	17.82	1.052
4.339	67.34	57.87	63.62	-18.59	-22.22	-9.228	10.88	394.6	138.1	16.90	1.055
4.299	73.45	63.53	69.84	-18.60	-22.31	-9.229	10.93	393.4	151.6	16.11	1.058
4.253	80.82	70.53	77.54	-18.62	-22.42	-9.231	10.99	391.6	168.4	15.25	1.063
4.212	87.85	77.49	85.18	-18.65	-22.52	-9.234	11.05	389.5	185.0	14.51	1.069
4.168	95.84	85.78	94.30	-18.69	-22.64	-9.237	11.13	386.7	204.8	13.74	1.077
4.122	104.5	95.39	104.9	-18.73	-22.77	-9.241	11.21	382.9	227.7	12.97	1.088
4.081	112.4	104.9	115.4	-18.76	-22.87	-9.245	11.27	378.8	250.5	12.30	1.099
4.038	120.7	115.8	127.3	-18.78	-22.97	-9.251	11.32	373.8	276.3	11.63	1.114

NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(T_0) = 7.50$, SOLAR ABUNDANCES. $\text{LOG}(T) = 7.5$ DOWN TO 4.0

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0363	0.0300	0.0330	-25.65	-22.73	-9.343	14.54	304.4	0.087	652.1	1.034
7.445	0.0435	0.0360	0.0395	-25.50	-22.74	-9.320	14.50	319.1	0.086	609.7	1.034
7.396	0.0504	0.0417	0.0458	-25.37	-22.74	-9.305	14.45	330.7	0.099	576.7	1.034
7.347	0.0581	0.0480	0.0528	-25.25	-22.74	-9.292	14.40	340.4	0.115	544.8	1.034
7.297	0.0668	0.0552	0.0607	-25.12	-22.73	-9.281	14.34	348.6	0.132	514.3	1.034
7.246	0.0765	0.0633	0.0696	-24.99	-22.71	-9.273	14.28	355.7	0.151	485.1	1.034
7.195	0.0876	0.0725	0.0797	-24.85	-22.69	-9.265	14.21	361.7	0.173	457.3	1.034
7.143	0.1001	0.0828	0.0910	-24.70	-22.66	-9.260	14.12	367.0	0.198	431.0	1.034
7.092	0.1141	0.0944	0.1038	-24.55	-22.63	-9.254	14.03	371.5	0.225	406.0	1.034
7.039	0.1301	0.1076	0.1183	-24.41	-22.59	-9.250	13.95	375.4	0.257	382.3	1.034
6.987	0.1481	0.1225	0.1347	-24.28	-22.58	-9.245	13.88	378.9	0.292	359.9	1.034
6.934	0.1684	0.1394	0.1532	-24.17	-22.58	-9.243	13.83	381.9	0.333	338.8	1.034
6.882	0.1915	0.1584	0.1742	-24.07	-22.60	-9.239	13.79	384.5	0.378	318.9	1.034
6.829	0.2175	0.1800	0.1979	-23.98	-22.61	-9.236	13.76	386.8	0.430	300.0	1.034
6.776	0.2470	0.2044	0.2247	-23.87	-22.61	-9.234	13.71	388.8	0.488	282.3	1.034
6.723	0.2803	0.2320	0.2550	-23.74	-22.59	-9.232	13.63	390.5	0.554	265.5	1.034
6.670	0.3181	0.2632	0.2894	-23.60	-22.56	-9.230	13.55	392.1	0.628	249.8	1.034
6.617	0.3608	0.2986	0.3283	-23.46	-22.53	-9.229	13.47	393.4	0.713	234.9	1.035
6.563	0.4091	0.3386	0.3722	-23.32	-22.51	-9.228	13.38	394.6	0.808	221.0	1.035
6.510	0.4637	0.3839	0.4220	-23.19	-22.48	-9.227	13.31	395.6	0.916	207.8	1.035
6.457	0.5255	0.4351	0.4784	-23.03	-22.43	-9.225	13.20	396.5	1.039	195.4	1.035
6.403	0.5954	0.4931	0.5421	-22.84	-22.35	-9.225	13.07	397.3	1.177	183.7	1.035
6.350	0.6744	0.5587	0.6142	-22.62	-22.24	-9.224	12.90	398.0	1.334	172.7	1.035
6.296	0.7638	0.6329	0.6958	-22.38	-22.10	-9.224	12.72	398.6	1.511	162.4	1.035
6.243	0.8649	0.7169	0.7881	-22.15	-21.99	-9.223	12.54	399.1	1.711	152.7	1.035
6.189	0.9794	0.8119	0.8926	-22.01	-21.95	-9.223	12.46	399.5	1.938	143.6	1.035
6.136	1.109	0.9195	1.011	-21.90	-21.95	-9.221	12.40	399.9	2.195	135.0	1.035
6.082	1.255	1.041	1.145	-21.81	-21.97	-9.222	12.37	400.3	2.486	126.9	1.036
6.028	1.421	1.179	1.296	-21.71	-21.98	-9.222	12.32	400.6	2.815	119.3	1.036
5.975	1.609	1.335	1.468	-21.61	-21.98	-9.221	12.27	400.8	3.187	112.2	1.036
5.921	1.821	1.511	1.661	-21.49	-21.97	-9.221	12.21	401.1	3.608	105.4	1.036
5.868	2.061	1.711	1.881	-21.36	-21.94	-9.220	12.13	401.3	4.084	99.13	1.036
5.814	2.332	1.936	2.128	-21.19	-21.89	-9.220	12.02	401.4	4.621	93.20	1.036

TABLE A.8 : NEQ ZERO FIELD, INITIAL TEMPERATURE SERIES, *CONTINUED.*NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(T_0) = 7.50$, *CONT.*

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
5.761	2.640	2.191	2.409	-21.03	-21.83	-9.220	11.91	401.6	5.231	87.62	1.036
5.707	2.985	2.478	2.724	-20.89	-21.80	-9.220	11.82	401.7	5.915	82.41	1.036
5.654	3.378	2.805	3.084	-20.75	-21.77	-9.219	11.74	401.9	6.696	77.47	1.036
5.600	3.823	3.175	3.490	-20.60	-21.73	-9.220	11.64	402.0	7.578	72.83	1.036
5.546	4.325	3.592	3.949	-20.43	-21.66	-9.220	11.52	402.0	8.575	68.47	1.036
5.493	4.893	4.065	4.469	-20.24	-21.58	-9.219	11.39	402.1	9.704	64.37	1.036
5.440	5.523	4.589	5.045	-20.05	-21.49	-9.220	11.25	402.2	10.95	60.59	1.037
5.389	6.222	5.171	5.684	-19.88	-21.43	-9.219	11.13	402.2	12.34	57.08	1.037
5.336	7.019	5.834	6.414	-19.74	-21.39	-9.220	11.05	402.2	13.93	53.74	1.037
5.283	7.932	6.595	7.250	-19.61	-21.37	-9.220	10.97	402.2	15.74	50.55	1.037
5.229	8.974	7.464	8.205	-19.50	-21.37	-9.220	10.91	402.2	17.82	47.51	1.037
5.176	10.15	8.447	9.286	-19.40	-21.37	-9.219	10.87	402.2	20.16	44.66	1.037
5.122	11.49	9.561	10.51	-19.31	-21.39	-9.219	10.83	402.1	22.82	41.98	1.038
5.068	12.99	10.82	11.90	-19.23	-21.42	-9.220	10.80	402.0	25.83	39.45	1.038
5.014	14.69	12.25	13.46	-19.17	-21.46	-9.220	10.80	401.9	29.23	37.08	1.038
4.961	16.61	13.86	15.24	-19.10	-21.51	-9.220	10.78	401.7	33.09	34.84	1.039
4.907	18.77	15.69	17.25	-19.04	-21.55	-9.220	10.77	401.4	37.45	32.74	1.040
4.853	21.22	17.75	19.52	-18.98	-21.60	-9.221	10.77	401.1	42.38	30.77	1.040
4.800	23.97	20.09	22.09	-18.93	-21.66	-9.221	10.77	400.8	47.96	28.91	1.041
4.746	27.09	22.74	25.00	-18.88	-21.71	-9.221	10.77	400.6	54.28	27.17	1.042
4.693	30.53	25.66	28.21	-18.84	-21.78	-9.222	10.78	400.3	61.26	25.56	1.043
4.646	33.98	28.60	31.44	-18.80	-21.83	-9.222	10.79	400.0	68.28	24.20	1.044
4.604	37.41	31.54	34.67	-18.77	-21.88	-9.222	10.80	399.7	75.28	23.04	1.045
4.547	42.53	35.95	39.52	-18.72	-21.95	-9.223	10.81	399.2	85.81	21.57	1.046
4.497	47.62	40.36	44.36	-18.67	-22.00	-9.223	10.81	398.6	96.33	20.34	1.047
4.452	52.66	44.75	49.19	-18.63	-22.05	-9.224	10.81	398.1	106.8	19.30	1.049
4.412	57.59	49.10	53.97	-18.61	-22.10	-9.224	10.83	397.4	117.2	18.41	1.051
4.364	64.00	54.83	60.28	-18.59	-22.18	-9.225	10.86	396.4	130.9	17.40	1.053
4.321	70.22	60.51	66.52	-18.59	-22.26	-9.227	10.90	395.3	144.4	16.54	1.056
4.273	77.73	67.54	74.25	-18.61	-22.37	-9.229	10.96	393.6	161.2	15.62	1.061
4.230	84.91	74.51	81.91	-18.63	-22.48	-9.232	11.02	391.6	177.9	14.84	1.066
4.185	93.08	82.82	91.05	-18.67	-22.60	-9.234	11.10	388.9	197.7	14.02	1.074
4.143	100.7	91.08	100.1	-18.71	-22.71	-9.238	11.17	385.8	217.4	13.32	1.082
4.100	109.0	100.6	110.6	-18.74	-22.83	-9.242	11.24	381.8	240.2	12.61	1.094
4.055	117.6	111.5	122.6	-18.77	-22.93	-9.248	11.30	376.8	266.2	11.90	1.108
4.015	125.5	122.3	134.4	-18.78	-23.01	-9.254	11.34	371.7	291.9	11.28	1.123

NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(T_0) = 8.50$, SOLAR ABUNDANCES.
 $\text{LOG}(T) = 8.5$ DOWN TO 4.0

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
8.500	0.0036	0.0030	0.0033	-27.31	-22.38	-9.345	15.20	304.5	0.009	2062.1	1.034
8.444	0.0044	0.0036	0.0040	-27.17	-22.41	-9.316	15.18	319.4	0.009	1926.1	1.034
8.395	0.0051	0.0042	0.0046	-27.06	-22.43	-9.302	15.14	331.0	0.010	1821.8	1.034
8.346	0.0058	0.0048	0.0053	-26.96	-22.45	-9.293	15.11	340.6	0.011	1721.1	1.034
8.296	0.0067	0.0055	0.0061	-26.86	-22.47	-9.281	15.08	348.9	0.013	1624.6	1.034
8.245	0.0077	0.0063	0.0070	-26.76	-22.49	-9.272	15.05	355.9	0.015	1532.4	1.034
8.194	0.0088	0.0073	0.0080	-26.66	-22.51	-9.265	15.02	361.9	0.017	1444.7	1.034
8.142	0.0100	0.0083	0.0091	-26.57	-22.53	-9.261	14.99	367.2	0.020	1361.4	1.034
8.091	0.0114	0.0095	0.0104	-26.47	-22.55	-9.254	14.95	371.7	0.023	1282.5	1.034
8.038	0.0130	0.0108	0.0119	-26.38	-22.57	-9.250	14.92	375.6	0.026	1207.7	1.034
7.986	0.0148	0.0123	0.0135	-26.29	-22.59	-9.246	14.89	379.1	0.029	1137.1	1.034
7.934	0.0169	0.0140	0.0154	-26.19	-22.61	-9.241	14.86	382.0	0.033	1070.3	1.034
7.881	0.0192	0.0159	0.0175	-26.10	-22.63	-9.238	14.82	384.7	0.038	1007.3	1.034
7.828	0.0218	0.0180	0.0198	-26.01	-22.64	-9.237	14.79	387.0	0.043	947.9	1.034
7.775	0.0248	0.0205	0.0225	-25.92	-22.66	-9.234	14.76	389.0	0.049	891.8	1.034
7.722	0.0281	0.0233	0.0256	-25.82	-22.68	-9.232	14.72	390.7	0.056	838.9	1.034
7.669	0.0319	0.0264	0.0290	-25.73	-22.69	-9.230	14.68	392.3	0.063	789.2	1.034
7.616	0.0362	0.0299	0.0329	-25.63	-22.71	-9.228	14.64	393.7	0.071	742.3	1.034
7.562	0.0410	0.0339	0.0373	-25.53	-22.72	-9.228	14.59	394.9	0.081	698.1	1.034
7.509	0.0465	0.0385	0.0423	-25.44	-22.73	-9.226	14.56	395.9	0.092	656.5	1.034
7.456	0.0527	0.0436	0.0480	-25.33	-22.74	-9.225	14.51	396.9	0.104	617.4	1.034
7.402	0.0598	0.0494	0.0543	-25.23	-22.74	-9.225	14.46	397.7	0.118	580.5	1.034
7.349	0.0677	0.0560	0.0616	-25.12	-22.74	-9.223	14.41	398.4	0.134	545.9	1.034

TABLE A.8 : NEQ ZERO FIELD, INITIAL TEMPERATURE SERIES, CONTINUED.

NEQ COOLING CURVE : ZERO FIELD, LOG(T₀) = 8.50, CONT.

Log(T)	n _e	n _H	n _t	log(Λ _{net})	log(Λ _N)	log(U)	log(τ _c)	P ₁₂	ρ ₂₄	C _i	μ ₂₄
7.295	0.0767	0.0635	0.0698	-25.00	-22.73	-9.223	14.34	399.0	0.151	513.3	1.034
7.242	0.0869	0.0719	0.0790	-24.88	-22.71	-9.222	14.27	399.6	0.172	482.6	1.034
7.188	0.0984	0.0814	0.0895	-24.74	-22.69	-9.222	14.19	400.1	0.194	453.7	1.034
7.135	0.1115	0.0922	0.1014	-24.60	-22.66	-9.221	14.10	400.5	0.220	426.6	1.034
7.081	0.1262	0.1044	0.1148	-24.46	-22.62	-9.221	14.02	400.9	0.249	401.0	1.034
7.027	0.1429	0.1182	0.1300	-24.32	-22.59	-9.221	13.93	401.2	0.282	377.0	1.034
6.974	0.1618	0.1339	0.1472	-24.20	-22.58	-9.220	13.87	401.5	0.320	354.5	1.034
6.920	0.1832	0.1516	0.1666	-24.10	-22.59	-9.220	13.82	401.8	0.362	333.2	1.034
6.866	0.2074	0.1716	0.1887	-24.01	-22.60	-9.220	13.78	402.0	0.410	313.3	1.034
6.813	0.2348	0.1943	0.2136	-23.91	-22.61	-9.219	13.74	402.2	0.464	294.5	1.034
6.759	0.2658	0.2199	0.2418	-23.80	-22.61	-9.219	13.68	402.3	0.525	276.8	1.034
6.705	0.3008	0.2490	0.2737	-23.67	-22.58	-9.220	13.61	402.5	0.594	260.2	1.034
6.652	0.3405	0.2818	0.3098	-23.53	-22.55	-9.219	13.52	402.6	0.673	244.6	1.034
6.598	0.3854	0.3190	0.3507	-23.39	-22.52	-9.219	13.44	402.7	0.762	230.0	1.035
6.544	0.4362	0.3611	0.3970	-23.26	-22.50	-9.219	13.36	402.8	0.862	216.2	1.035
6.491	0.4937	0.4088	0.4494	-23.12	-22.46	-9.218	13.27	402.9	0.976	203.2	1.035
6.437	0.5587	0.4627	0.5086	-22.95	-22.41	-9.219	13.16	402.9	1.104	191.0	1.035
6.383	0.6322	0.5237	0.5757	-22.75	-22.32	-9.219	13.01	403.0	1.250	179.5	1.035
6.329	0.7154	0.5927	0.6516	-22.52	-22.19	-9.219	12.83	403.0	1.415	168.8	1.035
6.276	0.8094	0.6708	0.7374	-22.28	-22.05	-9.218	12.65	403.0	1.601	158.6	1.035
6.222	0.9158	0.7591	0.8345	-22.08	-21.96	-9.219	12.50	403.0	1.812	149.1	1.035
6.168	1.036	0.8592	0.9445	-21.96	-21.95	-9.219	12.43	403.0	2.051	140.2	1.035
6.115	1.173	0.9724	1.069	-21.86	-21.96	-9.218	12.39	403.0	2.321	131.8	1.036
6.061	1.327	1.101	1.210	-21.77	-21.97	-9.219	12.35	403.0	2.627	123.9	1.036
6.007	1.501	1.245	1.369	-21.67	-21.98	-9.219	12.31	403.0	2.973	116.4	1.036
5.954	1.699	1.409	1.549	-21.56	-21.98	-9.218	12.25	403.0	3.365	109.4	1.036
5.900	1.922	1.595	1.753	-21.44	-21.96	-9.219	12.18	402.9	3.807	102.9	1.036
5.846	2.174	1.805	1.984	-21.29	-21.93	-9.219	12.09	402.9	4.308	96.71	1.036
5.793	2.460	2.042	2.245	-21.12	-21.87	-9.218	11.97	402.9	4.874	90.92	1.036
5.739	2.782	2.309	2.539	-20.97	-21.82	-9.219	11.87	402.9	5.513	85.49	1.036
5.686	3.146	2.612	2.872	-20.83	-21.79	-9.218	11.79	402.9	6.236	80.38	1.036
5.632	3.560	2.956	3.250	-20.69	-21.76	-9.219	11.70	402.9	7.057	75.56	1.036
5.578	4.028	3.345	3.677	-20.54	-21.71	-9.219	11.60	402.9	7.985	71.03	1.036
5.525	4.556	3.784	4.160	-20.35	-21.63	-9.219	11.47	402.9	9.033	66.78	1.036
5.471	5.152	4.281	4.706	-20.15	-21.54	-9.219	11.32	402.8	10.22	62.79	1.037
5.419	5.807	4.825	5.304	-19.98	-21.46	-9.219	11.20	402.8	11.52	59.14	1.037
5.367	6.543	5.438	5.979	-19.82	-21.41	-9.219	11.10	402.8	12.98	55.70	1.037
5.315	7.387	6.141	6.751	-19.68	-21.38	-9.218	11.01	402.7	14.66	52.42	1.037
5.261	8.352	6.945	7.635	-19.56	-21.37	-9.219	10.94	402.7	16.58	49.28	1.037
5.207	9.449	7.860	8.640	-19.46	-21.37	-9.219	10.90	402.6	18.76	46.32	1.037
5.154	10.69	8.895	9.778	-19.36	-21.38	-9.219	10.85	402.5	21.23	43.54	1.037
5.100	12.09	10.07	11.07	-19.28	-21.41	-9.219	10.82	402.4	24.03	40.92	1.038
5.046	13.67	11.39	12.52	-19.21	-21.44	-9.220	10.81	402.3	27.20	38.46	1.038
4.992	15.46	12.89	14.17	-19.14	-21.48	-9.220	10.79	402.1	30.78	36.14	1.039
4.939	17.48	14.59	16.04	-19.08	-21.53	-9.220	10.78	401.9	34.83	33.97	1.039
4.885	19.75	16.51	18.15	-19.02	-21.57	-9.220	10.78	401.6	39.42	31.92	1.040
4.831	22.32	18.69	20.55	-18.96	-21.62	-9.221	10.77	401.2	44.61	29.99	1.041
4.777	25.22	21.15	23.25	-18.91	-21.68	-9.221	10.77	400.9	50.49	28.18	1.042
4.724	28.50	23.94	26.31	-18.87	-21.74	-9.221	10.79	400.6	57.14	26.48	1.042
4.673	31.95	26.88	29.55	-18.83	-21.80	-9.222	10.79	400.3	64.16	24.98	1.043
4.628	35.39	29.82	32.78	-18.79	-21.85	-9.222	10.80	400.0	71.17	23.71	1.044
4.588	38.81	32.75	36.01	-18.76	-21.90	-9.222	10.81	399.6	78.18	22.61	1.045
4.533	43.93	37.16	40.85	-18.71	-21.96	-9.223	10.81	399.1	88.71	21.21	1.046
4.484	49.01	41.57	45.70	-18.66	-22.01	-9.223	10.81	398.6	99.23	20.04	1.048
4.440	54.02	45.95	50.52	-18.62	-22.06	-9.225	10.81	398.0	109.7	19.05	1.049
4.389	60.53	51.72	56.86	-18.60	-22.14	-9.225	10.84	397.1	123.5	17.93	1.052
4.344	66.85	57.43	63.13	-18.59	-22.22	-9.226	10.88	396.0	137.1	17.00	1.055
4.303	72.99	63.08	69.35	-18.60	-22.30	-9.228	10.92	394.7	150.6	16.19	1.058
4.257	80.37	70.09	77.05	-18.62	-22.41	-9.230	10.99	392.9	167.3	15.33	1.063
4.216	87.43	77.04	84.69	-18.64	-22.51	-9.232	11.04	390.9	183.9	14.58	1.068
4.172	95.46	85.33	93.81	-18.68	-22.63	-9.235	11.12	388.0	203.7	13.80	1.076
4.132	103.0	93.57	102.9	-18.72	-22.74	-9.238	11.19	384.8	223.4	13.13	1.085
4.089	111.1	103.1	113.4	-18.75	-22.85	-9.244	11.26	380.7	246.2	12.44	1.097
4.046	119.5	114.0	125.3	-18.78	-22.95	-9.249	11.32	375.7	272.0	11.75	1.111
4.002	128.1	126.1	138.6	-18.78	-23.03	-9.256	11.35	370.0	301.0	11.09	1.129

TABLE A.9 : NEQ FULL FIELD ABUNDANCE SERIES

NEQ COOLING CURVE : FULL FIELD, $\text{Log}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -0.5$

Log(T)	Number Densities			Cooling Properties				General Plasma Properties ^a			
	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_1	$\bar{\mu}_{24}$
7.500	0.0349	0.0300	0.0324	-25.78	-22.83	-9.356	14.65	296.1	0.078	663.9	0.998
7.444	0.0420	0.0360	0.0389	-25.63	-22.85	-9.332	14.60	310.6	0.081	620.4	0.998
7.396	0.0486	0.0417	0.0451	-25.52	-22.86	-9.316	14.57	321.8	0.093	586.8	0.998
7.346	0.0561	0.0481	0.0520	-25.40	-22.87	-9.304	14.53	331.2	0.108	554.3	0.998
7.296	0.0644	0.0553	0.0597	-25.29	-22.87	-9.294	14.49	339.2	0.124	523.3	0.998
7.246	0.0739	0.0634	0.0685	-25.17	-22.88	-9.284	14.44	346.1	0.142	493.6	0.998
7.194	0.0845	0.0725	0.0784	-25.05	-22.87	-9.278	14.38	351.9	0.163	465.3	0.998
7.143	0.0966	0.0829	0.0895	-24.93	-22.87	-9.271	14.33	357.0	0.186	438.5	0.998
7.091	0.1102	0.0945	0.1021	-24.81	-22.86	-9.266	14.27	361.4	0.212	413.1	0.998
7.039	0.1255	0.1077	0.1164	-24.68	-22.85	-9.261	14.20	365.3	0.241	389.0	0.998
6.986	0.1429	0.1227	0.1325	-24.56	-22.84	-9.258	14.14	368.6	0.275	366.2	0.998
6.934	0.1626	0.1395	0.1507	-24.46	-22.85	-9.254	14.10	371.5	0.313	344.7	0.998
6.881	0.1848	0.1586	0.1713	-24.36	-22.86	-9.251	14.06	374.1	0.355	324.4	0.998
6.828	0.2100	0.1802	0.1947	-24.26	-22.87	-9.249	14.02	376.3	0.404	305.3	0.998
6.775	0.2384	0.2046	0.2211	-24.15	-22.87	-9.247	13.96	378.3	0.458	287.2	0.998
6.722	0.2706	0.2323	0.2509	-24.03	-22.87	-9.245	13.90	380.0	0.520	270.2	0.998
6.669	0.3071	0.2636	0.2847	-23.91	-22.85	-9.243	13.84	381.5	0.591	254.2	0.998
6.616	0.3483	0.2990	0.3229	-23.78	-22.83	-9.241	13.76	382.8	0.670	239.1	0.998
6.563	0.3949	0.3390	0.3662	-23.65	-22.81	-9.239	13.69	384.0	0.760	224.8	0.998
6.509	0.4477	0.3844	0.4152	-23.52	-22.79	-9.239	13.61	385.0	0.861	211.4	0.998
6.456	0.5074	0.4357	0.4706	-23.38	-22.76	-9.237	13.53	385.9	0.976	198.8	0.998
6.403	0.5750	0.4937	0.5333	-23.21	-22.69	-9.236	13.42	386.7	1.106	187.0	0.998
6.349	0.6514	0.5594	0.6043	-23.01	-22.60	-9.236	13.27	387.3	1.253	175.8	0.998
6.296	0.7379	0.6338	0.6846	-22.78	-22.49	-9.235	13.10	387.9	1.420	165.3	0.998
6.242	0.8358	0.7179	0.7755	-22.58	-22.39	-9.235	12.95	388.5	1.608	155.4	0.998
6.189	0.9466	0.8131	0.8783	-22.43	-22.35	-9.234	12.85	388.9	1.822	146.1	0.998
6.135	1.072	0.9209	0.9948	-22.33	-22.36	-9.234	12.81	389.3	2.063	137.4	0.998
6.081	1.214	1.043	1.127	-22.23	-22.36	-9.233	12.76	389.7	2.336	129.1	0.998
6.028	1.374	1.181	1.276	-22.11	-22.36	-9.233	12.70	390.0	2.646	121.4	0.998
5.974	1.556	1.337	1.444	-21.99	-22.34	-9.233	12.63	390.3	2.996	114.1	0.998
5.921	1.761	1.514	1.635	-21.85	-22.31	-9.232	12.55	390.5	3.391	107.3	0.998
5.867	1.994	1.714	1.851	-21.69	-22.25	-9.232	12.44	390.7	3.839	100.9	0.998
5.814	2.256	1.939	2.094	-21.49	-22.16	-9.231	12.29	390.9	4.344	94.87	0.999
5.760	2.552	2.194	2.370	-21.30	-22.08	-9.232	12.16	391.1	4.915	89.20	0.999
5.706	2.889	2.483	2.682	-21.15	-22.03	-9.232	12.06	391.2	5.564	83.86	0.999
5.653	3.270	2.811	3.036	-21.01	-22.01	-9.231	11.98	391.4	6.298	78.83	0.999
5.599	3.701	3.181	3.437	-20.87	-21.97	-9.231	11.89	391.5	7.128	74.11	0.999
5.546	4.187	3.600	3.888	-20.69	-21.90	-9.231	11.76	391.6	8.065	69.68	0.999
5.492	4.736	4.073	4.399	-20.48	-21.80	-9.231	11.61	391.6	9.124	65.52	0.999
5.439	5.354	4.604	4.973	-20.27	-21.70	-9.231	11.45	391.7	10.32	61.62	0.999
5.387	6.032	5.188	5.604	-20.10	-21.63	-9.231	11.33	391.7	11.62	58.06	0.999
5.335	6.802	5.851	6.320	-19.95	-21.58	-9.231	11.23	391.8	13.11	54.67	0.999
5.282	7.685	6.612	7.143	-19.82	-21.56	-9.231	11.16	391.8	14.81	51.43	0.999
5.228	8.695	7.483	8.083	-19.71	-21.56	-9.231	11.10	391.8	16.76	48.34	0.999
5.175	9.838	8.469	9.148	-19.61	-21.57	-9.230	11.06	391.8	18.97	45.44	0.999
5.121	11.13	9.585	10.35	-19.53	-21.59	-9.231	11.03	391.7	21.47	42.71	1.000
5.067	12.59	10.85	11.72	-19.45	-21.62	-9.231	11.00	391.7	24.30	40.14	1.000
5.013	14.24	12.28	13.26	-19.39	-21.66	-9.232	11.00	391.5	27.51	37.73	1.000
4.960	16.09	13.89	15.01	-19.33	-21.71	-9.231	10.99	391.4	31.13	35.46	1.001
4.906	18.19	15.72	16.98	-19.28	-21.77	-9.232	10.99	391.1	35.22	33.32	1.001
4.852	20.55	17.79	19.22	-19.23	-21.83	-9.232	10.99	390.8	39.85	31.32	1.002
4.799	23.21	20.13	21.74	-19.19	-21.89	-9.232	11.01	390.5	45.10	29.43	1.003
4.745	26.20	22.78	24.60	-19.15	-21.96	-9.233	11.02	390.1	51.03	27.65	1.004
4.691	29.61	25.78	27.85	-19.11	-22.02	-9.233	11.03	389.7	57.75	25.98	1.005
4.642	33.13	28.90	31.21	-19.07	-22.08	-9.233	11.04	389.4	64.74	24.53	1.006
4.597	36.66	32.04	34.61	-19.03	-22.13	-9.234	11.05	389.0	71.77	23.28	1.007
4.556	40.21	35.20	38.03	-18.98	-22.17	-9.234	11.04	388.7	78.87	22.20	1.008
4.501	45.55	39.99	43.20	-18.91	-22.20	-9.235	11.02	388.1	89.60	20.81	1.010
4.452	50.83	44.77	48.36	-18.84	-22.24	-9.235	11.00	387.4	100.3	19.65	1.011
4.408	56.00	49.51	53.48	-18.79	-22.27	-9.236	10.99	386.7	110.9	18.67	1.013
4.357	62.68	55.74	60.21	-18.76	-22.34	-9.237	11.01	385.6	124.9	17.57	1.016
4.311	69.12	61.89	66.85	-18.75	-22.41	-9.239	11.04	384.2	138.7	16.65	1.020

a. $P_{12} = P \times 10^{12}$, $\rho_{24} = \rho \times 10^{24}$, $\mu_{24} = \mu \times 10^{24}$

TABLE A.9 : NEQ FULL FIELD ABUNDANCE SERIES, *CONTINUED.*NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -0.5$, *CONT.*

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
4.270	75.32	67.99	73.45	-18.76	-22.51	-9.241	11.09	382.7	152.3	15.85	1.024
4.224	82.78	75.63	81.70	-18.80	-22.63	-9.244	11.17	380.4	169.4	14.98	1.030
4.182	89.90	83.36	90.04	-18.86	-22.76	-9.247	11.27	377.6	186.7	14.22	1.038
4.135	98.04	92.93	100.4	-18.94	-22.93	-9.251	11.38	373.4	208.2	13.39	1.049
4.089	105.7	103.2	111.5	-19.04	-23.11	-9.258	11.52	368.1	231.2	12.62	1.064
4.041	113.2	115.2	124.4	-19.15	-23.29	-9.267	11.66	360.8	258.1	11.82	1.086
3.992	119.9	128.9	139.2	-19.24	-23.46	-9.278	11.77	351.6	288.7	11.03	1.114

NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -1.0$

Log(T)	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0339	0.0300	0.0319	-25.85	-22.89	-9.366	14.70	289.5	0.072	673.9	0.968
7.444	0.0408	0.0360	0.0384	-25.71	-22.91	-9.341	14.67	303.7	0.077	629.5	0.968
7.396	0.0472	0.0417	0.0444	-25.60	-22.92	-9.326	14.63	314.7	0.089	595.4	0.968
7.346	0.0545	0.0481	0.0512	-25.49	-22.94	-9.314	14.60	323.9	0.102	562.5	0.968
7.296	0.0626	0.0553	0.0589	-25.39	-22.95	-9.303	14.57	331.7	0.118	531.0	0.968
7.245	0.0718	0.0634	0.0675	-25.28	-22.96	-9.295	14.53	338.4	0.135	500.9	0.968
7.194	0.0821	0.0726	0.0773	-25.17	-22.97	-9.287	14.48	344.2	0.154	472.2	0.968
7.143	0.0938	0.0829	0.0883	-25.06	-22.98	-9.281	14.44	349.1	0.176	445.0	0.968
7.091	0.1070	0.0946	0.1007	-24.95	-22.99	-9.275	14.39	353.4	0.201	419.2	0.968
7.039	0.1220	0.1078	0.1148	-24.85	-22.99	-9.270	14.35	357.2	0.229	394.7	0.968
6.986	0.1388	0.1227	0.1306	-24.74	-23.00	-9.267	14.30	360.4	0.261	371.6	0.968
6.934	0.1579	0.1396	0.1486	-24.64	-23.01	-9.263	14.26	363.3	0.297	349.8	0.968
6.881	0.1795	0.1587	0.1689	-24.54	-23.02	-9.261	14.22	365.8	0.337	329.2	0.968
6.828	0.2040	0.1803	0.1919	-24.44	-23.03	-9.258	14.18	368.0	0.383	309.8	0.968
6.775	0.2316	0.2048	0.2180	-24.33	-23.04	-9.256	14.12	369.9	0.435	291.5	0.968
6.722	0.2629	0.2324	0.2474	-24.22	-23.04	-9.254	14.07	371.6	0.494	274.2	0.968
6.669	0.2983	0.2637	0.2807	-24.11	-23.03	-9.252	14.02	373.0	0.561	257.9	0.968
6.616	0.3384	0.2992	0.3184	-23.99	-23.02	-9.250	13.95	374.3	0.636	242.6	0.968
6.562	0.3837	0.3392	0.3611	-23.87	-23.01	-9.250	13.89	375.5	0.721	228.2	0.968
6.509	0.4350	0.3846	0.4094	-23.75	-23.00	-9.248	13.83	376.5	0.818	214.6	0.968
6.456	0.4930	0.4359	0.4640	-23.61	-22.97	-9.247	13.74	377.4	0.927	201.8	0.968
6.402	0.5587	0.4940	0.5258	-23.47	-22.93	-9.247	13.66	378.1	1.050	189.7	0.969
6.349	0.6330	0.5598	0.5958	-23.30	-22.87	-9.245	13.54	378.8	1.190	178.4	0.969
6.295	0.7171	0.6342	0.6750	-23.11	-22.79	-9.245	13.41	379.4	1.348	167.7	0.969
6.242	0.8123	0.7184	0.7646	-22.93	-22.72	-9.244	13.28	379.9	1.527	157.7	0.969
6.188	0.9200	0.8137	0.8660	-22.79	-22.70	-9.244	13.20	380.4	1.730	148.3	0.969
6.135	1.042	0.9215	0.9808	-22.69	-22.70	-9.243	13.15	380.8	1.959	139.4	0.969
6.081	1.180	1.044	1.111	-22.58	-22.70	-9.243	13.09	381.2	2.219	131.1	0.969
6.027	1.336	1.182	1.258	-22.46	-22.68	-9.243	13.03	381.5	2.512	123.2	0.969
5.974	1.513	1.338	1.424	-22.31	-22.65	-9.242	12.93	381.8	2.845	115.8	0.969
5.920	1.712	1.515	1.612	-22.16	-22.60	-9.242	12.84	382.0	3.221	108.9	0.969
5.867	1.939	1.715	1.825	-21.97	-22.52	-9.241	12.70	382.2	3.646	102.4	0.969
5.813	2.194	1.941	2.066	-21.75	-22.41	-9.241	12.54	382.4	4.126	96.27	0.969
5.760	2.482	2.196	2.337	-21.54	-22.31	-9.241	12.38	382.6	4.669	90.52	0.969
5.706	2.809	2.485	2.645	-21.38	-22.25	-9.241	12.27	382.7	5.284	85.11	0.969
5.652	3.179	2.813	2.994	-21.25	-22.23	-9.241	12.20	382.8	5.981	80.01	0.969
5.599	3.598	3.184	3.389	-21.11	-22.20	-9.241	12.11	383.0	6.770	75.21	0.969
5.545	4.072	3.603	3.835	-20.92	-22.11	-9.241	11.97	383.0	7.660	70.71	0.969
5.492	4.605	4.075	4.337	-20.69	-21.99	-9.240	11.80	383.1	8.664	66.50	0.969
5.438	5.210	4.611	4.908	-20.47	-21.88	-9.241	11.63	383.2	9.804	62.52	0.969
5.386	5.877	5.201	5.536	-20.28	-21.79	-9.240	11.49	383.2	11.06	58.87	0.969
5.334	6.629	5.868	6.246	-20.12	-21.74	-9.240	11.39	383.3	12.48	55.43	0.969
5.281	7.493	6.633	7.060	-20.00	-21.72	-9.240	11.32	383.3	14.10	52.13	0.969
5.227	8.479	7.508	7.991	-19.89	-21.72	-9.240	11.26	383.3	15.96	49.00	0.969
5.173	9.594	8.497	9.044	-19.79	-21.73	-9.240	11.22	383.3	18.07	46.06	0.969
5.119	10.85	9.617	10.24	-19.71	-21.75	-9.241	11.19	383.3	20.45	43.30	0.970
5.066	12.28	10.88	11.58	-19.64	-21.79	-9.240	11.18	383.2	23.14	40.69	0.970
5.012	13.89	12.32	13.11	-19.57	-21.83	-9.240	11.16	383.1	26.19	38.25	0.970
4.958	15.70	13.94	14.84	-19.52	-21.89	-9.241	11.16	382.9	29.64	35.95	0.971
4.905	17.73	15.77	16.79	-19.47	-21.95	-9.241	11.16	382.7	33.53	33.78	0.971
4.851	20.03	17.84	18.99	-19.43	-22.01	-9.242	11.18	382.4	37.94	31.75	0.972
4.797	22.63	20.20	21.50	-19.39	-22.08	-9.242	11.19	382.0	42.94	29.83	0.973

TABLE A.9 : NEQ FULL FIELD ABUNDANCE SERIES, *CONTINUED.*

NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -1.0$, *CONT.*

$\text{Log}(T)$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
4.744	25.55	22.86	24.33	-19.35	-22.15	-9.242	11.20	381.6	48.60	28.02	0.974
4.690	28.85	25.87	27.53	-19.31	-22.21	-9.243	11.22	381.1	55.00	26.32	0.975
4.638	32.45	29.15	31.03	-19.27	-22.27	-9.243	11.23	380.8	61.98	24.79	0.976
4.591	36.09	32.49	34.58	-19.21	-22.31	-9.244	11.21	380.4	69.07	23.47	0.977
4.548	39.77	35.88	38.19	-19.15	-22.33	-9.244	11.20	380.0	76.28	22.32	0.978
4.490	45.33	41.02	43.66	-19.04	-22.34	-9.244	11.14	379.4	87.22	20.86	0.980
4.439	50.80	46.14	49.11	-18.95	-22.35	-9.245	11.10	378.7	98.10	19.65	0.982
4.394	56.11	51.17	54.47	-18.89	-22.37	-9.246	11.09	377.9	108.8	18.64	0.984
4.341	62.90	57.74	61.46	-18.84	-22.43	-9.248	11.08	376.7	122.8	17.52	0.987
4.295	69.37	64.19	68.32	-18.84	-22.51	-9.250	11.13	375.2	136.5	16.58	0.991
4.254	75.57	70.59	75.13	-18.86	-22.61	-9.252	11.18	373.4	150.1	15.77	0.996
4.207	82.96	78.62	83.68	-18.92	-22.76	-9.255	11.28	370.7	167.1	14.89	1.003
4.164	89.95	86.83	92.42	-19.00	-22.92	-9.259	11.40	367.3	184.6	14.11	1.012
4.123	96.53	95.51	101.7	-19.11	-23.10	-9.264	11.54	362.9	203.1	13.37	1.025
4.080	102.7	105.3	112.0	-19.26	-23.32	-9.272	11.72	356.7	223.8	12.63	1.042
4.030	107.9	118.1	125.7	-19.53	-23.66	-9.285	12.01	345.9	251.1	11.74	1.075

NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -1.5$
 $\text{Log}(T) = 7.49$ down to 4.00

$\text{Log}(T)$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0339	0.0300	0.0319	-25.88	-22.91	-9.366	14.73	289.2	0.072	674.8	0.966
7.444	0.0407	0.0361	0.0384	-25.74	-22.93	-9.342	14.69	303.4	0.076	630.2	0.966
7.395	0.0472	0.0418	0.0444	-25.63	-22.95	-9.327	14.66	314.4	0.088	596.1	0.966
7.346	0.0544	0.0482	0.0513	-25.53	-22.97	-9.314	14.64	323.6	0.102	563.1	0.966
7.296	0.0625	0.0554	0.0589	-25.42	-22.99	-9.304	14.60	331.4	0.117	531.5	0.966
7.245	0.0717	0.0635	0.0675	-25.32	-23.01	-9.295	14.57	338.0	0.134	501.4	0.966
7.194	0.0820	0.0726	0.0773	-25.22	-23.02	-9.288	14.53	343.8	0.154	472.7	0.966
7.142	0.0937	0.0830	0.0883	-25.12	-23.04	-9.282	14.50	348.8	0.176	445.4	0.966
7.091	0.1069	0.0946	0.1007	-25.02	-23.05	-9.276	14.46	353.1	0.201	419.6	0.966
7.038	0.1218	0.1079	0.1148	-24.92	-23.07	-9.272	14.42	356.8	0.228	395.2	0.966
6.986	0.1386	0.1228	0.1307	-24.83	-23.08	-9.268	14.39	360.1	0.260	372.0	0.966
6.934	0.1577	0.1397	0.1486	-24.73	-23.10	-9.264	14.35	362.9	0.296	350.2	0.966
6.881	0.1793	0.1588	0.1690	-24.63	-23.11	-9.261	14.31	365.4	0.336	329.6	0.966
6.828	0.2037	0.1804	0.1920	-24.54	-23.13	-9.258	14.28	367.6	0.382	310.1	0.966
6.775	0.2313	0.2048	0.2180	-24.44	-23.14	-9.256	14.23	369.5	0.434	291.8	0.966
6.722	0.2625	0.2325	0.2474	-24.34	-23.15	-9.254	14.19	371.2	0.493	274.5	0.966
6.669	0.2979	0.2638	0.2807	-24.24	-23.16	-9.252	14.15	372.6	0.559	258.2	0.966
6.616	0.3379	0.2993	0.3185	-24.13	-23.16	-9.251	14.09	373.9	0.634	242.9	0.966
6.562	0.3831	0.3394	0.3611	-24.03	-23.17	-9.250	14.05	375.1	0.719	228.4	0.966
6.509	0.4343	0.3847	0.4094	-23.92	-23.17	-9.249	14.00	376.1	0.815	214.8	0.966
6.456	0.4923	0.4361	0.4640	-23.81	-23.16	-9.247	13.94	377.0	0.924	202.0	0.966
6.402	0.5579	0.4942	0.5259	-23.68	-23.15	-9.247	13.87	377.7	1.047	189.9	0.966
6.349	0.6321	0.5600	0.5959	-23.54	-23.12	-9.246	13.78	378.4	1.186	178.6	0.966
6.295	0.7161	0.6344	0.6751	-23.39	-23.07	-9.245	13.69	379.0	1.344	167.9	0.966
6.242	0.8112	0.7186	0.7647	-23.24	-23.03	-9.244	13.59	379.6	1.522	157.9	0.966
6.188	0.9188	0.8139	0.8661	-23.12	-23.02	-9.244	13.52	380.0	1.724	148.5	0.966
6.135	1.041	0.9218	0.9809	-23.01	-23.02	-9.243	13.47	380.4	1.953	139.6	0.966
6.081	1.178	1.044	1.111	-22.91	-23.02	-9.243	13.42	380.8	2.212	131.2	0.966
6.027	1.334	1.182	1.258	-22.79	-23.01	-9.243	13.36	381.1	2.504	123.4	0.966
5.974	1.511	1.338	1.424	-22.65	-22.99	-9.242	13.27	381.4	2.836	116.0	0.966
5.920	1.711	1.515	1.613	-22.51	-22.95	-9.242	13.19	381.7	3.211	109.0	0.966
5.866	1.937	1.716	1.826	-22.35	-22.89	-9.242	13.08	381.9	3.635	102.5	0.966
5.813	2.192	1.942	2.067	-22.14	-22.79	-9.242	12.93	382.1	4.115	96.36	0.966
5.759	2.481	2.198	2.339	-21.93	-22.70	-9.242	12.77	382.2	4.658	90.59	0.966
5.706	2.809	2.488	2.648	-21.79	-22.66	-9.241	12.68	382.4	5.272	85.17	0.966
5.652	3.179	2.817	2.997	-21.66	-22.64	-9.241	12.61	382.5	5.968	80.06	0.966
5.598	3.599	3.188	3.393	-21.52	-22.61	-9.241	12.52	382.6	6.755	75.26	0.966
5.544	4.073	3.609	3.840	-21.33	-22.52	-9.241	12.38	382.7	7.646	70.75	0.966
5.491	4.607	4.082	4.344	-21.08	-22.38	-9.241	12.19	382.8	8.648	66.53	0.966
5.438	5.209	4.616	4.912	-20.83	-22.24	-9.241	11.99	382.9	9.779	62.57	0.966
5.384	5.895	5.223	5.558	-20.62	-22.13	-9.241	11.84	383.0	11.07	58.83	0.966
5.330	6.671	5.912	6.291	-20.45	-22.07	-9.241	11.72	383.0	12.53	55.30	0.966

TABLE A.9 : NEQ FULL FIELD ABUNDANCE SERIES, *CONTINUED*.NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(\text{To}) = 7.50$, $[\text{Fe}/\text{H}] = -1.5$, *CONT.*

$\text{Log}(\text{T})$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(\text{U})$	$\log(\tau_c)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
5.277	7.550	6.691	7.120	-20.32	-22.05	-9.240	11.64	383.1	14.18	51.98	0.966
5.223	8.544	7.573	8.059	-20.21	-22.05	-9.241	11.59	383.1	16.04	48.86	0.966
5.169	9.667	8.571	9.120	-20.11	-22.06	-9.241	11.54	383.1	18.16	45.93	0.967
5.116	10.94	9.700	10.32	-20.02	-22.08	-9.240	11.50	383.0	20.55	43.17	0.967
5.062	12.37	10.98	11.68	-19.94	-22.10	-9.241	11.48	382.9	23.26	40.58	0.967
5.008	13.98	12.42	13.22	-19.87	-22.14	-9.241	11.46	382.8	26.32	38.13	0.968
4.955	15.79	14.05	14.95	-19.82	-22.19	-9.241	11.46	382.5	29.76	35.85	0.968
4.902	17.80	15.87	16.89	-19.77	-22.25	-9.242	11.47	382.1	33.62	33.71	0.969
4.849	20.07	17.94	19.09	-19.73	-22.32	-9.242	11.48	381.7	38.01	31.69	0.970
4.795	22.64	20.30	21.60	-19.70	-22.39	-9.243	11.50	381.1	43.00	29.77	0.972
4.741	25.54	22.97	24.44	-19.65	-22.45	-9.244	11.50	380.5	48.66	27.96	0.974
4.688	28.80	26.00	27.66	-19.60	-22.50	-9.244	11.51	379.8	55.07	26.26	0.975
4.634	32.45	29.39	31.27	-19.52	-22.53	-9.246	11.48	379.2	62.26	24.68	0.977
4.585	36.27	32.93	35.04	-19.43	-22.53	-9.246	11.44	378.7	69.77	23.30	0.978
4.540	40.16	36.54	38.89	-19.32	-22.51	-9.246	11.37	378.3	77.42	22.10	0.979
4.499	44.07	40.19	42.77	-19.20	-22.48	-9.246	11.29	377.8	85.15	21.06	0.981
4.444	49.78	45.58	48.50	-19.06	-22.45	-9.247	11.20	377.1	96.56	19.76	0.982
4.397	55.23	50.77	54.03	-18.97	-22.44	-9.248	11.16	376.3	107.6	18.70	0.985
4.356	60.41	55.81	59.39	-18.91	-22.47	-9.249	11.14	375.4	118.2	17.82	0.987
4.308	66.99	62.37	66.37	-18.89	-22.54	-9.251	11.16	373.9	132.1	16.82	0.991
4.265	73.24	68.84	73.25	-18.91	-22.64	-9.253	11.22	372.2	145.8	15.98	0.996
4.217	80.65	76.93	81.86	-18.97	-22.79	-9.256	11.32	369.5	163.0	15.06	1.003
4.172	87.63	85.22	90.69	-19.06	-22.96	-9.261	11.45	365.9	180.5	14.24	1.013
4.129	94.13	94.08	100.1	-19.20	-23.18	-9.267	11.62	361.1	199.3	13.46	1.026
4.084	99.92	104.4	111.1	-19.43	-23.47	-9.276	11.88	353.5	221.1	12.64	1.048
4.031	95.08	118.0	125.5	-20.05	-24.12	-9.309	12.47	345.2	249.9	11.75	1.133

NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(\text{To}) = 7.50$, $[\text{Fe}/\text{H}] = -2.0$

$\text{Log}(\text{T})$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(\text{U})$	$\log(\tau_c)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0338	0.0300	0.0319	-25.89	-22.92	-9.366	14.74	289.1	0.072	675.0	0.965
7.444	0.0407	0.0361	0.0384	-25.75	-22.94	-9.342	14.70	303.3	0.076	630.4	0.965
7.395	0.0471	0.0418	0.0444	-25.64	-22.96	-9.327	14.67	314.3	0.088	596.2	0.965
7.346	0.0543	0.0482	0.0513	-25.54	-22.98	-9.314	14.65	323.5	0.102	563.3	0.965
7.296	0.0625	0.0554	0.0589	-25.44	-23.00	-9.304	14.62	331.3	0.117	531.7	0.965
7.245	0.0716	0.0635	0.0675	-25.34	-23.02	-9.296	14.59	337.9	0.134	501.5	0.965
7.194	0.0820	0.0726	0.0773	-25.24	-23.04	-9.288	14.55	343.7	0.154	472.8	0.965
7.142	0.0936	0.0830	0.0883	-25.14	-23.06	-9.282	14.52	348.6	0.176	445.6	0.965
7.091	0.1068	0.0947	0.1007	-25.05	-23.08	-9.276	14.49	352.9	0.200	419.7	0.965
7.038	0.1217	0.1079	0.1148	-24.95	-23.10	-9.272	14.45	356.7	0.228	395.3	0.965
6.986	0.1386	0.1228	0.1307	-24.86	-23.11	-9.268	14.42	359.9	0.260	372.2	0.965
6.933	0.1576	0.1397	0.1486	-24.76	-23.13	-9.265	14.38	362.8	0.296	350.3	0.965
6.881	0.1792	0.1588	0.1690	-24.67	-23.15	-9.261	14.35	365.3	0.336	329.7	0.965
6.828	0.2036	0.1804	0.1920	-24.57	-23.16	-9.259	14.31	367.4	0.382	310.2	0.965
6.775	0.2312	0.2049	0.2180	-24.48	-23.18	-9.256	14.27	369.4	0.434	291.9	0.965
6.722	0.2624	0.2325	0.2474	-24.38	-23.20	-9.254	14.23	371.0	0.492	274.6	0.965
6.669	0.2977	0.2639	0.2808	-24.29	-23.21	-9.253	14.20	372.5	0.558	258.3	0.965
6.616	0.3377	0.2993	0.3185	-24.19	-23.22	-9.251	14.15	373.8	0.633	242.9	0.965
6.562	0.3829	0.3394	0.3611	-24.09	-23.23	-9.250	14.11	375.0	0.718	228.5	0.965
6.509	0.4341	0.3848	0.4094	-23.99	-23.24	-9.249	14.06	376.0	0.814	214.9	0.965
6.456	0.4921	0.4361	0.4641	-23.89	-23.25	-9.247	14.02	376.8	0.923	202.1	0.965
6.402	0.5577	0.4943	0.5259	-23.78	-23.25	-9.247	13.97	377.6	1.046	190.0	0.965
6.349	0.6319	0.5600	0.5959	-23.67	-23.24	-9.246	13.91	378.3	1.185	178.7	0.965
6.295	0.7158	0.6345	0.6751	-23.54	-23.22	-9.246	13.84	378.9	1.343	168.0	0.965
6.242	0.8109	0.7187	0.7647	-23.42	-23.21	-9.244	13.77	379.4	1.521	157.9	0.965
6.188	0.9184	0.8140	0.8662	-23.30	-23.21	-9.244	13.70	379.9	1.723	148.5	0.965
6.134	1.040	0.9219	0.9810	-23.20	-23.21	-9.244	13.66	380.3	1.951	139.6	0.965
6.081	1.178	1.044	1.111	-23.09	-23.21	-9.243	13.60	380.7	2.209	131.3	0.965
6.027	1.334	1.182	1.258	-22.98	-23.21	-9.243	13.55	381.0	2.502	123.4	0.965
5.974	1.510	1.339	1.424	-22.86	-23.19	-9.242	13.48	381.3	2.833	116.0	0.965
5.920	1.710	1.516	1.613	-22.73	-23.17	-9.242	13.41	381.6	3.207	109.1	0.965
5.866	1.936	1.716	1.826	-22.59	-23.14	-9.242	13.32	381.8	3.631	102.5	0.965
5.813	2.192	1.943	2.067	-22.42	-23.07	-9.242	13.21	382.0	4.111	96.39	0.965

TABLE A.9 : NEQ FULL FIELD ABUNDANCE SERIES, *CONTINUED*.NEQ COOLING CURVE : FULL FIELD, $\text{Log}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -2.0$, *CONT.*

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
5.759	2.481	2.199	2.340	-22.24	-23.01	-9.242	13.08	382.1	4.654	90.62	0.965
5.705	2.809	2.489	2.649	-22.10	-22.97	-9.242	12.99	382.3	5.268	85.18	0.965
5.652	3.179	2.818	2.999	-21.98	-22.96	-9.241	12.93	382.4	5.964	80.08	0.965
5.598	3.599	3.190	3.394	-21.84	-22.93	-9.241	12.84	382.5	6.751	75.28	0.965
5.544	4.074	3.611	3.842	-21.66	-22.86	-9.241	12.71	382.7	7.641	70.76	0.965
5.491	4.610	4.086	4.348	-21.43	-22.73	-9.241	12.54	382.7	8.648	66.53	0.965
5.437	5.214	4.622	4.918	-21.17	-22.58	-9.241	12.33	382.8	9.781	62.56	0.965
5.384	5.898	5.228	5.563	-20.95	-22.47	-9.241	12.17	382.9	11.06	58.83	0.965
5.330	6.674	5.917	6.296	-20.79	-22.41	-9.241	12.06	382.9	12.52	55.30	0.965
5.276	7.553	6.696	7.125	-20.66	-22.39	-9.241	11.98	383.0	14.17	51.99	0.965
5.223	8.547	7.578	8.064	-20.54	-22.38	-9.240	11.92	383.0	16.04	48.87	0.966
5.169	9.671	8.577	9.126	-20.42	-22.37	-9.241	11.85	383.0	18.15	45.94	0.966
5.115	10.94	9.707	10.33	-20.31	-22.36	-9.241	11.79	383.0	20.54	43.18	0.966
5.062	12.37	10.98	11.69	-20.19	-22.35	-9.241	11.73	382.8	23.25	40.58	0.966
5.008	13.98	12.43	13.23	-20.10	-22.37	-9.241	11.69	382.6	26.31	38.14	0.967
4.955	15.77	14.05	14.95	-20.03	-22.40	-9.241	11.67	382.3	29.73	35.86	0.968
4.903	17.74	15.84	16.85	-19.98	-22.46	-9.242	11.67	381.8	33.52	33.75	0.969
4.851	19.94	17.86	19.00	-19.96	-22.53	-9.242	11.71	381.2	37.79	31.76	0.971
4.798	22.44	20.17	21.46	-19.93	-22.61	-9.243	11.73	380.5	42.69	29.86	0.972
4.744	25.29	22.83	24.29	-19.88	-22.67	-9.245	11.73	379.8	48.31	28.04	0.974
4.690	28.50	25.84	27.49	-19.80	-22.70	-9.246	11.70	379.0	54.67	26.33	0.976
4.637	32.14	29.24	31.11	-19.69	-22.69	-9.246	11.64	378.3	61.87	24.73	0.978
4.584	36.19	33.01	35.13	-19.56	-22.66	-9.247	11.56	377.8	69.86	23.25	0.980
4.536	40.32	36.87	39.24	-19.40	-22.60	-9.247	11.45	377.3	78.03	21.99	0.981
4.493	44.42	40.72	43.33	-19.26	-22.54	-9.248	11.35	376.9	86.18	20.91	0.982
4.437	50.29	46.27	49.24	-19.09	-22.48	-9.249	11.24	376.2	97.92	19.60	0.984
4.391	55.77	51.53	54.83	-18.99	-22.47	-9.249	11.18	375.4	109.0	18.55	0.986
4.350	60.94	56.59	60.22	-18.93	-22.50	-9.250	11.16	374.4	119.8	17.68	0.988
4.302	67.48	63.17	67.21	-18.91	-22.57	-9.252	11.18	372.9	133.7	16.70	0.992
4.260	73.69	69.65	74.12	-18.93	-22.67	-9.254	11.24	371.1	147.4	15.87	0.997
4.212	81.03	77.79	82.77	-19.00	-22.83	-9.258	11.35	368.3	164.6	14.96	1.005
4.167	87.91	86.16	91.68	-19.11	-23.01	-9.263	11.50	364.6	182.3	14.14	1.015
4.124	94.27	95.22	101.3	-19.27	-23.25	-9.269	11.69	359.3	201.5	13.35	1.030
4.077	99.54	106.1	112.9	-19.57	-23.62	-9.280	12.01	350.2	224.6	12.49	1.057
4.036	93.91	116.7	124.1	-20.58	-24.65	-9.309	13.00	343.2	246.9	11.79	1.132

NEQ COOLING CURVE : FULL FIELD, $\text{Log}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -3.0$

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0338	0.0300	0.0319	-25.89	-22.92	-9.366	14.74	289.1	0.072	674.9	0.965
7.444	0.0407	0.0361	0.0384	-25.75	-22.95	-9.342	14.70	303.3	0.076	630.5	0.965
7.395	0.0471	0.0418	0.0444	-25.65	-22.97	-9.327	14.68	314.2	0.088	596.3	0.965
7.346	0.0543	0.0482	0.0513	-25.54	-22.99	-9.314	14.65	323.4	0.102	563.4	0.965
7.296	0.0625	0.0554	0.0589	-25.44	-23.01	-9.304	14.62	331.2	0.117	531.8	0.965
7.245	0.0716	0.0635	0.0675	-25.34	-23.03	-9.296	14.59	337.9	0.134	501.6	0.965
7.194	0.0819	0.0726	0.0773	-25.25	-23.05	-9.288	14.56	343.6	0.154	472.9	0.965
7.142	0.0936	0.0830	0.0883	-25.15	-23.07	-9.282	14.53	348.6	0.176	445.6	0.965
7.091	0.1068	0.0947	0.1007	-25.06	-23.09	-9.276	14.50	352.9	0.200	419.8	0.965
7.038	0.1217	0.1079	0.1148	-24.96	-23.11	-9.272	14.46	356.6	0.228	395.3	0.965
6.986	0.1385	0.1228	0.1307	-24.87	-23.13	-9.268	14.43	359.9	0.260	372.2	0.965
6.933	0.1576	0.1397	0.1486	-24.78	-23.15	-9.265	14.40	362.7	0.296	350.4	0.965
6.881	0.1791	0.1588	0.1690	-24.68	-23.16	-9.261	14.36	365.2	0.336	329.7	0.965
6.828	0.2035	0.1804	0.1920	-24.59	-23.18	-9.259	14.33	367.4	0.382	310.3	0.965
6.775	0.2311	0.2049	0.2180	-24.50	-23.20	-9.256	14.29	369.3	0.433	291.9	0.965
6.722	0.2623	0.2326	0.2474	-24.40	-23.22	-9.255	14.25	371.0	0.492	274.6	0.965
6.669	0.2977	0.2639	0.2808	-24.31	-23.23	-9.253	14.22	372.5	0.558	258.3	0.965
6.616	0.3376	0.2993	0.3185	-24.22	-23.25	-9.251	14.18	373.8	0.633	243.0	0.965
6.562	0.3829	0.3394	0.3611	-24.12	-23.26	-9.250	14.14	374.9	0.718	228.5	0.965
6.509	0.4341	0.3848	0.4094	-24.03	-23.28	-9.249	14.10	375.9	0.814	214.9	0.965
6.456	0.4920	0.4362	0.4641	-23.93	-23.29	-9.247	14.06	376.8	0.923	202.1	0.965
6.402	0.5576	0.4943	0.5259	-23.83	-23.30	-9.247	14.02	377.6	1.046	190.0	0.965
6.349	0.6318	0.5601	0.5959	-23.73	-23.31	-9.246	13.97	378.3	1.185	178.7	0.965

TABLE A.9 : NEQ FULL FIELD ABUNDANCE SERIES *CONTINUED.*NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(\text{To}) = 7.50$, $[\text{Fe}/\text{H}] = -3.0$, *CONT.*

$\text{Log}(\text{T})$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(\text{U})$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
6.295	0.7157	0.6345	0.6751	-23.62	-23.31	-9.246	13.92	378.9	1.342	168.0	0.965
6.242	0.8108	0.7187	0.7647	-23.52	-23.31	-9.244	13.87	379.4	1.520	158.0	0.965
6.188	0.9183	0.8141	0.8662	-23.41	-23.32	-9.244	13.81	379.9	1.722	148.5	0.965
6.134	1.040	0.9220	0.9810	-23.31	-23.32	-9.244	13.77	380.3	1.950	139.6	0.965
6.081	1.178	1.044	1.111	-23.21	-23.32	-9.243	13.72	380.6	2.209	131.3	0.965
6.027	1.334	1.182	1.258	-23.10	-23.32	-9.243	13.67	381.0	2.501	123.4	0.965
5.974	1.510	1.339	1.424	-22.99	-23.32	-9.242	13.61	381.3	2.832	116.0	0.965
5.920	1.710	1.516	1.613	-22.87	-23.31	-9.242	13.55	381.5	3.206	109.1	0.965
5.866	1.936	1.716	1.826	-22.75	-23.30	-9.242	13.48	381.7	3.630	102.6	0.965
5.813	2.191	1.943	2.067	-22.63	-23.28	-9.242	13.42	381.9	4.109	96.41	0.965
5.759	2.481	2.199	2.340	-22.49	-23.26	-9.242	13.33	382.1	4.652	90.63	0.965
5.705	2.808	2.490	2.649	-22.37	-23.24	-9.242	13.26	382.3	5.266	85.20	0.965
5.652	3.179	2.818	2.999	-22.24	-23.21	-9.241	13.19	382.4	5.961	80.09	0.965
5.598	3.599	3.190	3.394	-22.10	-23.19	-9.241	13.10	382.5	6.748	75.29	0.965
5.544	4.073	3.611	3.842	-21.95	-23.14	-9.241	13.00	382.6	7.638	70.77	0.965
5.490	4.611	4.087	4.349	-21.78	-23.08	-9.242	12.89	382.7	8.646	66.53	0.965
5.437	5.218	4.626	4.922	-21.59	-23.00	-9.241	12.75	382.8	9.786	62.54	0.965
5.383	5.906	5.236	5.571	-21.41	-22.93	-9.241	12.63	382.9	11.08	58.80	0.965
5.329	6.684	5.926	6.305	-21.24	-22.87	-9.241	12.51	382.9	12.53	55.27	0.965
5.276	7.564	6.707	7.136	-21.08	-22.82	-9.241	12.40	383.0	14.19	51.96	0.965
5.222	8.561	7.591	8.077	-20.92	-22.76	-9.241	12.30	383.0	16.06	48.84	0.965
5.168	9.687	8.592	9.142	-20.75	-22.69	-9.241	12.18	383.0	18.17	45.91	0.965
5.115	10.96	9.724	10.35	-20.57	-22.62	-9.240	12.06	382.9	20.57	43.15	0.965
5.061	12.39	11.00	11.71	-20.39	-22.56	-9.241	11.93	382.8	23.27	40.56	0.966
5.007	13.99	12.45	13.24	-20.26	-22.53	-9.242	11.85	382.5	26.33	38.12	0.967
4.954	15.78	14.07	14.97	-20.17	-22.54	-9.242	11.81	382.1	29.76	35.83	0.968
4.903	17.71	15.83	16.85	-20.12	-22.60	-9.242	11.81	381.6	33.49	33.76	0.969
4.852	19.84	17.80	18.94	-20.11	-22.68	-9.243	11.85	380.9	37.66	31.80	0.971
4.800	22.27	20.06	21.34	-20.09	-22.77	-9.244	11.88	380.1	42.43	29.93	0.973
4.747	25.07	22.69	24.14	-20.05	-22.83	-9.245	11.90	379.3	48.00	28.11	0.975
4.693	28.25	25.68	27.32	-19.95	-22.84	-9.246	11.85	378.4	54.32	26.40	0.977
4.639	31.86	29.06	30.92	-19.81	-22.80	-9.247	11.76	377.8	61.47	24.79	0.979
4.586	35.96	32.89	35.00	-19.64	-22.74	-9.247	11.64	377.3	69.57	23.29	0.980
4.535	40.30	36.95	39.32	-19.45	-22.65	-9.248	11.50	376.8	78.17	21.96	0.982
4.490	44.56	40.95	43.57	-19.28	-22.57	-9.249	11.37	376.4	86.62	20.84	0.983
4.434	50.52	46.60	49.58	-19.10	-22.50	-9.249	11.25	375.7	98.57	19.52	0.985
4.388	56.01	51.89	55.21	-18.99	-22.48	-9.250	11.18	374.9	109.8	18.48	0.987
4.347	61.17	56.96	60.61	-18.94	-22.51	-9.251	11.17	373.9	120.5	17.62	0.989
4.300	67.69	63.54	67.61	-18.92	-22.58	-9.253	11.20	372.4	134.4	16.65	0.993
4.257	73.87	70.03	74.52	-18.94	-22.68	-9.255	11.25	370.6	148.1	15.82	0.998
4.210	81.16	78.17	83.18	-19.01	-22.84	-9.258	11.37	367.7	165.4	14.91	1.006
4.165	87.97	86.57	92.11	-19.12	-23.03	-9.263	11.51	363.8	183.1	14.10	1.017
4.122	94.19	95.66	101.8	-19.29	-23.27	-9.270	11.71	358.3	202.3	13.31	1.032
4.075	99.07	106.7	113.5	-19.62	-23.67	-9.281	12.06	348.5	225.6	12.43	1.061

NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(\text{To}) = 7.50$, $[\text{Fe}/\text{H}] = \text{NIL}$, ZERO METALS

$\text{Log}(\text{T})$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(\text{U})$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0338	0.0300	0.0319	-25.89	-22.92	-9.366	14.74	289.1	0.072	674.9	0.965
7.444	0.0407	0.0361	0.0384	-25.75	-22.95	-9.342	14.70	303.3	0.076	630.5	0.965
7.395	0.0471	0.0418	0.0444	-25.65	-22.97	-9.327	14.68	314.2	0.088	596.3	0.965
7.346	0.0543	0.0482	0.0513	-25.54	-22.99	-9.314	14.65	323.4	0.102	563.4	0.965
7.296	0.0625	0.0554	0.0589	-25.44	-23.01	-9.304	14.62	331.2	0.117	531.8	0.965
7.245	0.0716	0.0635	0.0675	-25.34	-23.03	-9.296	14.59	337.9	0.134	501.6	0.965
7.194	0.0819	0.0726	0.0773	-25.25	-23.05	-9.288	14.56	343.6	0.154	472.9	0.965
7.142	0.0936	0.0830	0.0883	-25.15	-23.07	-9.282	14.53	348.6	0.176	445.6	0.965
7.091	0.1068	0.0947	0.1007	-25.06	-23.09	-9.276	14.50	352.9	0.200	419.8	0.965
7.038	0.1217	0.1079	0.1148	-24.97	-23.11	-9.272	14.47	356.6	0.228	395.3	0.965
6.986	0.1385	0.1228	0.1307	-24.87	-23.13	-9.268	14.43	359.9	0.260	372.2	0.965
6.933	0.1576	0.1397	0.1486	-24.78	-23.15	-9.265	14.40	362.7	0.295	350.4	0.965
6.881	0.1791	0.1588	0.1690	-24.68	-23.16	-9.261	14.36	365.2	0.336	329.7	0.965
6.828	0.2035	0.1804	0.1920	-24.59	-23.18	-9.259	14.33	367.4	0.382	310.3	0.965

TABLE A.9 : NEQ FULL FIELD ABUNDANCE SERIES, *CONTINUED.*

NEQ COOLING CURVE : ZERO FIELD, LOG(T₀) = 7.50, [Fe/H] = ZERO METALS, *CONT.*

Log(T)	n _e	n _H	n _t	log(Λ_{net})	log(Λ_N)	log(U)	log(τ_c)	P ₁₂	ρ_{24}	C ₁	$\bar{\mu}_{24}$
6.775	0.2311	0.2049	0.2180	-24.50	-23.20	-9.256	14.29	369.3	0.433	291.9	0.965
6.722	0.2623	0.2326	0.2474	-24.41	-23.22	-9.255	14.26	371.0	0.492	274.6	0.965
6.669	0.2977	0.2639	0.2808	-24.31	-23.24	-9.253	14.22	372.5	0.558	258.3	0.965
6.616	0.3376	0.2993	0.3185	-24.22	-23.25	-9.251	14.18	373.8	0.633	243.0	0.965
6.562	0.3829	0.3394	0.3611	-24.13	-23.27	-9.250	14.15	374.9	0.718	228.5	0.965
6.509	0.4341	0.3848	0.4094	-24.03	-23.28	-9.249	14.10	375.9	0.814	214.9	0.965
6.456	0.4920	0.4362	0.4641	-23.94	-23.29	-9.247	14.07	376.8	0.923	202.1	0.965
6.402	0.5576	0.4943	0.5259	-23.84	-23.31	-9.247	14.03	377.6	1.045	190.0	0.965
6.349	0.6317	0.5601	0.5959	-23.74	-23.32	-9.246	13.98	378.3	1.185	178.7	0.965
6.295	0.7157	0.6345	0.6751	-23.63	-23.32	-9.246	13.93	378.9	1.342	168.0	0.965
6.242	0.8107	0.7187	0.7647	-23.53	-23.32	-9.244	13.88	379.4	1.520	158.0	0.965
6.188	0.9183	0.8141	0.8662	-23.43	-23.33	-9.244	13.83	379.9	1.722	148.5	0.965
6.134	1.040	0.9220	0.9810	-23.33	-23.33	-9.244	13.79	380.3	1.950	139.6	0.965
6.081	1.178	1.044	1.111	-23.22	-23.34	-9.243	13.73	380.6	2.208	131.3	0.965
6.027	1.334	1.182	1.258	-23.11	-23.34	-9.243	13.68	381.0	2.501	123.4	0.965
5.974	1.510	1.339	1.424	-23.00	-23.34	-9.242	13.62	381.3	2.832	116.0	0.965
5.920	1.710	1.516	1.613	-22.89	-23.33	-9.242	13.57	381.5	3.206	109.1	0.965
5.866	1.936	1.716	1.826	-22.78	-23.32	-9.242	13.51	381.7	3.630	102.6	0.965
5.813	2.191	1.943	2.067	-22.66	-23.31	-9.242	13.45	381.9	4.109	96.41	0.965
5.759	2.481	2.199	2.340	-22.53	-23.30	-9.242	13.37	382.1	4.652	90.63	0.965
5.705	2.808	2.490	2.649	-22.41	-23.28	-9.242	13.30	382.2	5.266	85.20	0.965
5.652	3.179	2.818	2.999	-22.28	-23.26	-9.241	13.23	382.4	5.961	80.09	0.965
5.598	3.599	3.190	3.394	-22.14	-23.23	-9.241	13.14	382.5	6.748	75.29	0.965
5.544	4.073	3.611	3.842	-22.00	-23.19	-9.241	13.05	382.6	7.638	70.78	0.965
5.490	4.611	4.087	4.349	-21.85	-23.15	-9.242	12.96	382.7	8.646	66.53	0.965
5.437	5.219	4.627	4.923	-21.69	-23.10	-9.241	12.85	382.8	9.786	62.54	0.965
5.383	5.907	5.237	5.572	-21.53	-23.05	-9.241	12.75	382.8	11.08	58.79	0.965
5.329	6.685	5.927	6.307	-21.36	-22.98	-9.241	12.63	382.9	12.54	55.26	0.965
5.276	7.566	6.709	7.138	-21.18	-22.92	-9.240	12.50	383.0	14.19	51.95	0.965
5.222	8.563	7.593	8.079	-21.00	-22.84	-9.241	12.38	383.0	16.06	48.83	0.965
5.168	9.689	8.594	9.144	-20.81	-22.75	-9.241	12.24	383.0	18.18	45.90	0.965
5.114	10.96	9.727	10.35	-20.61	-22.66	-9.241	12.09	382.9	20.57	43.14	0.965
5.061	12.39	11.01	11.71	-20.42	-22.59	-9.241	11.96	382.8	23.28	40.55	0.966
5.007	14.00	12.45	13.25	-20.28	-22.55	-9.241	11.87	382.5	26.33	38.11	0.967
4.954	15.79	14.07	14.97	-20.19	-22.56	-9.242	11.83	382.1	29.76	35.83	0.968
4.903	17.71	15.83	16.84	-20.14	-22.62	-9.242	11.83	381.6	33.49	33.76	0.969
4.852	19.83	17.79	18.93	-20.13	-22.70	-9.243	11.87	380.9	37.64	31.81	0.971
4.801	22.24	20.04	21.33	-20.12	-22.79	-9.244	11.91	380.1	42.40	29.94	0.973
4.747	25.04	22.67	24.12	-20.07	-22.85	-9.245	11.91	379.2	47.95	28.12	0.975
4.693	28.22	25.65	27.30	-19.98	-22.86	-9.246	11.88	378.4	54.26	26.41	0.977
4.640	31.82	29.03	30.89	-19.83	-22.82	-9.246	11.78	377.7	61.41	24.80	0.979
4.586	35.91	32.86	34.96	-19.65	-22.75	-9.247	11.65	377.2	69.50	23.30	0.981
4.535	40.29	36.95	39.32	-19.46	-22.66	-9.248	11.51	376.7	78.16	21.96	0.982
4.490	44.56	40.97	43.59	-19.28	-22.57	-9.249	11.37	376.3	86.65	20.84	0.983
4.434	50.53	46.63	49.62	-19.10	-22.50	-9.249	11.25	375.6	98.64	19.51	0.985
4.387	56.03	51.92	55.25	-18.99	-22.48	-9.250	11.18	374.8	109.8	18.47	0.987
4.347	61.19	57.00	60.65	-18.94	-22.51	-9.251	11.17	373.8	120.6	17.61	0.989
4.299	67.71	63.58	67.65	-18.92	-22.58	-9.253	11.20	372.3	134.5	16.64	0.994
4.257	73.88	70.07	74.55	-18.94	-22.68	-9.255	11.25	370.5	148.2	15.81	0.998
4.209	81.16	78.21	83.21	-19.01	-22.84	-9.259	11.36	367.6	165.4	14.91	1.006
4.165	87.96	86.60	92.14	-19.12	-23.03	-9.263	11.51	363.7	183.2	14.09	1.017
4.122	94.15	95.69	101.8	-19.29	-23.27	-9.270	11.71	358.2	202.4	13.30	1.033
4.075	98.97	106.7	113.5	-19.62	-23.67	-9.282	12.06	348.4	225.6	12.43	1.062

TABLE A.10 : NEQ ZERO FIELD ABUNDANCE SERIES

NEQ COOLING CURVE : ZERO FIELD, $\text{Log}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -0.5$

Log(T)	Number Densities			Cooling Properties				General Plasma Properties ^a			
	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	ρ_{24}	C_1	$\bar{\mu}_{24}$
7.500	0.0349	0.0300	0.0324	-25.78	-22.83	-9.356	14.65	296.1	0.078	663.9	0.998
7.444	0.0420	0.0360	0.0389	-25.63	-22.85	-9.332	14.60	310.6	0.081	620.4	0.998
7.396	0.0486	0.0417	0.0451	-25.52	-22.86	-9.316	14.57	321.8	0.093	586.8	0.998
7.346	0.0561	0.0481	0.0520	-25.40	-22.87	-9.304	14.53	331.2	0.108	554.3	0.998
7.296	0.0644	0.0553	0.0597	-25.29	-22.87	-9.294	14.49	339.2	0.124	523.3	0.998
7.246	0.0739	0.0634	0.0685	-25.17	-22.88	-9.284	14.44	346.1	0.142	493.6	0.998
7.194	0.0845	0.0725	0.0784	-25.05	-22.87	-9.278	14.38	351.9	0.163	465.3	0.998
7.143	0.0966	0.0829	0.0895	-24.93	-22.87	-9.271	14.33	357.0	0.186	438.5	0.998
7.091	0.1102	0.0945	0.1021	-24.80	-22.85	-9.266	14.26	361.4	0.212	413.1	0.998
7.039	0.1255	0.1077	0.1164	-24.68	-22.84	-9.261	14.20	365.3	0.241	389.0	0.998
6.986	0.1429	0.1227	0.1325	-24.56	-22.84	-9.258	14.14	368.6	0.275	366.2	0.998
6.934	0.1626	0.1395	0.1507	-24.45	-22.84	-9.254	14.09	371.5	0.313	344.7	0.998
6.881	0.1848	0.1586	0.1713	-24.35	-22.85	-9.251	14.05	374.1	0.355	324.4	0.998
6.828	0.2100	0.1802	0.1947	-24.25	-22.86	-9.249	14.01	376.3	0.404	305.3	0.998
6.775	0.2384	0.2046	0.2211	-24.14	-22.86	-9.247	13.95	378.3	0.458	287.2	0.998
6.722	0.2706	0.2323	0.2509	-24.02	-22.85	-9.245	13.89	380.0	0.520	270.2	0.998
6.669	0.3071	0.2636	0.2847	-23.89	-22.83	-9.243	13.82	381.5	0.591	254.2	0.998
6.616	0.3483	0.2990	0.3229	-23.76	-22.81	-9.241	13.74	382.8	0.670	239.1	0.998
6.563	0.3949	0.3390	0.3662	-23.63	-22.79	-9.239	13.67	384.0	0.760	224.8	0.998
6.509	0.4477	0.3844	0.4152	-23.50	-22.76	-9.239	13.59	385.0	0.861	211.4	0.998
6.456	0.5074	0.4357	0.4706	-23.35	-22.73	-9.237	13.50	385.9	0.976	198.8	0.998
6.403	0.5750	0.4937	0.5333	-23.18	-22.66	-9.236	13.39	386.6	1.106	187.0	0.998
6.349	0.6514	0.5594	0.6043	-22.98	-22.57	-9.236	13.24	387.3	1.253	175.8	0.998
6.296	0.7379	0.6338	0.6846	-22.76	-22.46	-9.235	13.08	387.9	1.420	165.3	0.998
6.242	0.8357	0.7179	0.7755	-22.56	-22.37	-9.235	12.93	388.4	1.608	155.4	0.998
6.189	0.9465	0.8131	0.8783	-22.42	-22.34	-9.234	12.84	388.9	1.822	146.1	0.998
6.135	1.072	0.9209	0.9947	-22.32	-22.34	-9.234	12.80	389.3	2.063	137.4	0.998
6.081	1.214	1.043	1.126	-22.21	-22.35	-9.234	12.74	389.7	2.336	129.1	0.998
6.028	1.374	1.181	1.276	-22.10	-22.34	-9.233	12.69	390.0	2.646	121.4	0.998
5.974	1.556	1.337	1.444	-21.97	-22.32	-9.233	12.61	390.3	2.995	114.1	0.999
5.921	1.761	1.514	1.635	-21.83	-22.29	-9.232	12.53	390.5	3.391	107.3	0.999
5.867	1.993	1.713	1.851	-21.66	-22.23	-9.232	12.41	390.7	3.839	100.9	0.999
5.814	2.255	1.939	2.094	-21.46	-22.13	-9.231	12.26	390.9	4.343	94.87	0.999
5.760	2.552	2.194	2.370	-21.27	-22.06	-9.232	12.13	391.1	4.915	89.20	0.999
5.706	2.888	2.483	2.682	-21.12	-22.01	-9.232	12.03	391.2	5.563	83.86	0.999
5.653	3.269	2.811	3.036	-20.99	-21.99	-9.231	11.96	391.3	6.297	78.83	0.999
5.599	3.700	3.181	3.436	-20.84	-21.95	-9.231	11.86	391.4	7.127	74.11	0.999
5.546	4.186	3.599	3.888	-20.66	-21.87	-9.231	11.73	391.5	8.064	69.68	0.999
5.492	4.735	4.072	4.398	-20.45	-21.77	-9.231	11.58	391.6	9.12	65.52	0.999
5.439	5.351	4.602	4.972	-20.24	-21.67	-9.231	11.42	391.7	10.31	61.63	0.999
5.387	6.029	5.186	5.602	-20.06	-21.59	-9.231	11.29	391.7	11.62	58.06	0.999
5.335	6.801	5.851	6.320	-19.92	-21.55	-9.231	11.20	391.8	13.11	54.67	0.999
5.282	7.687	6.614	7.145	-19.79	-21.53	-9.231	11.13	391.8	14.82	51.42	0.999
5.228	8.698	7.486	8.087	-19.68	-21.53	-9.231	11.07	391.8	16.77	48.33	0.999
5.174	9.841	8.473	9.152	-19.59	-21.54	-9.231	11.03	391.8	18.98	45.43	0.999
5.121	11.13	9.590	10.36	-19.50	-21.56	-9.231	11.00	391.7	21.48	42.70	1.000
5.067	12.59	10.85	11.72	-19.43	-21.60	-9.231	10.98	391.6	24.32	40.13	1.000
5.013	14.24	12.28	13.27	-19.36	-21.64	-9.231	10.97	391.5	27.52	37.72	1.000
4.959	16.10	13.90	15.02	-19.30	-21.69	-9.232	10.96	391.3	31.15	35.44	1.001
4.906	18.20	15.73	17.00	-19.24	-21.73	-9.231	10.95	391.1	35.25	33.31	1.002
4.852	20.56	17.81	19.24	-19.19	-21.79	-9.232	10.96	390.7	39.90	31.30	1.003
4.798	23.22	20.15	21.77	-19.14	-21.84	-9.233	10.96	390.3	45.15	29.40	1.004
4.744	26.23	22.81	24.64	-19.09	-21.90	-9.233	10.96	390.0	51.10	27.62	1.005
4.691	29.63	25.81	27.88	-19.05	-21.97	-9.233	10.97	389.6	57.83	25.96	1.005
4.641	33.14	28.92	31.24	-19.01	-22.02	-9.234	10.98	389.3	64.78	24.51	1.006
4.597	36.63	32.03	34.59	-18.97	-22.07	-9.234	10.99	388.9	71.75	23.28	1.007
4.557	40.13	35.15	37.96	-18.93	-22.11	-9.234	10.99	388.6	78.74	22.21	1.008
4.502	45.35	39.84	43.04	-18.87	-22.16	-9.235	10.98	388.0	89.26	20.85	1.010
4.454	50.52	44.53	48.10	-18.81	-22.20	-9.236	10.97	387.3	99.76	19.70	1.012
4.411	55.59	49.18	53.12	-18.77	-22.24	-9.237	10.97	386.6	110.2	18.73	1.013
4.360	62.12	55.28	59.71	-18.73	-22.30	-9.238	10.98	385.5	123.8	17.64	1.017
4.315	68.40	61.29	66.20	-18.73	-22.38	-9.240	11.02	384.1	137.3	16.73	1.020

a. $P_{12} = P \times 10^{12}$, $\rho_{24} = \rho \times 10^{24}$, $\mu_{24} = \mu \times 10^{24}$

TABLE A.10 : NEQ ZERO FIELD ABUNDANCE SERIES, *CONTINUED.*NEQ COOLING CURVE : ZERO FIELD, $\text{Log}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -0.5$, *CONT.*

$\text{Log}(T)$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	p_{24}	C_i	$\bar{\mu}_{24}$
4.275	74.41	67.22	72.61	-18.74	-22.47	-9.241	11.06	382.5	150.6	15.94	1.024
4.230	81.52	74.53	80.51	-18.77	-22.59	-9.244	11.13	380.2	167.0	15.09	1.031
4.190	88.16	81.77	88.32	-18.81	-22.70	-9.247	11.21	377.5	183.2	14.36	1.038
4.147	95.43	90.35	97.60	-18.88	-22.85	-9.251	11.31	373.7	202.4	13.59	1.049
4.102	102.9	100.3	108.3	-18.95	-23.00	-9.257	11.42	368.4	224.6	12.81	1.064
4.061	109.1	110.1	118.9	-19.01	-23.13	-9.265	11.50	362.3	246.6	12.12	1.081
4.019	114.9	121.1	130.9	-19.06	-23.24	-9.274	11.57	354.8	271.4	11.43	1.104

NEQ COOLING CURVE : ZERO FIELD, $\text{Log}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -1.0$

$\text{Log}(T)$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	p_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0339	0.0300	0.0319	-25.85	-22.89	-9.366	14.70	289.5	0.072	673.9	0.968
7.444	0.0408	0.0360	0.0384	-25.71	-22.91	-9.341	14.67	303.7	0.077	629.5	0.968
7.396	0.0472	0.0417	0.0444	-25.60	-22.92	-9.326	14.63	314.7	0.089	595.4	0.968
7.346	0.0545	0.0481	0.0512	-25.49	-22.94	-9.314	14.60	323.9	0.102	562.5	0.968
7.296	0.0626	0.0553	0.0589	-25.39	-22.95	-9.303	14.57	331.7	0.118	531.0	0.968
7.245	0.0718	0.0634	0.0675	-25.28	-22.96	-9.295	14.53	338.4	0.135	500.9	0.968
7.194	0.0821	0.0726	0.0773	-25.17	-22.97	-9.287	14.48	344.2	0.154	472.2	0.968
7.143	0.0938	0.0829	0.0883	-25.06	-22.98	-9.281	14.44	349.1	0.176	445.0	0.968
7.091	0.1070	0.0946	0.1007	-24.95	-22.99	-9.275	14.39	353.4	0.201	419.2	0.968
7.039	0.1220	0.1078	0.1148	-24.84	-22.99	-9.270	14.34	357.2	0.229	394.7	0.968
6.986	0.1388	0.1227	0.1306	-24.74	-23.00	-9.267	14.30	360.4	0.261	371.6	0.968
6.934	0.1579	0.1396	0.1486	-24.64	-23.01	-9.263	14.26	363.3	0.297	349.8	0.968
6.881	0.1795	0.1587	0.1689	-24.53	-23.02	-9.261	14.21	365.8	0.337	329.2	0.968
6.828	0.2040	0.1803	0.1919	-24.43	-23.03	-9.258	14.17	368.0	0.383	309.8	0.968
6.775	0.2316	0.2048	0.2180	-24.33	-23.03	-9.256	14.12	369.9	0.435	291.5	0.968
6.722	0.2629	0.2324	0.2474	-24.21	-23.03	-9.254	14.06	371.6	0.494	274.2	0.968
6.669	0.2983	0.2637	0.2807	-24.10	-23.02	-9.252	14.01	373.0	0.561	257.9	0.968
6.616	0.3384	0.2992	0.3184	-23.98	-23.01	-9.250	13.94	374.3	0.636	242.6	0.968
6.562	0.3837	0.3392	0.3611	-23.85	-23.00	-9.250	13.87	375.5	0.721	228.2	0.968
6.509	0.4350	0.3846	0.4094	-23.73	-22.98	-9.248	13.81	376.5	0.818	214.6	0.968
6.456	0.4930	0.4359	0.4640	-23.59	-22.95	-9.247	13.72	377.4	0.927	201.8	0.968
6.402	0.5587	0.4940	0.5258	-23.44	-22.91	-9.247	13.63	378.1	1.050	189.7	0.969
6.349	0.6330	0.5598	0.5958	-23.27	-22.85	-9.245	13.51	378.8	1.190	178.4	0.969
6.295	0.7171	0.6342	0.6750	-23.08	-22.77	-9.245	13.38	379.4	1.348	167.7	0.969
6.242	0.8122	0.7184	0.7646	-22.91	-22.70	-9.244	13.26	379.9	1.527	157.7	0.969
6.188	0.9199	0.8137	0.8661	-22.78	-22.68	-9.244	13.19	380.4	1.730	148.3	0.969
6.135	1.042	0.9215	0.9808	-22.67	-22.68	-9.243	13.13	380.8	1.959	139.4	0.969
6.081	1.180	1.044	1.111	-22.56	-22.68	-9.243	13.07	381.1	2.219	131.1	0.969
6.027	1.336	1.182	1.258	-22.44	-22.66	-9.243	13.01	381.5	2.512	123.2	0.969
5.974	1.512	1.338	1.424	-22.29	-22.63	-9.242	12.91	381.7	2.845	115.8	0.969
5.920	1.712	1.515	1.612	-22.14	-22.58	-9.242	12.82	382.0	3.221	108.9	0.969
5.867	1.938	1.715	1.825	-21.95	-22.49	-9.241	12.68	382.2	3.646	102.4	0.969
5.813	2.193	1.940	2.065	-21.71	-22.37	-9.242	12.50	382.4	4.126	96.27	0.969
5.760	2.482	2.196	2.337	-21.51	-22.28	-9.241	12.35	382.6	4.668	90.53	0.969
5.706	2.809	2.485	2.645	-21.36	-22.23	-9.241	12.25	382.7	5.284	85.11	0.969
5.652	3.179	2.813	2.994	-21.24	-22.21	-9.241	12.19	382.8	5.981	80.01	0.969
5.599	3.598	3.184	3.389	-21.09	-22.18	-9.241	12.09	382.9	6.769	75.21	0.969
5.545	4.071	3.602	3.834	-20.89	-22.09	-9.241	11.94	383.0	7.659	70.72	0.969
5.492	4.604	4.074	4.336	-20.66	-21.96	-9.240	11.77	383.1	8.662	66.50	0.969
5.438	5.209	4.610	4.907	-20.43	-21.84	-9.241	11.59	383.2	9.802	62.52	0.969
5.386	5.874	5.200	5.534	-20.25	-21.76	-9.241	11.46	383.2	11.06	58.88	0.969
5.334	6.629	5.868	6.246	-20.10	-21.71	-9.240	11.37	383.3	12.48	55.43	0.969
5.280	7.495	6.636	7.063	-19.97	-21.70	-9.241	11.29	383.3	14.11	52.12	0.969
5.227	8.482	7.511	7.994	-19.87	-21.70	-9.240	11.24	383.3	15.97	48.99	0.969
5.173	9.597	8.501	9.048	-19.77	-21.71	-9.240	11.20	383.3	18.07	46.05	0.969
5.119	10.86	9.621	10.24	-19.69	-21.74	-9.241	11.17	383.3	20.46	43.29	0.970
5.065	12.28	10.89	11.59	-19.62	-21.77	-9.241	11.15	383.2	23.15	40.69	0.970
5.012	13.89	12.32	13.12	-19.55	-21.81	-9.240	11.14	383.1	26.20	38.24	0.970
4.958	15.70	13.95	14.84	-19.50	-21.87	-9.241	11.14	382.9	29.65	35.93	0.971
4.904	17.74	15.78	16.80	-19.44	-21.92	-9.242	11.13	382.6	33.56	33.77	0.972
4.851	20.04	17.86	19.01	-19.39	-21.97	-9.241	11.14	382.3	37.98	31.73	0.972
4.797	22.63	20.22	21.52	-19.34	-22.03	-9.242	11.14	381.9	42.98	29.81	0.974

TABLE A.10 : NEQ ZERO FIELD ABUNDANCE SERIES, *CONTINUED*.NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -1.0$, *CONT.*

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
4.743	25.55	22.88	24.35	-19.30	-22.09	-9.243	11.15	381.4	48.64	28.00	0.975
4.689	28.86	25.89	27.56	-19.25	-22.15	-9.243	11.16	381.0	55.05	26.31	0.976
4.638	32.42	29.15	31.03	-19.21	-22.21	-9.243	11.17	380.6	61.98	24.78	0.977
4.592	36.00	32.44	34.53	-19.15	-22.25	-9.243	11.15	380.2	68.96	23.48	0.978
4.549	39.59	35.75	38.05	-19.10	-22.28	-9.245	11.14	379.8	76.01	22.35	0.979
4.492	44.99	40.76	43.39	-19.01	-22.30	-9.245	11.11	379.2	86.67	20.92	0.981
4.442	50.31	45.76	48.70	-18.93	-22.32	-9.246	11.08	378.5	97.28	19.72	0.982
4.398	55.49	50.68	53.94	-18.86	-22.34	-9.247	11.05	377.7	107.7	18.72	0.985
4.346	62.11	57.10	60.78	-18.82	-22.40	-9.248	11.06	376.4	121.4	17.61	0.988
4.301	68.39	63.38	67.46	-18.81	-22.47	-9.250	11.09	374.9	134.8	16.68	0.992
4.260	74.33	69.54	74.02	-18.82	-22.57	-9.253	11.14	373.1	147.9	15.88	0.997
4.215	81.25	77.13	82.09	-18.87	-22.69	-9.256	11.23	370.4	164.0	15.03	1.004
4.175	87.57	84.60	90.05	-18.93	-22.83	-9.259	11.32	367.2	179.9	14.29	1.013
4.132	94.23	93.44	99.46	-19.02	-22.99	-9.265	11.44	362.5	198.7	13.51	1.026
4.087	100.5	103.6	110.3	-19.12	-23.17	-9.273	11.57	355.9	220.2	12.71	1.045
4.042	105.5	115.0	122.4	-19.23	-23.34	-9.284	11.70	346.7	244.4	11.91	1.073
4.002	108.3	126.1	134.3	-19.32	-23.48	-9.297	11.80	336.4	268.2	11.20	1.105

NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -1.5$

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0339	0.0300	0.0319	-25.88	-22.91	-9.366	14.73	289.2	0.072	674.8	0.966
7.444	0.0407	0.0361	0.0384	-25.74	-22.93	-9.342	14.69	303.4	0.076	630.2	0.966
7.395	0.0472	0.0418	0.0444	-25.63	-22.95	-9.327	14.66	314.4	0.088	596.1	0.966
7.346	0.0544	0.0482	0.0513	-25.53	-22.97	-9.314	14.64	323.6	0.102	563.1	0.966
7.296	0.0625	0.0554	0.0589	-25.42	-22.99	-9.304	14.60	331.4	0.117	531.5	0.966
7.245	0.0717	0.0635	0.0675	-25.32	-23.01	-9.295	14.57	338.0	0.134	501.4	0.966
7.194	0.0820	0.0726	0.0773	-25.22	-23.02	-9.288	14.53	343.8	0.154	472.7	0.966
7.142	0.0937	0.0830	0.0883	-25.12	-23.04	-9.282	14.50	348.8	0.176	445.4	0.966
7.091	0.1069	0.0946	0.1007	-25.02	-23.05	-9.276	14.46	353.1	0.201	419.6	0.966
7.038	0.1218	0.1079	0.1148	-24.92	-23.07	-9.272	14.42	356.8	0.228	395.2	0.966
6.986	0.1386	0.1228	0.1307	-24.83	-23.08	-9.268	14.39	360.1	0.260	372.0	0.966
6.934	0.1577	0.1397	0.1486	-24.73	-23.10	-9.264	14.35	362.9	0.296	350.2	0.966
6.881	0.1793	0.1588	0.1690	-24.63	-23.11	-9.261	14.31	365.4	0.336	329.6	0.966
6.828	0.2037	0.1804	0.1920	-24.53	-23.13	-9.258	14.27	367.6	0.382	310.1	0.966
6.775	0.2313	0.2048	0.2180	-24.44	-23.14	-9.256	14.23	369.5	0.434	291.8	0.966
6.722	0.2625	0.2325	0.2474	-24.34	-23.15	-9.254	14.19	371.2	0.493	274.5	0.966
6.669	0.2979	0.2638	0.2807	-24.23	-23.15	-9.252	14.14	372.6	0.559	258.2	0.966
6.616	0.3379	0.2993	0.3185	-24.13	-23.16	-9.251	14.09	373.9	0.634	242.9	0.966
6.562	0.3831	0.3394	0.3611	-24.02	-23.16	-9.250	14.04	375.1	0.719	228.4	0.966
6.509	0.4343	0.3847	0.4094	-23.91	-23.16	-9.249	13.99	376.1	0.815	214.8	0.966
6.456	0.4923	0.4361	0.4640	-23.79	-23.15	-9.247	13.92	377.0	0.924	202.0	0.966
6.402	0.5579	0.4942	0.5259	-23.67	-23.14	-9.247	13.86	377.7	1.047	189.9	0.966
6.349	0.6321	0.5600	0.5959	-23.53	-23.11	-9.246	13.77	378.4	1.186	178.6	0.966
6.295	0.7161	0.6344	0.6751	-23.38	-23.06	-9.245	13.68	379.0	1.344	167.9	0.966
6.242	0.8112	0.7186	0.7647	-23.23	-23.02	-9.244	13.58	379.6	1.522	157.9	0.966
6.188	0.9188	0.8139	0.8661	-23.11	-23.01	-9.244	13.51	380.0	1.724	148.4	0.966
6.135	1.041	0.9218	0.9809	-23.00	-23.01	-9.243	13.46	380.4	1.953	139.6	0.966
6.081	1.178	1.044	1.111	-22.89	-23.01	-9.243	13.40	380.8	2.212	131.2	0.966
6.027	1.334	1.182	1.258	-22.78	-23.00	-9.243	13.35	381.1	2.504	123.4	0.966
5.974	1.511	1.338	1.424	-22.64	-22.97	-9.242	13.26	381.4	2.836	116.0	0.966
5.920	1.711	1.515	1.613	-22.50	-22.94	-9.242	13.18	381.7	3.211	109.0	0.966
5.866	1.937	1.716	1.826	-22.32	-22.87	-9.242	13.05	381.9	3.635	102.5	0.966
5.813	2.192	1.942	2.067	-22.10	-22.76	-9.242	12.89	382.1	4.115	96.36	0.966
5.759	2.481	2.198	2.339	-21.91	-22.67	-9.242	12.75	382.2	4.657	90.59	0.966
5.706	2.808	2.488	2.648	-21.77	-22.64	-9.241	12.66	382.4	5.272	85.17	0.966
5.652	3.179	2.817	2.997	-21.65	-22.63	-9.241	12.60	382.5	5.968	80.06	0.966
5.598	3.599	3.188	3.393	-21.51	-22.60	-9.241	12.51	382.6	6.755	75.26	0.966
5.544	4.073	3.609	3.840	-21.31	-22.50	-9.241	12.36	382.7	7.646	70.75	0.966
5.491	4.606	4.081	4.343	-21.05	-22.35	-9.241	12.16	382.8	8.647	66.54	0.966
5.438	5.208	4.615	4.911	-20.79	-22.20	-9.241	11.95	382.9	9.778	62.58	0.966
5.384	5.894	5.223	5.558	-20.59	-22.10	-9.241	11.81	383.0	11.07	58.83	0.966
5.330	6.671	5.912	6.291	-20.43	-22.05	-9.241	11.70	383.0	12.52	55.30	0.966

TABLE A.10 : NEQ ZERO FIELD ABUNDANCE SERIES, *CONTINUED*.

NEQ COOLING CURVE : FULL FIELD, $\text{LOG}(\text{To}) = 7.50$, $[\text{Fe}/\text{H}] = -1.5$, *CONT.*

Log(T)	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
5.277	7.549	6.691	7.120	-20.30	-22.03	-9.240	11.62	383.1	14.18	51.98	0.966
5.223	8.543	7.572	8.058	-20.20	-22.04	-9.241	11.58	383.1	16.04	48.87	0.966
5.169	9.666	8.570	9.119	-20.10	-22.04	-9.241	11.53	383.1	18.16	45.93	0.967
5.116	10.93	9.699	10.32	-20.01	-22.06	-9.240	11.49	383.0	20.55	43.17	0.967
5.062	12.37	10.98	11.68	-19.92	-22.08	-9.241	11.46	382.9	23.25	40.58	0.967
5.008	13.98	12.42	13.22	-19.85	-22.12	-9.241	11.44	382.7	26.32	38.13	0.968
4.955	15.78	14.04	14.94	-19.79	-22.16	-9.241	11.43	382.4	29.75	35.85	0.969
4.902	17.78	15.86	16.88	-19.74	-22.22	-9.242	11.44	382.0	33.61	33.71	0.970
4.849	20.04	17.93	19.08	-19.69	-22.28	-9.242	11.44	381.5	37.99	31.69	0.971
4.795	22.60	20.29	21.59	-19.65	-22.34	-9.244	11.45	380.8	42.99	29.76	0.973
4.742	25.47	22.96	24.44	-19.60	-22.39	-9.244	11.45	380.0	48.65	27.95	0.975
4.688	28.70	25.99	27.65	-19.54	-22.44	-9.245	11.44	379.2	55.06	26.24	0.977
4.635	32.28	29.33	31.21	-19.47	-22.47	-9.246	11.42	378.6	62.13	24.68	0.979
4.588	35.92	32.73	34.83	-19.38	-22.48	-9.246	11.38	378.0	69.34	23.35	0.980
4.544	39.61	36.18	38.50	-19.29	-22.47	-9.247	11.33	377.5	76.66	22.19	0.981
4.486	45.15	41.41	44.07	-19.14	-22.44	-9.247	11.24	376.8	87.74	20.72	0.983
4.435	50.56	46.56	49.55	-19.02	-22.42	-9.248	11.17	376.0	98.65	19.52	0.985
4.390	55.74	51.56	54.87	-18.93	-22.42	-9.250	11.12	375.1	109.2	18.53	0.988
4.339	62.27	58.02	61.74	-18.88	-22.46	-9.251	11.12	373.8	122.9	17.44	0.991
4.295	68.41	64.29	68.42	-18.86	-22.53	-9.253	11.14	372.2	136.2	16.53	0.996
4.246	75.55	71.95	76.56	-18.89	-22.65	-9.256	11.21	369.8	152.4	15.58	1.002
4.203	82.09	79.45	84.55	-18.95	-22.79	-9.259	11.31	366.8	168.3	14.76	1.010
4.157	88.98	88.30	93.96	-19.04	-22.96	-9.265	11.44	362.4	187.1	13.92	1.023
4.116	94.64	96.98	103.2	-19.14	-23.13	-9.272	11.56	356.8	205.5	13.18	1.038
4.074	99.34	106.9	113.8	-19.27	-23.33	-9.281	11.71	348.6	226.5	12.41	1.063
4.031	101.8	117.9	125.5	-19.42	-23.53	-9.296	11.87	337.1	249.8	11.62	1.099

NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(\text{To}) = 7.50$, $[\text{Fe}/\text{H}] = -2.0$

Log(T)	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_c)$	P_{12}	P_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0338	0.0300	0.0319	-25.89	-22.92	-9.366	14.74	289.1	0.072	675.0	0.965
7.444	0.0407	0.0361	0.0384	-25.75	-22.94	-9.342	14.70	303.3	0.076	630.4	0.965
7.395	0.0471	0.0418	0.0444	-25.64	-22.96	-9.327	14.67	314.3	0.088	596.2	0.965
7.346	0.0543	0.0482	0.0513	-25.54	-22.98	-9.314	14.65	323.5	0.102	563.3	0.965
7.296	0.0625	0.0554	0.0589	-25.44	-23.00	-9.304	14.62	331.3	0.117	531.7	0.965
7.245	0.0716	0.0635	0.0675	-25.34	-23.02	-9.296	14.59	337.9	0.134	501.5	0.965
7.194	0.0820	0.0726	0.0773	-25.24	-23.04	-9.288	14.55	343.7	0.154	472.8	0.965
7.142	0.0936	0.0830	0.0883	-25.14	-23.06	-9.282	14.52	348.6	0.176	445.6	0.965
7.091	0.1068	0.0947	0.1007	-25.05	-23.08	-9.276	14.49	352.9	0.200	419.7	0.965
7.038	0.1217	0.1079	0.1148	-24.95	-23.10	-9.272	14.45	356.7	0.228	395.3	0.965
6.986	0.1386	0.1228	0.1307	-24.86	-23.11	-9.268	14.42	359.9	0.260	372.2	0.965
6.933	0.1576	0.1397	0.1486	-24.76	-23.13	-9.265	14.38	362.8	0.296	350.3	0.965
6.881	0.1792	0.1588	0.1690	-24.67	-23.15	-9.261	14.35	365.3	0.336	329.7	0.965
6.828	0.2036	0.1804	0.1920	-24.57	-23.16	-9.259	14.31	367.4	0.382	310.2	0.965
6.775	0.2312	0.2049	0.2180	-24.48	-23.18	-9.256	14.27	369.4	0.434	291.9	0.965
6.722	0.2624	0.2325	0.2474	-24.38	-23.19	-9.254	14.23	371.0	0.492	274.6	0.965
6.669	0.2977	0.2639	0.2808	-24.29	-23.21	-9.253	14.20	372.5	0.558	258.3	0.965
6.616	0.3377	0.2993	0.3185	-24.19	-23.22	-9.251	14.15	373.8	0.633	242.9	0.965
6.562	0.3829	0.3394	0.3611	-24.09	-23.23	-9.250	14.11	375.0	0.718	228.5	0.965
6.509	0.4341	0.3848	0.4094	-23.99	-23.24	-9.249	14.06	376.0	0.814	214.9	0.965
6.456	0.4921	0.4361	0.4641	-23.89	-23.24	-9.247	14.02	376.8	0.923	202.1	0.965
6.402	0.5577	0.4943	0.5259	-23.78	-23.24	-9.247	13.97	377.6	1.046	190.0	0.965
6.349	0.6319	0.5600	0.5959	-23.66	-23.24	-9.246	13.90	378.3	1.185	178.7	0.965
6.295	0.7158	0.6345	0.6751	-23.53	-23.22	-9.246	13.83	378.9	1.343	168.0	0.965
6.242	0.8109	0.7187	0.7647	-23.41	-23.20	-9.244	13.76	379.4	1.521	157.9	0.965
6.188	0.9184	0.8140	0.8662	-23.30	-23.20	-9.244	13.70	379.9	1.723	148.5	0.965
6.134	1.040	0.9219	0.9810	-23.20	-23.20	-9.244	13.66	380.3	1.951	139.6	0.965
6.081	1.178	1.044	1.111	-23.09	-23.21	-9.243	13.60	380.7	2.209	131.3	0.965
6.027	1.334	1.182	1.258	-22.98	-23.20	-9.243	13.55	381.0	2.502	123.4	0.965
5.974	1.510	1.339	1.424	-22.85	-23.19	-9.242	13.47	381.3	2.833	116.0	0.965
5.920	1.710	1.516	1.613	-22.72	-23.16	-9.242	13.40	381.6	3.207	109.1	0.965
5.866	1.936	1.716	1.826	-22.58	-23.12	-9.242	13.31	381.8	3.631	102.5	0.965
5.813	2.192	1.943	2.067	-22.40	-23.05	-9.242	13.19	382.0	4.111	96.39	0.965

TABLE A.10 : NEQ ZERO FIELD ABUNDANCE SERIES, *CONTINUED*.NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -2.0$, *CONT.*

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
5.759	2.481	2.199	2.340	-22.22	-22.99	-9.242	13.06	382.1	4.654	90.62	0.965
5.705	2.809	2.489	2.649	-22.09	-22.96	-9.242	12.98	382.3	5.268	85.18	0.965
5.652	3.179	2.818	2.999	-21.97	-22.95	-9.241	12.92	382.4	5.964	80.08	0.965
5.598	3.599	3.190	3.394	-21.83	-22.92	-9.241	12.83	382.5	6.751	75.28	0.965
5.544	4.074	3.611	3.842	-21.65	-22.84	-9.241	12.70	382.7	7.641	70.76	0.965
5.491	4.610	4.086	4.348	-21.40	-22.70	-9.241	12.51	382.7	8.648	66.53	0.965
5.437	5.213	4.621	4.917	-21.14	-22.55	-9.241	12.30	382.8	9.779	62.57	0.965
5.384	5.898	5.228	5.563	-20.93	-22.44	-9.241	12.15	382.9	11.06	58.83	0.965
5.330	6.674	5.916	6.295	-20.77	-22.39	-9.241	12.04	382.9	12.52	55.30	0.965
5.276	7.553	6.696	7.125	-20.64	-22.38	-9.241	11.96	383.0	14.17	51.99	0.965
5.223	8.547	7.578	8.063	-20.53	-22.37	-9.240	11.91	383.0	16.04	48.87	0.966
5.169	9.671	8.577	9.126	-20.41	-22.36	-9.241	11.84	383.0	18.15	45.94	0.966
5.115	10.94	9.706	10.33	-20.29	-22.34	-9.241	11.77	383.0	20.54	43.18	0.966
5.062	12.37	10.98	11.69	-20.17	-22.33	-9.241	11.71	382.8	23.24	40.58	0.966
5.008	13.97	12.43	13.22	-20.07	-22.34	-9.241	11.66	382.6	26.30	38.14	0.967
4.955	15.75	14.04	14.93	-19.99	-22.36	-9.242	11.63	382.1	29.70	35.87	0.968
4.904	17.68	15.81	16.82	-19.94	-22.42	-9.242	11.63	381.6	33.45	33.77	0.970
4.852	19.85	17.81	18.95	-19.91	-22.48	-9.243	11.65	380.9	37.69	31.79	0.971
4.799	22.30	20.10	21.39	-19.88	-22.56	-9.244	11.67	380.0	42.54	29.89	0.974
4.746	25.09	22.75	24.20	-19.83	-22.61	-9.245	11.68	378.9	48.14	28.06	0.977
4.692	28.23	25.74	27.39	-19.76	-22.64	-9.247	11.66	377.8	54.48	26.33	0.979
4.638	31.78	29.12	30.99	-19.65	-22.65	-9.248	11.60	376.9	61.63	24.73	0.982
4.588	35.53	32.67	34.76	-19.53	-22.62	-9.249	11.53	376.3	69.14	23.33	0.984
4.543	39.34	36.28	38.60	-19.40	-22.58	-9.249	11.44	375.7	76.77	22.12	0.985
4.502	43.15	39.90	42.46	-19.26	-22.52	-9.249	11.34	375.2	84.44	21.08	0.986
4.447	48.71	45.22	48.12	-19.09	-22.46	-9.251	11.22	374.5	95.70	19.78	0.988
4.401	53.97	50.32	53.54	-18.99	-22.45	-9.251	11.17	373.7	106.5	18.73	0.990
4.361	58.94	55.23	58.77	-18.92	-22.46	-9.252	11.14	372.7	116.9	17.86	0.993
4.313	65.20	61.57	65.52	-18.89	-22.52	-9.254	11.15	371.3	130.3	16.88	0.997
4.272	71.06	67.75	72.09	-18.89	-22.60	-9.256	11.19	369.5	143.4	16.05	1.002
4.226	77.86	75.31	80.13	-18.93	-22.73	-9.259	11.27	366.9	159.4	15.17	1.009
4.185	83.99	82.72	88.02	-19.00	-22.87	-9.263	11.37	363.7	175.1	14.41	1.018
4.141	90.30	91.46	97.32	-19.10	-23.05	-9.270	11.50	358.8	193.5	13.62	1.032
4.097	95.89	101.4	107.9	-19.24	-23.25	-9.278	11.67	351.4	214.7	12.80	1.053
4.051	99.31	112.5	119.7	-19.41	-23.48	-9.292	11.85	340.5	238.1	11.96	1.087
4.007	98.78	124.5	132.5	-19.60	-23.72	-9.313	12.04	324.9	263.5	11.10	1.139

NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = -3.0$

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0338	0.0300	0.0319	-25.89	-22.92	-9.366	14.74	289.1	0.072	674.9	0.965
7.444	0.0407	0.0361	0.0384	-25.75	-22.95	-9.342	14.70	303.3	0.076	630.5	0.965
7.395	0.0471	0.0418	0.0444	-25.65	-22.97	-9.327	14.68	314.2	0.088	596.3	0.965
7.346	0.0543	0.0482	0.0513	-25.54	-22.99	-9.314	14.65	323.4	0.102	563.4	0.965
7.296	0.0625	0.0554	0.0589	-25.44	-23.01	-9.304	14.62	331.2	0.117	531.8	0.965
7.245	0.0716	0.0635	0.0675	-25.34	-23.03	-9.296	14.59	337.9	0.134	501.6	0.965
7.194	0.0819	0.0726	0.0773	-25.25	-23.05	-9.288	14.56	343.6	0.154	472.9	0.965
7.142	0.0936	0.0830	0.0883	-25.15	-23.07	-9.282	14.53	348.6	0.176	445.6	0.965
7.091	0.1068	0.0947	0.1007	-25.06	-23.09	-9.276	14.50	352.9	0.200	419.8	0.965
7.038	0.1217	0.1079	0.1148	-24.96	-23.11	-9.272	14.46	356.6	0.228	395.3	0.965
6.986	0.1385	0.1228	0.1307	-24.87	-23.13	-9.268	14.43	359.9	0.260	372.2	0.965
6.933	0.1576	0.1397	0.1486	-24.78	-23.15	-9.265	14.40	362.7	0.296	350.4	0.965
6.881	0.1791	0.1588	0.1690	-24.68	-23.16	-9.261	14.36	365.2	0.336	329.7	0.965
6.828	0.2035	0.1804	0.1920	-24.59	-23.18	-9.259	14.33	367.4	0.382	310.3	0.965
6.775	0.2311	0.2049	0.2180	-24.50	-23.20	-9.256	14.29	369.3	0.433	291.9	0.965
6.722	0.2623	0.2326	0.2474	-24.40	-23.22	-9.255	14.25	371.0	0.492	274.6	0.965
6.669	0.2977	0.2639	0.2808	-24.31	-23.23	-9.253	14.22	372.5	0.558	258.3	0.965
6.616	0.3376	0.2993	0.3185	-24.22	-23.25	-9.251	14.18	373.8	0.633	243.0	0.965
6.562	0.3829	0.3394	0.3611	-24.12	-23.26	-9.250	14.14	374.9	0.718	228.5	0.965
6.509	0.4341	0.3848	0.4094	-24.03	-23.28	-9.249	14.10	375.9	0.814	214.9	0.965
6.456	0.4920	0.4362	0.4641	-23.93	-23.29	-9.247	14.06	376.8	0.923	202.1	0.965
6.402	0.5576	0.4943	0.5259	-23.83	-23.30	-9.247	14.02	377.6	1.046	190.0	0.965
6.349	0.6318	0.5601	0.5959	-23.73	-23.31	-9.246	13.97	378.3	1.185	178.7	0.965

TABLE A.10 : NEQ ZERO FIELD ABUNDANCE SERIES, *CONTINUED*.

NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(\text{To}) = 7.50$, $[\text{Fe}/\text{H}] = -3.0$, *CONT.*

$\text{Log}(\text{T})$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(\text{U})$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
6.295	0.7157	0.6345	0.6751	-23.62	-23.31	-9.246	13.92	378.9	1.342	168.0	0.965
6.242	0.8108	0.7187	0.7647	-23.52	-23.31	-9.244	13.87	379.4	1.520	158.0	0.965
6.188	0.9183	0.8141	0.8662	-23.41	-23.31	-9.244	13.81	379.9	1.722	148.5	0.965
6.134	1.040	0.9220	0.9810	-23.31	-23.32	-9.244	13.77	380.3	1.950	139.6	0.965
6.081	1.178	1.044	1.111	-23.20	-23.32	-9.243	13.71	380.6	2.209	131.3	0.965
6.027	1.334	1.182	1.258	-23.10	-23.32	-9.243	13.67	381.0	2.501	123.4	0.965
5.974	1.510	1.339	1.424	-22.99	-23.32	-9.242	13.61	381.3	2.832	116.0	0.965
5.920	1.710	1.516	1.613	-22.87	-23.31	-9.242	13.55	381.5	3.206	109.1	0.965
5.866	1.936	1.716	1.826	-22.75	-23.30	-9.242	13.48	381.7	3.630	102.5	0.965
5.813	2.191	1.943	2.067	-22.62	-23.28	-9.242	13.41	381.9	4.109	96.41	0.965
5.759	2.481	2.199	2.340	-22.49	-23.25	-9.242	13.33	382.1	4.652	90.63	0.965
5.705	2.808	2.490	2.649	-22.36	-23.23	-9.242	13.25	382.3	5.266	85.20	0.965
5.652	3.179	2.818	2.999	-22.23	-23.21	-9.241	13.18	382.4	5.961	80.09	0.965
5.598	3.599	3.190	3.394	-22.10	-23.18	-9.241	13.10	382.5	6.748	75.29	0.965
5.544	4.073	3.611	3.842	-21.95	-23.14	-9.241	13.00	382.6	7.638	70.77	0.965
5.490	4.611	4.087	4.349	-21.77	-23.08	-9.242	12.88	382.7	8.646	66.53	0.965
5.437	5.218	4.626	4.922	-21.58	-22.99	-9.241	12.74	382.8	9.786	62.54	0.965
5.383	5.906	5.236	5.571	-21.40	-22.92	-9.241	12.62	382.9	11.08	58.80	0.965
5.329	6.684	5.926	6.305	-21.24	-22.86	-9.241	12.51	382.9	12.53	55.27	0.965
5.276	7.564	6.707	7.136	-21.08	-22.81	-9.241	12.40	383.0	14.19	51.95	0.965
5.222	8.561	7.591	8.077	-20.91	-22.75	-9.241	12.29	383.0	16.06	48.84	0.965
5.168	9.687	8.592	9.142	-20.73	-22.68	-9.241	12.16	383.0	18.17	45.91	0.965
5.115	10.96	9.724	10.35	-20.54	-22.60	-9.240	12.03	382.9	20.57	43.15	0.965
5.061	12.38	11.00	11.70	-20.36	-22.52	-9.241	11.90	382.8	23.27	40.56	0.966
5.007	13.99	12.44	13.24	-20.22	-22.48	-9.242	11.81	382.5	26.32	38.12	0.967
4.955	15.75	14.05	14.95	-20.12	-22.49	-9.242	11.76	382.0	29.73	35.85	0.968
4.904	17.64	15.79	16.80	-20.07	-22.54	-9.243	11.76	381.3	33.40	33.79	0.970
4.854	19.71	17.73	18.86	-20.04	-22.61	-9.244	11.78	380.4	37.50	31.85	0.972
4.803	22.05	19.95	21.22	-20.03	-22.70	-9.245	11.82	379.3	42.20	29.98	0.975
4.750	24.76	22.54	23.98	-20.00	-22.77	-9.246	11.84	378.1	47.68	28.16	0.978
4.696	27.83	25.50	27.14	-19.92	-22.80	-9.248	11.81	376.8	53.94	26.43	0.982
4.642	31.32	28.86	30.70	-19.78	-22.77	-9.249	11.72	375.8	61.04	24.81	0.984
4.590	35.20	32.55	34.64	-19.62	-22.71	-9.250	11.61	375.2	68.86	23.34	0.986
4.543	39.13	36.30	38.62	-19.46	-22.63	-9.250	11.50	374.6	76.78	22.09	0.987
4.500	43.04	40.02	42.58	-19.30	-22.56	-9.251	11.38	374.1	84.65	21.02	0.989
4.445	48.65	45.42	48.32	-19.11	-22.48	-9.252	11.24	373.4	96.07	19.72	0.991
4.399	53.90	50.53	53.76	-19.00	-22.46	-9.253	11.18	372.6	106.9	18.67	0.993
4.359	58.85	55.44	58.99	-18.93	-22.47	-9.254	11.15	371.7	117.3	17.80	0.995
4.312	65.06	61.77	65.73	-18.89	-22.53	-9.255	11.15	370.3	130.7	16.83	0.999
4.271	70.88	67.94	72.28	-18.90	-22.61	-9.257	11.20	368.6	143.7	16.02	1.004
4.225	77.61	75.47	80.30	-18.94	-22.74	-9.260	11.28	365.9	159.6	15.14	1.011
4.184	83.68	82.87	88.17	-19.01	-22.88	-9.265	11.38	362.7	175.3	14.38	1.020
4.141	89.90	91.58	97.44	-19.12	-23.06	-9.270	11.52	357.8	193.7	13.59	1.034
4.096	95.34	101.5	108.0	-19.26	-23.27	-9.280	11.68	350.4	214.7	12.77	1.056
4.051	98.48	112.5	119.7	-19.43	-23.51	-9.294	11.87	339.2	238.0	11.94	1.091
4.008	97.33	124.4	132.4	-19.65	-23.76	-9.315	12.08	322.9	263.2	11.08	1.146

NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(\text{To}) = 7.50$, $[\text{Fe}/\text{H}] = \text{NIL}$, ZERO METALS

$\text{Log}(\text{T})$	n_e	n_H	n_t	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(\text{U})$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
7.500	0.0338	0.0300	0.0319	-25.89	-22.92	-9.366	14.74	289.1	0.072	674.9	0.965
7.444	0.0407	0.0361	0.0384	-25.75	-22.95	-9.342	14.70	303.3	0.076	630.5	0.965
7.395	0.0471	0.0418	0.0444	-25.65	-22.97	-9.327	14.68	314.2	0.088	596.3	0.965
7.346	0.0543	0.0482	0.0513	-25.54	-22.99	-9.314	14.65	323.4	0.102	563.4	0.965
7.296	0.0625	0.0554	0.0589	-25.44	-23.01	-9.304	14.62	331.2	0.117	531.8	0.965
7.245	0.0716	0.0635	0.0675	-25.34	-23.03	-9.296	14.59	337.9	0.134	501.6	0.965
7.194	0.0819	0.0726	0.0773	-25.25	-23.05	-9.288	14.56	343.6	0.154	472.9	0.965
7.142	0.0936	0.0830	0.0883	-25.15	-23.07	-9.282	14.53	348.6	0.176	445.6	0.965
7.091	0.1068	0.0947	0.1007	-25.06	-23.09	-9.276	14.50	352.9	0.200	419.8	0.965
7.038	0.1217	0.1079	0.1148	-24.97	-23.11	-9.272	14.47	356.6	0.228	395.3	0.965
6.986	0.1385	0.1228	0.1307	-24.87	-23.13	-9.268	14.43	359.9	0.260	372.2	0.965
6.933	0.1576	0.1397	0.1486	-24.78	-23.15	-9.265	14.40	362.7	0.295	350.4	0.965
6.881	0.1791	0.1588	0.1690	-24.68	-23.16	-9.261	14.36	365.2	0.336	329.7	0.965

TABLE A.10 : NEQ ZERO FIELD ABUNDANCE SERIES, *CONTINUED*.NEQ COOLING CURVE : ZERO FIELD, $\text{LOG}(T_0) = 7.50$, $[\text{Fe}/\text{H}] = \text{ZERO METALS}$, *CONT.*

$\text{Log}(T)$	n_e	n_H	n_i	$\log(\Lambda_{\text{net}})$	$\log(\Lambda_N)$	$\log(U)$	$\log(\tau_e)$	P_{12}	ρ_{24}	C_i	$\bar{\mu}_{24}$
6.828	0.2035	0.1804	0.1920	-24.59	-23.18	-9.259	14.33	367.4	0.382	310.3	0.965
6.775	0.2311	0.2049	0.2180	-24.50	-23.20	-9.256	14.29	369.3	0.433	291.9	0.965
6.722	0.2623	0.2326	0.2474	-24.41	-23.22	-9.255	14.26	371.0	0.492	274.6	0.965
6.669	0.2977	0.2639	0.2808	-24.31	-23.24	-9.253	14.22	372.5	0.558	258.3	0.965
6.616	0.3376	0.2993	0.3185	-24.22	-23.25	-9.251	14.18	373.8	0.633	243.0	0.965
6.562	0.3829	0.3394	0.3611	-24.13	-23.27	-9.250	14.15	374.9	0.718	228.5	0.965
6.509	0.4341	0.3848	0.4094	-24.03	-23.28	-9.249	14.10	375.9	0.814	214.9	0.965
6.456	0.4920	0.4362	0.4641	-23.94	-23.29	-9.247	14.07	376.8	0.923	202.1	0.965
6.402	0.5576	0.4943	0.5259	-23.84	-23.31	-9.247	14.03	377.6	1.045	190.0	0.965
6.349	0.6317	0.5601	0.5959	-23.74	-23.32	-9.246	13.98	378.3	1.185	178.7	0.965
6.295	0.7157	0.6345	0.6751	-23.63	-23.32	-9.246	13.93	378.9	1.342	168.0	0.965
6.242	0.8107	0.7187	0.7647	-23.53	-23.32	-9.244	13.88	379.4	1.520	158.0	0.965
6.188	0.9183	0.8141	0.8662	-23.43	-23.33	-9.244	13.83	379.9	1.722	148.5	0.965
6.134	1.040	0.9220	0.9810	-23.33	-23.33	-9.244	13.79	380.3	1.950	139.6	0.965
6.081	1.178	1.044	1.111	-23.22	-23.34	-9.243	13.73	380.6	2.208	131.3	0.965
6.027	1.334	1.182	1.258	-23.11	-23.34	-9.243	13.68	381.0	2.501	123.4	0.965
5.974	1.510	1.339	1.424	-23.00	-23.34	-9.242	13.62	381.3	2.832	116.0	0.965
5.920	1.710	1.516	1.613	-22.89	-23.33	-9.242	13.57	381.5	3.206	109.1	0.965
5.866	1.936	1.716	1.826	-22.77	-23.32	-9.242	13.50	381.7	3.630	102.6	0.965
5.813	2.191	1.943	2.067	-22.66	-23.31	-9.242	13.45	381.9	4.109	96.41	0.965
5.759	2.481	2.199	2.340	-22.53	-23.30	-9.242	13.37	382.1	4.652	90.63	0.965
5.705	2.808	2.490	2.649	-22.41	-23.28	-9.242	13.30	382.2	5.266	85.20	0.965
5.652	3.179	2.818	2.999	-22.28	-23.25	-9.241	13.23	382.4	5.961	80.09	0.965
5.598	3.599	3.190	3.394	-22.14	-23.23	-9.241	13.14	382.5	6.748	75.29	0.965
5.544	4.073	3.611	3.842	-22.00	-23.19	-9.241	13.05	382.6	7.638	70.78	0.965
5.490	4.611	4.087	4.349	-21.85	-23.15	-9.242	12.96	382.7	8.646	66.53	0.965
5.437	5.219	4.627	4.923	-21.69	-23.10	-9.241	12.85	382.8	9.786	62.54	0.965
5.383	5.907	5.237	5.572	-21.53	-23.05	-9.241	12.75	382.8	11.08	58.79	0.965
5.329	6.685	5.927	6.307	-21.36	-22.98	-9.241	12.63	382.9	12.54	55.26	0.965
5.276	7.566	6.709	7.138	-21.18	-22.91	-9.240	12.50	383.0	14.19	51.95	0.965
5.222	8.563	7.593	8.079	-20.99	-22.83	-9.241	12.37	383.0	16.06	48.83	0.965
5.168	9.689	8.594	9.144	-20.79	-22.74	-9.241	12.22	383.0	18.18	45.90	0.965
5.114	10.96	9.727	10.35	-20.59	-22.64	-9.241	12.07	382.9	20.57	43.14	0.965
5.061	12.39	11.00	11.71	-20.39	-22.55	-9.241	11.93	382.8	23.27	40.55	0.966
5.007	13.99	12.45	13.24	-20.24	-22.51	-9.242	11.83	382.5	26.33	38.11	0.967
4.955	15.75	14.05	14.95	-20.14	-22.51	-9.242	11.78	382.0	29.72	35.85	0.968
4.904	17.62	15.78	16.79	-20.09	-22.56	-9.243	11.78	381.3	33.37	33.80	0.970
4.854	19.68	17.70	18.84	-20.07	-22.63	-9.244	11.81	380.4	37.45	31.87	0.972
4.804	22.00	19.90	21.18	-20.06	-22.72	-9.245	11.85	379.3	42.10	30.02	0.975
4.751	24.68	22.48	23.92	-20.03	-22.80	-9.246	11.87	378.1	47.54	28.20	0.978
4.697	27.74	25.44	27.07	-19.94	-22.82	-9.248	11.83	376.7	53.81	26.46	0.982
4.631	32.12	29.64	31.54	-19.77	-22.77	-9.249	11.72	375.5	62.69	24.48	0.985
4.580	35.98	33.32	35.45	-19.60	-22.70	-9.250	11.60	374.9	70.47	23.07	0.987
4.534	39.93	37.08	39.45	-19.43	-22.62	-9.250	11.48	374.4	78.42	21.85	0.988
4.492	43.82	40.80	43.41	-19.27	-22.55	-9.251	11.36	373.9	86.30	20.82	0.989
4.438	49.39	46.16	49.12	-19.09	-22.48	-9.252	11.23	373.2	97.64	19.55	0.991
4.393	54.59	51.24	54.52	-18.99	-22.46	-9.253	11.17	372.4	108.4	18.54	0.993
4.341	61.08	57.73	61.42	-18.91	-22.49	-9.255	11.14	371.1	122.1	17.43	0.997
4.297	67.14	63.99	68.09	-18.89	-22.55	-9.256	11.16	369.6	135.3	16.53	1.001
4.248	74.18	71.62	76.20	-18.92	-22.67	-9.259	11.24	367.3	151.5	15.57	1.007
4.205	80.60	79.08	84.14	-18.97	-22.81	-9.262	11.32	364.4	167.3	14.76	1.015
4.159	87.34	87.86	93.49	-19.07	-22.98	-9.268	11.46	360.0	185.8	13.92	1.028
4.118	92.78	96.47	102.6	-19.19	-23.16	-9.275	11.60	354.3	204.0	13.18	1.044
4.076	97.05	106.3	113.1	-19.33	-23.37	-9.285	11.76	345.8	224.8	12.40	1.070
4.034	98.55	117.1	124.6	-19.52	-23.61	-9.301	11.96	333.3	247.7	11.60	1.110

Appendix B

Oxygen–Rich Spectra

B.1 N132D Spectra

FIGURE B.1: N132D Aperture 4

FIGURE B.2: N132D Aperture 5

FIGURE B.3: N132D Aperture 6

FIGURE B.4: N132D Aperture 7

FIGURE B.5: N132D Aperture 8

FIGURE B.6: N132D Aperture 9

FIGURE B.7: N132D Aperture 10

FIGURE B.8: N132D Aperture

FIGURE B.9: N132D Aperture 12

FIGURE B.10: N132D Aperture 14

FIGURE B.11: N132D Aperture 15

FIGURE B.12: N132D Aperture 16

FIGURE B.13: N132D Apertures 19 & 20

B.2 Puppis A Spectra

FIGURE B.14: Puppis A Omega Filament

FIGURE B.15: Puppis A Aperture O2

FIGURE B.16: Puppis A Aperture O3

FIGURE B.17: Puppis A Aperture O4

FIGURE B.18: Puppis A Aperture O5

FIGURE B.19: Puppis A Aperture O11

FIGURE B.20: Puppis A Aperture O12

FIGURE B.21: Puppis A Aperture O13

B.3 SNR G292.0+1.8 Spectrum

FIGURE B.22: SNR G292.0+1.8 Global

References

- Abramowitz, M. and Stegun, I. A. 1964, *Handbook of mathematical functions*, Dover, New York, 9th edition
- Aldrovandi, S. M. V. and Péquignot, D. 1973, *A&A*,25,137
- Aldrovandi, S. M. V. and Péquignot, D. 1977, *A&A*,47,321
- Allen, C. W. 1973, *Astrophysical Quantities*, Athlone Press, London, 3rd edition
- Aller, L. H. 1961, *The Abundances of the Elements*, Interscience, New York
- Anders, E. and Grevesse, N. 1989, *Geochimica et Cosmochimica Acta.*,53,197
- Arendt, R. G., Dwek, E., and Petre, R. 1991, *ApJ*,368,474
- Arendt, R. G., Dwek, E., Petre, R., Dickel, J. R., Roger, R. S., Milne, D. K., and Kesteven, M. J. 1990, *ApJ*,350,266
- Arnaud, M. and Rothenflug, R. 1985, *A&AS*,60,425
- Ashworth, W. 1980, *J. Hist. Astr.*,11,1
- Atherton, P. D., Taylor, K., Pike, C. D., Harmer, C. F., Parker, N., and Hook, R. N. 1982, *MNRAS*,201,661
- Axford, W. I. 1961, *Phil. Trans. R. Soc.*,253(A),301
- Baade, W. and Minkowski, R. 1954, *AJ*,119,206
- Balick, B. and Heckman, T. 1978, *ApJ*,226,L7
- Bashkin, S. and Stoner, J. O. 1975, *Atomic Energy Levels and Grotian Diagrams*, Vol. 1, North-Holland, Amsterdam
- Bashkin, S. and Stoner, J. O. 1978, *Atomic Energy Levels and Grotian Diagrams*, Vol. 2, North-Holland, Amsterdam
- Bashkin, S. and Stoner, J. O. 1981, *Atomic Energy Levels and Grotian Diagrams*, Vol. 3, North-Holland, Amsterdam
- Baum, S. A. 1990, *ApJS*,74,389
- Bell, A. R. 1977, *MNRAS*,179,573
- Bessell, M. S., Sutherland, R. S., and Ruan, K. 1991, *ApJ*,383,L71
- Bicknell, G. V. 1986, *ApJ*,300,591
- Bicknell, G. V. 1991, *Proc. A.S.A.*,9,93
- Bicknell, G. V., Cameron, R. A., and Gingold, R. A. 1990a, *ApJ*,357,373
- Bicknell, G. V., de Ruiter, H. R., Fanti, R., Morganti, R., and Parma, P. 1990b,

ApJ,354,98

- Binette, L. 1982, *Ph.D. thesis*, M.S.S.S.O, Australian National University
- Binette, L., Dopita, M. A., and Tuohy, I. R. 1985, ApJ,297,476
- Blair, W. P., Kirshner, R. P., and Winkler, P. F. 1983, ApJ,272,84
- Blair, W. P., Raymond, J. C., Danzinger, J., and Matteucci, F. 1989, ApJ,338,812
- Blanco, V. M., Graham, J. A., Lasker, B. M., and Osmer, P. S. 1975, ApJ,198,L63
- Böhringer, H. and Hensler, G. 1989, A&A,215,147
- Borkowski, K. and Shull, J. M. 1990, ApJ,348,169
- Braun, R., Goss, W. M., Caswell, J. L., and Roger, R. S. 1986, A&A,162,259
- Bregman, J. N. 1980, ApJ,236,577
- Bregman, J. N. 1988, in R. Pallavicini (ed.), *Hot Thin Plasmas in Astrophysics*, p. 247, Kluwer, Dordrecht
- Brocklehurst, M. 1971, MNRAS,153,471
- Burgess, A. 1958, MNRAS,118,477
- Burns, J. O. 1991, private communication
- Burns, J. O., Feigelson, E. D., and Schreier, E. J. 1983, ApJ,273,128
- Butler, S. E. and Dalgarno, A. 1980, ApJ,241,838
- Butler, S. E., Heil, T. G., and Dalgarno, A. 1980, ApJ,241,442
- Butler, S. E. and Raymond, J. C. 1980, ApJ,240,680
- Capriotti, E. R. 1965, ApJ,142,1101
- Chandrasekhar, S. 1961, *Hydrodynamic and Hydromagnetic Stability*, Clarendon Press, Oxford
- Che, A. and Köppen, J. 1983, A&A,118,107
- Chevalier, R. A. 1975, ApJ,200,698
- Chevalier, R. A. and Kirshner, R. P. 1978, ApJ,219,931
- Chevalier, R. A. and Kirshner, R. P. 1979, ApJ,233,154
- Clark, D. H., Murdin, P., Zarnecki, J. C., and Culhane, J. L. 1979, MNRAS,188,11P
- Clark, D. H., Tuohy, I. R., and Becker, R. H. 1980, MNRAS,193,129
- Clark, D. H., Tuohy, I. R., Long, K. S., Szymkowiak, A. E., Dopita, M. A., Mathewson, D. S., and Culhane, J. L. 1982, ApJ,255,440
- Clarke, D. A., Bridle, A. H., Burns, J. O., Perley, R. A., and Norman, M. L. 1992, ApJ,385,173
- Clegg, R. E. S. and Harrington, J. P. 1989, MNRAS,239,869
- Cox, D. P. 1972, ApJ,172,143
- Cox, D. P. and Tucker, M. H. 1969, ApJ,157,1157
- Dalgarno, A., Heil, T. G., and Butler, S. E. 1981, ApJ,245,793
- Danzinger, I. J. 1983, in I. J. Danzinger and P. Gorenstein (eds.), *IAU Sympo-*

- sium 101, Supernova Remnants and their X-Ray Emission*, p. 193, Reidel, Dordrecht
- Danzinger, I. J. and Dennefeld, M. 1976a, Pub. A.S.P.,88,44
- Danzinger, I. J. and Dennefeld, M. 1976b, ApJ,207,394
- Danzinger, I. J. and Leibowitz, E. M. 1985, MNRAS,216,365
- Dickel, J. R. and Milne, D. K. 1993, private communication
- Dopita, M. A. 1976, ApJ,209,345
- Dopita, M. A. 1977, ApJS,33,437
- Dopita, M. A. 1987, Aus. J. Phys.,40,789
- Dopita, M. A., Binette, L., and Schwartz, R. D. 1982, ApJ,261,183
- Dopita, M. A., Binette, L., and Tuohy, I. R. 1984, ApJ,282,142
- Dopita, M. A., Mathewson, D. S., and Ford, V. L. 1977, ApJ,214,179
- Dopita, M. A. and Metherringham, S. J. 1991, ApJ,367,115
- Dopita, M. A. and Tuohy, I. R. 1984, ApJ,282,135
- Dopita, M. A., Tuohy, I. R., and Mathewson, D. S. 1981, ApJ,248,L105
- Dwek, E. 1987, ApJ,322,812
- Edgar, R. J. and Chevalier, R. A. 1986, ApJ,310,L27
- Evans, I. N., Morganti, R., and Ford, H. C. 1992, in preparation
- Fabian, A. C., Thomas, P. A., Fall, S. M., and III, R. E. W. 1986, MNRAS,221,1049
- Fabian, A. C., Willingale, R., Pye, J. P., Murray, S. S., and Fabbiano, G. 1980, MNRAS,193,175
- Fabian, J. N. 1988, in R. Pallavicini (ed.), *Hot Thin Plasmas in Astrophysics*, p. 293, Kluwer, Dordrecht
- Feast, M. W. and Walker, A. R. 1987, Ann. Rev. Astr. Ap.,25(345)
- Fesen, R. A., Becker, R. H., and Blair, R. H. 1987, ApJ,313(378)
- Field, G. B. and Steigman, G. 1971, ApJ,166(59)
- Fryxell, B., Müller, E., and Arnett, D. 1991, ApJ,367(619)
- Fuhr, J. R., Martin, A., and Weise, W. L. 1988, Phys. Chem. Ref. Data.,17(4)
- Gaetz, T. J. 1990, ApJ,353,245
- Gaetz, T. J. and Salpeter, E. E. 1983, ApJS,52,155
- Gaunt, J. A. 1930, Phil. Trans. R. Soc.,229(A),163
- Goldsworthy, F. A. 1961, Phil. Trans. R. Soc.,253(A),277
- Goss, W. M., Shiver, P. A., Zealey, W. J., Murdin, P., and Clark, D. H. 1979, MNRAS,188,357
- Gould, R. J. 1978, ApJ,219,250
- Gould, R. J. and Jung, Y.-D. 1991, ApJ,373,271
- Graham, J. A. and Price, R. M. 1981, ApJ,247,813

- Gronenschild, E. H. B. M. and Mewe, R. 1978, *A&AS*,32,283
- Hamilton, A. J. S., Sarazin, C. L. S., and Chevalier, R. A. 1983, *ApJS*,51,115
- Hughes, J. P. 1987, *ApJ*,314,103
- Hughes, J. P. 1988, in R. Roger and T. Landecker (eds.), *IAU Colloquium 101, Supernova Remnants and the Interstellar Medium*, p. 125, Cambridge, Cambridge
- Innes, D. E. 1992, *A&A*,256,660
- Innes, D. E., Giddings, J. R., and Falle, S. A. E. G. 1987a, *MNRAS*,226,67
- Innes, D. E., Giddings, J. R., and Falle, S. A. E. G. 1987b, *MNRAS*,227,1021
- Itoh, H. 1981a, *Pub. Astr. Soc. Japan*,33,121
- Itoh, H. 1981b, *Pub. Astr. Soc. Japan*,33,521
- Jansen, F. A., Smith, A., Bleeker, J. A. M., de Korte, P. A. J., Peacock, A., and White, N. E. 1988, *ApJ*,331,949
- Jerius, D. and Teske, R. G. 1988, *ApJS*,66,99
- Johnson, L. C. 1972, *ApJ*,174,2237
- Johnston, M. D. and Yahil, A. 1984, *ApJ*,285,587
- Kahn, F. D. 1954, *Bull. Astr. Ints. Neth.*,12,187
- Kaler, J. B. 1976, *ApJ*,31,517
- Kamper, K. W. and van den Bergh, S. 1976, *ApJS*,32,351
- Karzas, W. J. and Latter, R. 1961, *ApJS*,6,167
- Kato, T. 1976, *ApJS*,30,397
- Kirshner, R. P., Morse, J. A., Winkler, P. F., and Blair, W. P. 1989, *ApJ*,342,260
- Kramers, H. A. 1923, *Phil. Mag.*,46,836
- Krolik, J. H., McKee, C. F., and Tarter, B. C. 1981, *ApJ*,249,422
- Kulkarni, S. R. and Heiles, C. 1988, in G. L. Verschur and K. I. Keller-mann (eds.), *Galactic and Extragalactic Radio Astronomy*, Chapt. 3, pp 95–153, Springer-Verlag, Berlin, 2nd. edition
- Landau, L. D. and Lifshitz, E. M. 1987, *Fluid Mechanics*, Vol. 6, Pergamon, Oxford, 2nd. english edition
- Landini, M. and Fosse, B. C. M. 1990, *A&AS*,82,229
- Lasker, B. M. 1978, *ApJ*,223,109
- Lasker, B. M. 1980, *ApJ*,237,765
- Lasker, B. M. 1988, in R. Roger and T. Landecker (eds.), *IAU Colloquium 101, Supernova Remnants and the Interstellar Medium*, p. 191, Cambridge, Cambridge
- Lasker, B. M. 1991, *ApJ*,371,568
- Levich, E. V. and Sunyaev, R. A. 1970, *Ap. Lett.*,7,69
- Li, H. and McCray, R. 1992, *ApJ*,387,309

- Lide, D. R. (ed) 1990, *CRC Handbook of Chemistry and Physics*, CRC Press, Boca Raton, 71st edition
- Lockhart, I. A., Goss, W. M., Caswell, J. L., and McAdam, W. B. 1977, MNRAS, 179, 147
- Long, K. S., Helfand, D. J., and Grabelsky, D. A. 1981, ApJ, 248, 925
- Lotz, W. 1967, ApJS, 14, 207
- Lozinskaya, T. A. 1992, *Supernovae and Stellar Wind in the Interstellar Medium*, American Institute of Physics, New York, 2nd edition
- Mair, G., Müller, E., Hillebrandt, W., and Arnold, C. N. 1988, A&A, 199, 114
- Mathewson, D. S. and Clark, J. N. 1973, ApJ, 180, 725
- Mathewson, D. S., Dopita, M. A., Tuohy, I. R., and Ford, V. L. 1980, ApJ, 242, L73
- Mathewson, D. S., Ford, V. L., Dopita, M. A., Tuohy, I. R., Long, K. S., and Helfand, D. J. 1983, ApJS, 51, 345
- McKee, C. F. 1988, in R. Roger and T. Landecker (eds.), *IAU Colloquium 101, Supernova Remnants and the Interstellar Medium*, p. 205, Cambridge, Cambridge
- McKee, C. F. and Cowie, L. L. 1975, ApJ, 195, 715
- McKee, C. F. and Hollenbach, D. J. 1980, Ann. Rev. Astr. Ap., 18, 219
- McKee, C. F. and Ostriker, J. P. 1977, ApJ, 218, 148
- Mendis, D. A. 1968a, MNRAS, 140, 435
- Mendis, D. A. 1968b, MNRAS, 141, 409
- Mendis, D. A. 1969, MNRAS, 142, 241
- Mendoza, C. and Zeppen, C. J. 1982, MNRAS, 198, 127
- Menzel, D. H. and Perkeris, C. L. 1935, MNRAS, 96, 77
- Mewe, R. and Gronenschild, E. H. B. M. 1981, A&AS, 45, 11
- Mewe, R., Gronenschild, E. H. B. M., and van den Oord, G. H. J. 1985, A&AS, 62, 197
- Mewe, R., Lemen, J. R., and van den Oord, G. H. J. 1986, A&AS, 65, 511
- Middleditch, J. and Pennypacker, C. R. 1986, Nature, 313, 659
- Mills, B. Y., Turtle, A. J., and Watkinson, A. 1978, MNRAS, 185, 263
- Morganti, R., Fosbury, R. A. E., Hook, R. N., Robinson, A., and Tsvetanov, Z. 1992, MNRAS, 256, 1P
- Morganti, R., Robinson, A., Fosbury, R. A. E., di Serego Alighieri, S., Tadhunter, C., and Malin, D. F. 1991, MNRAS, 249, 91
- Müller, E., Mair, G., and Hillebrandt, W. 1989, A&A, 216, 19
- Murdin, P. and Clark, D. H. 1979, MNRAS, 189, 501
- Norman, M. L., Burns, J. O., and Sulkanen, M. 1988, Nature, 335, 146
- Nussbaumer, H. and Storey, P. J. 1980, A&A, 89, 308

- Nussbaumer, H. and Storey, P. J. 1984, A&AS,56,293
- Nussbaumer, H. and Storey, P. J. 1986, A&AS,64,545
- Nussbaumer, H. and Storey, P. J. 1987, A&AS,69,123
- Nussbaumer, H. and Storey, P. J. 1988, A&A,193,327
- Oke, J. B. 1974, ApJS,27,21
- Osterbrock, D. E. 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, University Science Books, Mill Valley, California
- Péquignot, D. 1985, in D. Péquignot (ed.), *Workshop on Model Nebulae*, p. 363, l'Observatoire de Paris
- Peterson, B. A., Dickens, R. J., and Cannon, R. D. 1975, Proc. A.S.A.,2(6),366
- Petre, R., Canizares, C. R., Kriss, G. A., and Winkler, P. F. 1982, ApJ,258,22
- Pradhan, A. K. 1976, MNRAS,177,31
- Pravdo, S. H. and Smith, B. W. 1979, ApJ,234,L195
- Pullman, N. J. 1976, *Matrix theory and its applications, selected topics*, Dekker, NewYork
- Raymond, J. C. 1976, *Ph.D. thesis*, Physics, University of Wisconsin
- Raymond, J. C. 1979, ApJS,39,1
- Raymond, J. C. and Smith, B. W. 1977, ApJS,35,419
- Reynolds, S. P. and Chevalier, R. A. 1981, ApJ,245,912
- Robinson, A. 1989, in E. J. A. Meurs and R. A. E. Fosbury (eds.), *Extranuclear Activity in Galaxies*, p. 259, E.S.O., E.S.O., Garching
- Robinson, A. 1992, Private Communication
- Robinson, A., Binette, L., Fosbury, R. A. E., and Tadhunter, C. N. 1987, MNRAS,227,97
- Rodgers, A. W., Conroy, P., and Bloxham, G. 1988a, Pub. A.S.P.,100,626
- Rodgers, A. W., van Harmelen, J., King, D., Conroy, P., and Harding, P. 1988b, Pub. A.S.P.,100,841
- Russell, S. C. 1989, Ph.d., Mount Stromlo and Siding Spring Observatories, Australian National University
- Sarazin, C. 1986, ApJ,384,508
- Sarazin, C. 1988, *X-ray Emission from Clusters of Galaxies*, Cambridge, Cambridge
- Savage, B. D. and de Boer, K. S. 1981, ApJ,243,460
- Savage, B. D. and Massa, D. 1987, ApJ,314,380
- Schmutzler, T. and Tscharnuter, W. M. 1992, A&A (submitted)
- Schwartz, J., McCray, R., and Stein, R. F. 1972, ApJ,175,673
- Seaton, M. J. 1958, Rev. Mod. Phys.,30,979
- Seaton, M. J. 1959, MNRAS,119,81

- Seward, F. D. and Harnden, F. R. 1984, ApJ,287,L19
- Seward, F. D. and Mitchell, M. 1981, ApJ,243,736
- Shapiro, P. R. and Field, B. G. 1976, ApJ,205,762
- Shapiro, P. R. and Moore, R. T. 1976, ApJ,207,460
- Shull, M. J. and McKee, C. F. 1979, ApJ,227,131
- Shull, M. J. and van Steenberg, M. 1982, ApJS,48,95
- Silk, J. 1991, Private Communication
- Stathakis, R. A., Dopita, M. A., Cannon, R. D., and Sadler, E. M. 1991, in S. E. Woosley (ed.), *Supernovae*, p. 95, Springer, New York
- Stone, J. M. and Norman, M. L. 1992, ApJ,390,L17
- Tadhunter, C. N., Robinson, A., and Morganti, R. 1989, in E. J. A. Meurs and R. A. E. Fosbury (eds.), *Extranuclear Activity in Galaxies*, p. 293, E.S.O., E.S.O., Garching
- Tucker, M. H. and Gould, R. J. 1966, ApJ,144,244
- Tuohy, I. R., Clark, D. H., and Burton, W. M. 1982, ApJ,260,L65
- Tuohy, I. R. and Dopita, M. A. 1983, ApJ,268,L11
- van Breugel, W. J. M., Miley, G. K., Heckman, T. H., Butcher, H. R., and Bridle, A. H. 1985, ApJ,290,496
- van den Bergh, S. and Kamper, K. W. 1983, ApJ,268,129
- van den Bergh, S. and Kamper, K. W. 1985, ApJ,293,537
- van Gorkom J. 1992, private communication
- Weaver, T. A., Zimmerman, G. B., and Woosley, S. E. 1978, ApJ,225,1021
- Weisheit, J. C. 1974, ApJ,190,735
- Westerlund, B. E. and Mathewson, D. S. 1966, MNRAS,131,371
- Wheeler, J. C., Sneden, C., and Turan, J. W. 1989, in G. Burbidge, D. Layzer, and J. G. Phillips (eds.), *Ann. Rev. Astr. Astrophys.*, Vol. 27, p. 279, Annual Reviews, California
- Whitford, A. E. 1958, ApJ,63,201
- Whittle, M. 1989, in D. E. Osterbrock and J. S. Miller (eds.), *Active Galactic Nuclei*, p. 349, I.A.U., Kluwer, Dordrecht
- Winkler, P. F., Canizares, C. R., and Bromley, B. C. 1983, in J. Danziger and P. Gorenstein (eds.), *IAU Symposium 101, Supernova Remnants and their X-ray Emission*, p. 245, Reidel, Dordrecht
- Winkler, P. F., Canizares, C. R., Clark, G. W., Markert, T. H., and Petre, R. 1981, ApJ,245,574
- Winkler, P. F., Hearn, D. R., Richardson, J. A., and Behnken, J. M. 1979, ApJ,299,L123
- Winkler, P. F. and Kirshner, R. P. 1985, ApJ,299,981

- Winkler, P. F., Kirshner, R. P., Hughes, J. P., and Heathcote, S. R. 1989, *Nature*, 337, 48
- Winkler, P. F., Tuttle, J. H., Kirshner, R. P., and Irwin, M. J. 1988, in R. Roger and T. Landecker (eds.), *IAU Colloquium 101, Supernova Remnants and the Interstellar Medium*, p. 65, Cambridge, Cambridge
- Woosley, S. E., Axelrod, T. S., and Weaver, T. A. 1984, in C. Chiosi and A. Renzini (eds.), *Stellar Nucleosynthesis*, p. 263, Reidel, Dordrecht
- Woosley, S. E. and Weaver, T. A. 1981, in M. J. Rees and R. J. Stoneham (eds.), *Supernovae: A Survey of Current Research*, p. 79, Reidel, Dordrecht
- Woosley, S. E. and Weaver, T. A. 1986, in G. Burbidge, D. Layzer, and J. G. Phillips (eds.), *Ann. Rev. Astr. Astrophys.*, Vol. 24, p. 205, Annual Reviews, California
- Younger, S. M. 1981, *J. Quant. Spec. Rad. Trans.*, 26, 329
- Younger, S. M. 1982, *J. Quant. Spec. Rad. Trans.*, 27, 541
- Younger, S. M. 1983, *J. Quant. Spec. Rad. Trans.*, 29, 61
- Zeippen, C. J. 1982, *MNRAS*, 198, 111