THE NATURE OF CYANOGEN INHOMOGENEITIES
WITHIN STAR CLUSTERS

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ADDENDUM

After this thesis had been bound, a referee's report was received on the contents of Chapter 7, which had been submitted for publication (with the exception that the captions to Figures 1 and 2 were shorter than in this thesis). It was therefore decided to include the reply to the referee's comments in an addendum to this thesis.

The referee considered that in view of the small spectral differences found between E23 and E22 an explanation should be given as to why these observed differences are considered significant enough to warrant comparison with synthetic spectra. In reply, the following two paragraphs were written to amplify the discussion in the last paragraph of §II (pp. 180 and 183 of the thesis).

The spectra for the two program stars are shown overlapped in Figures 1a and 2a, where the thicker line represents that for E22. During data reduction the spectra were convolved with a gaussian of 2 pixels FWHM. The instrumental profiles corresponding to the resultant spectra have resolutions of 0.6 and 0.4 Å (FWHM) for Fig. 1a and 2a respectively. Figure 1a shows the region of the G-band, where both spectra are normalised at 4316 Å, while the region of the 4216 Å v = -1 CN band is shown in Fig. 2a, the normalisation being affected at 4217 Å. The spectra are in intensity units. The counts recorded at 4316 Å were ~ 1.2 x 10^3 per channel, and at 4217 Å were ~ 570 per channel. The normalisation of the G-band spectra at 4316 Å also produces good coincidence of the two spectra in relatively CH-free regions such as those near 4295 Å, 4302 Å, 4308 Å, 4319 Å, 4322 Å and 4326 Å. There are slight disagreements at wavelengths such as 4318 Å,
4319.5 Å and 4320.5 Å, but these are compatible with photon statistical errors. The normalisation of the CN spectra at λ4217 likewise produces satisfactory coincidence at 4188 Å, 4191.5 Å, 4197 - 4198 Å, 4202 Å and 4218 Å for example. The disagreements in the spectra in other CN free regions e.g. 4188 Å, 4200 - 4201 Å, 4208 Å and 4219 Å, are 1-2 times that expected from photon statistics.

The spectra in Fig. 2a indicate that E23 exhibits the stronger cyanogen bands, in agreement with the DDO photometry of Smith (1982). In addition, Fig. 1a shows that this star also has an enhanced G-band, suggesting that E23 has a higher carbon abundance than E22. It is important to mention that normalising the spectra at λ4318 say, will not remove the evidence for stronger G-band absorption (particularly at λ4323) in E23. There is no evidence from the present data for the existence of a CH, CN anticorrelation, as is the case between the globular cluster CN-weak and CN-rich giants. This is the main result of the present paper. It therefore seems worthwhile to investigate whether the carbon abundance difference between E23 and E22, as measured from the differences in the G-band spectra, can also explain the difference in λ4216 CN band strengths, without recourse to invoking a nitrogen abundance difference between the two stars. To address this question synthetic spectra have been computed for comparison with the observed spectra.

In addition to these comments, a more thorough analysis of the uncertainties in the measured C and N abundance differences between E23 and E22 resulting from the uncertainties in the observed spectra is presented below. This discussion amplifies the contents of the first paragraph of § IIIb (p. 187 of the thesis).

The carbon abundance difference, Δ[C/A], between E23 and E22
was assessed from the spectral differences at the reference wavelengths 4323 Å, 4313 Å, 4311 Å, 4310 Å and 4300.5 Å. The average of the five values of \( \Delta[C/A] \) determined at these points is

\[
\Delta[C/A] = [C/A]_{E23} - [C/A]_{E22} = 0.12 \pm 0.02.
\]

The error of 0.02, which is the standard error in the mean, is derived from the range in the five independent \( \Delta[C/A] \) measurements by using small sample statistics (Keeping 1962). The standard deviation in a \( \Delta[C/A] \) measurement obtained at a single wavelength is 0.04, which is compatible with the uncertainties introduced by photon statistical noise. Good agreement is therefore obtained between the \( \Delta[C/A] \) values inferred at different wavelengths. Another source of error will derive from the photon noise in the counts recorded at \( \lambda 4316 \), where the spectra are normalised. This will systematically effect the five reference points at which \( \Delta[C/A] \) is measured. The error introduced into \( \Delta[C/A] \) by the uncertainty in the normalisation is \( \lesssim 0.04 \) dex. The total error in \( \Delta[C/A] \) due to uncertainties in the observed spectra, both at the normalisation and five reference wavelengths, is \( \lesssim 0.05 \) dex. The present spectra are therefore of high enough quality to warrant comparison with synthetic spectra, despite the result that the carbon abundance difference thereby found is very small. Theoretical spectra computed for a difference of 0.2 dex in \( [C/A] \) did not give a good representation of the observed spectral differences.

Figure 2a,b shows that a \([C/A]\) difference of 0.1 dex also adequately reproduces the observed differences in the CN bands. Comparison of synthetic spectra with \([C/A] = 0.2, [N/A] = -0.3\) and \([C/A] = 0.2, [N/A] = -0.2\) shows that the features at \( \lambda 4215 \) and \( \lambda 4197 \) are most sensitive to changes in nitrogen abundance. If the observed spectral differences at these two wavelengths, plus that at \( \lambda 4195 \), are
assumed to be entirely due to a carbon abundance difference between E23 and E22, then the difference derived is $\Delta[C/A] = 0.11 \pm 0.04$, where 0.04 is the standard error in the mean of the measurements made at the three reference wavelengths. The standard error in a $\Delta[C/A]$ value determined at a single wavelength is 0.08 dex, so that to within the errors the above result is consistent with the spectral differences seen near $\lambda 4193$, $\lambda 4209$, and $\lambda\lambda 4211 - 4213.5$. There does not appear to be a need with the present data to invoke a large nitrogen abundance difference between the two stars. A small difference nevertheless cannot be ruled out. At $\lambda 4215$ and $\lambda 4197$, an error of 0.04 in $\Delta[C/A]$ could disguise a difference of $\approx 0.08$ dex in $[N/A]$. In addition, uncertainties in the normalisation could mask a nitrogen difference. If it is assumed that the error in the counts recorded at $\lambda 4217$ is twice that due to photon statistics (in view of the mismatch discussed above for regions free of CN absorption), the incorrect normalisation could disguise a $[N/A]$ difference of $\leq 0.15$ dex. Hence, a total difference of $\approx 0.17$ dex in $[N/A]$ between E22 and E23 cannot be ruled out.

Uncertainties in the spectrum synthesis analysis due to errors in the values of $T_{\text{eff}}$ and log $g$ adopted for E22 and E23 are given on pp. 183 - 190 of the thesis. In addition, it should be noted that the spectrum synthesis calculations of Cottrell and Norris (1978) for giants of similar gravities and $[\text{A/H}]$ abundance to E23, and $T_{\text{eff}} \sim 5000$ K, show that a change of 0.4 in log $g$ alters the CN features by only $\approx 2\%$. Thus the luminosity dependence of the CN bands would not be apparent between the likely log $g$ differences between E23 and E22.

If slight differences ($\approx 0.1 - 0.2$ dex) in $[\text{A/H}]$ exist between E23 and E22, the uncertainty that this will introduce into the measured
value of $\Delta [C/A]$ will be small. Cottrell (1978) has shown that estimates of $[C/A]$ based on the G-band strength are insensitive to the value of $[A/H]$ adopted e.g. for a model atmosphere with $T_{\text{eff}}/\log g/ [A/H] = 4100/0.80 - 2.7$, he finds that an uncertainty of $\pm 0.3$ in $[A/H]$ would cause an error of only $\pm 0.05$ in the $[C/A]$ measurement. Synthetic spectra calculated by this candidate for models with temperatures and gravities similar to that of E23 but with $[A/H]$ values of 0.2 and 0.0, showed negligible differences after being normalised at $\lambda 4217$. Hence, even if it should transpire that E23 and E22 differ in $[A/H]$, the present data would still indicate the existence of a $[C/A]$ difference between these stars.

An uncertainty in the analysis may result from the atmospheric structure of E23 being different to that of E22 as a consequence of higher CO line blanketing (the CN molecule has a negligible effect in this regard; Gustafsson et al. 1975). Gustafsson et al. (1975) find for a model atmosphere with $T_{\text{eff}} = 6000$ K, $\log g = 2.25$ and $[A/H] = 0$, that the temperature at an optical depth of $\tau = 2.5 \times 10^{-3}$ for a model which includes CO and CN blanketing is only 10-20 K cooler than for a model in which no allowance for this is made. In view of the insensitivity of the G-band strength to changes in $T_{\text{eff}}$ (see p. 189; Cottrell 1978; Day 1980), differences in temperature structure, $T(\tau)$, between E23 and E22 due to differences in CO blanketing are therefore expected to have a negligible effect on the measurement of $\Delta [C/A]$. This expectation is borne out by the analysis of Day (1980), who for a model of HR 6791 ($T_{\text{eff}} = 5000 \pm 125$ K, $\log g = 2.9 \pm 0.2$, $[Fe/H] = + 0.18 \pm 0.15$) has analysed the effects of CO blanketing on $T(\tau)$ for models with $[C/Fe] = 0$ and $[C/Fe] = -1.1$. He finds that the use of these two models to measure a carbon abundance from the $\lambda 4323$ CH
feature would produce differences of only $0.15 \pm 0.05$ dex, a higher abundance being determined from the C deficient model. In view of the much milder $[C/A]$ difference between E23 and E22, the uncertainty in $\Delta[C/A]$ due to differences in CO blanketing is negligible.

It is concluded that uncertainties in the values of $T_{\text{eff}}'$, $\log g$ and $[A/H]$ adopted for E23 and E22 do not contribute as large an error to the determination of $\Delta[C/A] = [C/A]_{E23} - [C/A]_{E22}$ as does photon noise in the observed spectra. For example, a difference of 100 K in $T_{\text{eff}}$ between E23 and E22 would mask a $[C/A]$ difference of only $\sim 0.02$ dex in $[C/A]$, whereas a difference of 0.2 in $\log g$ would mask a difference of $\lesssim 0.01$ dex.

REFERENCES


ERRATUM

p. 7

$^{15}\text{N}(p,\gamma)^{12}\text{C}$ should read $^{15}\text{N}(p,\alpha)^{12}\text{C}$

p. 163

Reference 11) is missing. This should be Wheeler 1979.

p. 182

In the caption to Fig. 2a $\sim 530$ per pixel should read $\sim 570$ per pixel.
To my parents, who have always done so much for me
The work described in this thesis is that of the candidate alone except where outlined below:

- Chapters 2 and 3 constitute part of joint publications with Dr. J. Norris, whose main contributions were the reduction of most of the NGC 3201 data, the measurement of the G-band equivalent widths for the M5 stars, and the inspection of Dr. R. Zinn's spectra of M5 giants.

- Chapter 5 consists entirely of the contributions made by this candidate to a joint paper with Dr. J. Norris (Ap. J., 254, 594).

- Chapter 8 has been submitted as a joint paper with Dr. M. Dopita, who conceived the idea of using narrow band interference filters with the AAT/IPCS combination to measure the strength of the $\lambda$3883 CN band, and participated with the observations. All of the data analysis and interpretation is the work of the candidate.

August, 1982
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I would like to thank my supervisors Drs John Norris and Michael Dopita for their continual encouragement, support and advice, without which this thesis would not have been possible. Both of them have given freely of their time and energy, and I have valued not only their supervision but their friendship as well.

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I would like to thank Mrs Sue Parkes for drawing the diagrams included in this thesis, and to Mr Keith Smith for photographing them. I am also grateful to Mrs Kerryn Hyde and Miss Maria Sharr for the care with which they have typed this thesis.

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Spectroscopic and photometric observations have been made of the cyanogen band strength distributions within the five globular clusters NGC 362, NGC 3201, M5, M71 and M55. Of these, the first three, and probably M71, are found to exhibit bimodal CN distributions. In NGC 3201, M5 and M71, the CN-enhanced giants, on average, have weaker CH and/or CO bands than the CN-poor giants. This suggests the presence of a C,N abundance anticorrelation between the CN-weak and CN-strong populations of giants.

The clusters M71 and M55 were observed in order to determine whether the nature of the cyanogen distributions depend on cluster mass or morphology. M71 presents an interesting contrast with 47 Tuc, since both clusters have a similar abundance, but very different masses ($M_{47 \text{Tuc}} \sim 10^6 M_\odot$, $M_{M71} \sim 7 \times 10^4 M_\odot$) and central mass concentrations ($c[= \log_{10} \frac{r_t}{r_c}] \sim 2.0$ for 47 Tuc, and $\gtrsim 1.2$ for M71). M71 was found to possess a family of cyanogen enhanced stars similar to those in 47 Tuc, indicating that bimodal cyanogen variations (unaccompanied by substantial Ca or Fe inhomogeneities) result from a mechanism which is independent of cluster mass or central concentration. In contrast to this result, M55 does not contain extremely CN-rich giants analogous to those found in the clusters ωCen and M22, which are similar to M55 in their baselevel metal abundance, but have much higher masses.

The clusters M5 and NGC 362 both display bimodal cyanogen distributions in which the ratio of CN-rich to CN-weak giants is $> 2.5$, whereas in clusters such as 47 Tuc, NGC 6752 and M4 this
ratio is \( \sim 1.4 \). In NGC 362 the cyanogen variations have been found among subgiants \( \sim 1.7 \) magnitudes fainter than the luminosity predicted by Sweigart and Mengel for the onset of CN anomalies produced by rotation-induced meridional circulation.

The implications of a carbon, nitrogen anticorrelation among the stars in clusters displaying a bimodal CN distribution have been explored. With regard to the mixing theory, it is not sufficient merely to dredge up part of the CN-burning shell at one point during the evolution of the star and dilute it throughout the envelope. Rather an active CN-processing of the envelope, by continual cycling through the CN-shell, is required. The observations of a C,N anticorrelation appear to be incompatible with the theory of primordial self-enrichment if the CN-weak stars are identified as those which formed out of the original proto-cloud gas, and the CN-rich stars are assumed to represent the enriched generation.

Observations have also been obtained of giants in the open cluster IC 4651 and the Sculptor dwarf spheroidal galaxy for comparison with the globular cluster data. IC 4651, a cluster with a metal abundance slightly lower than that of the Hyades, is found to possess one giant with enhanced \( \lambda 4216 \) CN bands. A spectrum synthesis technique was employed to determine the carbon and nitrogen abundance differences between this star, and a more typical cluster member. It was found that this CN-strong giant is enhanced by \( \sim 0.1 \) dex in \([C/A]\), and by \( \lesssim 0.1 \) dex in \([N/A]\). The enhanced \( \lambda 4216 \) CN bands can be attributed to the mild carbon overabundance, whereas carbon depletions are generally seen in the CN-rich globular cluster giants.
Photometric observations show that the giant star population within the Sculptor dwarf spheroidal galaxy exhibits variations in both the cyanogen and calcium abundances. These variations are correlated in the sense that giants with strong CN bands generally possess strengthened CaII H and K lines. Sculptor appears to be similar in this regard to the globular cluster ωCen, as originally suggested by Norris and Bessell.
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CHAPTER 1

INTRODUCTION

I. GENERAL

One of the more unexpected results of globular cluster research over the past decade has been the discovery that these systems are not chemically homogeneous. The study of these abundance inhomogeneities offers the possibility of providing much information concerning the processes that occur within stars during their evolution and/or the events responsible for the chemical enrichment of the galactic halo.

The most widespread of the abundance anomalies seem to be those of the molecules containing nitrogen and/or carbon e.g. cyanogen (CN), CH, NH and CO. Of these, the work presented in this thesis will concentrate on measuring cyanogen band strengths for samples of stars within several globular clusters, and determining their distribution. In addition, members of the open cluster and dwarf spheroidal galaxy populations will be studied, since these systems are so morphologically different from the globular clusters. The ultimate motivation of this work is to provide constraints for theories of the origin of abundance variations within old population star clusters.

In this first chapter the available information concerning cluster CN inhomogeneities will be summarised. Much of this material has been previously reviewed by Kraft (1979), McClure
At the outset it is useful to distinguish between the collective abundance of the elements C, N and O, denoted $Z_{\text{CNO}}$ and that of the remaining heavy elements, denoted as $Z_{\text{Fe}}$.

II. A SUMMARY OF THE CYANOGEN INHOMOGENEITIES IN STAR CLUSTERS

a) The Globular Clusters

The early DDO photometry of Osborn (1971) revealed one giant in each of the clusters M5 and M10 which appeared to have enhanced CN bands when compared to other cluster members of similar temperatures and gravities. The more extensive DDO photometric surveys of Hesser, Hartwick and McClure (1977), McClure and Norris (1974) and Bessell and Norris (1976) showed that variations of this band occurred within many clusters (e.g. M5, M10, ωCen, NGC 362, 47 Tuc, NGC 6352 and M71).

The DDO color $C(41-42)$ measures the strength of the blue λ4216 ($\Delta v=-1$) CN band, and is sensitive to the metal abundance for stars with $[\text{Fe/H}] \lesssim -1.0$, as indicated by the spectrum synthesis calculations of Deming (1978), which are based on model atmospheres. One of the most notable of clusters with such a metal abundance is 47 Tuc. Norris and Freeman (1979) have presented $C(41-42)$ colors for 142 of its red giants, and shown that the cyanogen distribution is bimodal, with roughly equal numbers of CN-rich and CN-poor giants. A similar CN distribution exists among the red horizontal branch stars (Norris and Freeman 1982a).

Evidence that these cyanogen variations are the consequence of carbon and nitrogen abundance variations comes from the spectrum synthesis calculations of Norris and Cottrell (1979), Dickens, Bell and Gustafsson (1979), and Norris and Freeman (1982a).
Among clusters with metallicities in the range $-1.9 < [\text{Fe/H}] < -1.2$ (on the abundance scale of Zinn 1980b) the $\lambda 4216$ CN band is weak, although it can still be used to identify stars with large nitrogen abundances, as in Cen for example (Bessell and Norris 1976). The violet ($\Delta v=0$) band at $\lambda 3883$ is now the best indicator of cyanogen variations. Quantitative surveys of the strength of this band among giants in the clusters NGC 6752 (Norris et al. 1981), M4 (Norris 1981), M3 and M13 (Suntzeff 1981), and NGC 3201 (Da Costa, Frogel and Cohen; 1981), $\omega$ Cen (Norris 1980), and M22 (Norris and Freeman 1982b) are now available. In addition, Zinn (1977) has presented qualitative assessments of the $\lambda \lambda 3883$ and 4216 CN, and $\lambda 4310$ G-band strengths for giants in M5. Norris et al. (1981) and Norris (1981) find that bimodal CN distributions exist in both NGC 6752 and M4, with there being approximately equal numbers of CN-weak and CN-strong giants. Suntzeff (1981), from a sample of 25 M13 giant branch stars, finds 19 to be CN-rich, 5 to be CN-poor, and one to be CN-moderate. Three of the five CN-poor giants are situated at the tip of the giant branch so that CN-rich stars dominate at most luminosities. In addition, 8 out of 10 asymptotic giant branch stars are classified as CN-poor, and 2 as CN-moderate. In M3, Suntzeff's sample comprises 6 CN-rich and 7 CN-poor giants above a magnitude of $M_{V,0} = -0.4$. However, below this level only CN-poor stars are evident. Da Costa, Frogel and Cohen (1981) report that NGC 3201 is essentially homogeneous with regard to cyanogen.

In $\omega$ Cen (Norris 1980) and M22 (Norris and Freeman 1982b) it is not possible to classify stars into either a distinct CN-rich or CN-poor group since a continuous distribution of $\lambda 3883$ CN band strengths is seen. This is one of a number of characteristics that seem to distinguish these two clusters from the others mentioned above. Some of the other characteristics will be summarised below.
Other clusters in which variations of the $\lambda 3883$ CN band have been found include NGC 7006, M2 (McClure and Hesser 1981), NGC 288 (McClure and Hesser 1981; Canterna, Harris and Ferrall 1982), NGC 362 (Canterna, Harris and Ferrall 1982), and NGC 1851 (Hesser et al. 1982).

In clusters with abundances of $[\text{Fe/H}] < -1.9$ (on the Zinn 1980b scale), the $\lambda 3883$ CN band is very weak, although Carbon et al. (1982) were able to detect it on 10 Å resolution spectra of M92 giants ($[\text{Fe/H}] \sim -2.3$, Zinn 1980b) with high C and/or N abundances. At very low metal abundances, the G-band or the NH bands near $\lambda 3360$ must be turned to in the search for inhomogeneities in $Z_{\text{CNO}}$.

b) The Old Open Clusters.

The situation in the old disk open clusters is quite different. Since these clusters usually have abundances of $[\text{Fe/H}] \sim -0.6$, DDO photometry is well suited to surveying the $\lambda 4216$ CN band strengths among their red giants. A recent tabulation of open clusters for which DDO colors are available is given by Janes (1979). The number of giants available for study within the open clusters is much less than in the globular clusters. However it is apparent that they are much more chemically homogeneous than the globulars, as was first pointed out by Hesser, Hartwick and McClure (1976). Giants with anomalously strong CN bands have been found in Melotte 66 (Dawson 1978; Anthony-Twarog, Twarog, and McClure 1979) and NGC 2420 (McClure, Forrester and Gibson 1974) but only in small numbers ($\sim 2$ per cluster). A comparison between NGC 2420 and 47 Tuc is quite interesting, since the giants in both clusters have similar ultraviolet U-B excesses (Demarque and McClure 1977). As mentioned above, fifty percent of the giants in 47 Tuc display enhanced $\lambda 4216$
CN bands (Norris and Freeman 1979). However, from a survey of 13 giants in NGC 2420, McClure, Forrester and Gibson (1974) find only two with enhanced CN. It appears that open clusters do not share in the extent of the globular cluster CN anomalies.

c) The Dwarf Spheroidal Galaxies.

Recent work has shown that the dwarf spheroidal galaxies are chemically inhomogeneous. Their color-magnitude diagrams (see e.g. the reviews by Hodge 1971 and Zinn 1980a, and references therein) show giant branches similar to those of the globular clusters, indicating low metallicities. The canonical picture developed of the dwarf spheroidals was that they contained an ancient population of stars similar to the globular clusters. This concept is now known to be over-simplified, as is evident from the review by Zinn (1980a).

Firstly, the horizontal branches of these systems e.g. Sculptor (Hodge 1965, Kunkel and Demers 1977) and Draco (Baade and Swope 1961, Stetson 1979), are too red to be consistent with the metal abundances indicated by the giant branch slopes unless differences in another parameter e.g. the helium abundance, age or $\frac{\text{[C+N+O/Fe]}}{}$ (cf. Rood 1973) exist between them and the globular clusters.

Other evidence for differences in the stellar populations between dwarf spheroidals and globular clusters comes from the existence of "anomalous" cepheids in the former. These do not obey the period-luminosity relation of the cluster cepheids, being brighter for a given period. This behaviour can be understood if the anomalous cepheids are \( \sim 2 \) times more massive (\( \sim 1.5 \, M_\odot \)) than globular cluster stars (Norris and Zinn 1975, Demarque and

The Fornax and Carina dwarf spheroidals appear to possess luminous carbon stars (Aaronson and Mould 1980; Cannon, Niss and Norgaard-Nielsen 1981; Mould et al. 1982, Frogel et al. 1982) of a type unknown within globular clusters of the Galaxy. These observations suggest that, unlike the globular clusters, at least some of the dwarf spheroidals possess an intermediate age population (Aaronson and Mould 1980).

In addition to these peculiarities, all of the dwarf spheroidals which have been studied in detail, show heavy element ($Z_{\text{Fe}}$) variations among their red giants. This effect is most extensively documented for the Draco system (Zinn 1978, 1980c; Kinman, Kraft and Suntzeff 1981), although $Z_{\text{Fe}}$ inhomogeneities have been found among small ($\leq$5) samples of giants in Ursa Minor (Zinn 1981), Sculptor (Norris and Bessell 1978) and the globular clusters in Fornax (see Zinn and Persson 1981, and references therein). An interesting comparison has been made by Zinn (1978) between the Draco system and the globular cluster M92. Both have similar masses ($\sim 10^5 M_\odot$), and yet while M92 is relatively homogeneous in $Z_{\text{Fe}}$, a range in $Z_{\text{Fe}}$ exists in Draco ($\Delta [\text{Fe/H}] \sim 0.6 \text{ dex}$). In view of these $Z_{\text{Fe}}$ inhomogeneities, it might be expected that the dwarf spheroidals will also display exotic anomalies in $Z_{\text{CNO}}$.

In the next two sections, the theories concerning the origin of cyanogen anomalies within star clusters will be reviewed. The emphasis will be almost entirely given to theories for the globular cluster anomalies, since it is for these that the great majority of the data are available.
III. THE ROLE OF MIXING WITHIN GLOBULAR CLUSTER STARS

The CN-cycle of hydrogen burning consists of the reaction chain:

\[
^{12}\text{C}(p,\gamma)^{13}\text{N}(e^+\nu)^{13}\text{C}(p,\gamma)^{14}\text{N}(p,\gamma)^{15}\text{O}(e^+\nu)^{15}\text{N}(p,\gamma)^{12}\text{C}
\]

The (p,\gamma) reactions are the slowest in this sequence, leading to a buildup of the \(^{14}\text{N}\) and \(^{13}\text{C}\) abundances. The ON-cycle

\[
^{15}\text{N}(p,\gamma)^{16}\text{O}(p,\gamma)^{17}\text{F}(e^+\nu)^{17}\text{O}(p,\alpha)^{14}\text{N}
\]

also operates within stellar interiors, and results in the conversion of \(^{16}\text{O}\) to \(^{14}\text{N}\). These reactions constitute the so-called CNO bi-cycle, and lead to an increase in the \(^{14}\text{N}\) abundance, and a depletion of \(^{12}\text{C}\) and \(^{16}\text{O}\).

Within low mass (∼1M☉) main sequence stars \(^{12}\text{C}\) is converted almost entirely to \(^{14}\text{N}\) over the inner 30% (by mass), whereas partial ON processing occurs over the inner 10% (Iben 1977, Castellani 1980). When hydrogen is exhausted over the inner 10% of the star, the matter in this region begins to contract, hydrogen burning commences in a thin shell, and the envelope of the star expands. Once the star begins to ascend the giant branch, a convective envelope extends inward in mass. The convective boundary eventually enters the region of earlier \(^{12}\text{C}\) to \(^{14}\text{N}\) conversion, with the result that nitrogen enriched, carbon depleted material is brought to the surface (the first dredge-up phase). Consequently, the surface carbon and nitrogen abundances of giants which have undergone mixing should be anticorrelated as compared to those in unmixed stars.

A C,N anticorrelation has in fact been found among the red giants in NGC 6752 (Da Costa and Cottrell 1980, Norris et al. 1981),
M3 and M13 (Suntzeff 1981), and the asymptotic branch giants (Norris and Cottrell 1979) and red horizontal branch stars of 47 Tuc (Norris and Freeman 1982a). The spectroscopic characteristic of the anticorrelation is the presence of a stronger λ3883 CN band and a weaker G band in the presumably mixed stars. However the size of the nitrogen overabundances found by the above authors in the CN-rich giants (e.g. 7-8 times that in the presumably unmixed CN-weak giants for NGC 6752 and 47 Tuc) are too large to be explained in terms of the standard mixing episode described above. After the first dredge-up the surface nitrogen abundance is predicted to change by an amount (Iben 1977) \( \Delta Z_{14} \), which is given by \( \Delta Z_{14}/Z_{14} = z_{12}^{1} / Z_{14}^{1} \) where \( z_{14}^{1} \) and \( z_{12}^{1} \) are the initial nitrogen and carbon mass fractions. For an initially solar C/N ratio, \( \Delta Z_{14}/Z_{14}^{1} \sim 1.6 \), which is far too small to explain the globular cluster giant observations.

One way around this difficulty is to postulate the dredge-up of ON as well as CN processed material. This possibility has been considered by Sweigart and Mengel (1979), who studied the possible effects of meridional circulation within red giants. Their models of static giants (\( \log[L/L_\odot] = 2.3 - 2.7 \)) indicate that external to the hydrogen burning shell exist zones of material which have been partially processed through the ON and CN cycles. An ON processed region lies interior to the CN region, although in neither does the CNO cycle burn to equilibrium. Sweigart and Mengel argue that meridional circulation currents induced by the rotation of the giants, can penetrate the ON and CN burning shells and transport \(^{14}N\) into the stellar atmosphere. Meridional currents are inhibited by gradients in molecular weight, so that this process cannot operate until the hydrogen burning shell has burned through
the hydrogen discontinuity marking the innermost extent of the convective envelope. The meridional circulation theory therefore predicts a luminosity limit which a star must exceed before surface nitrogen anomalies become apparent. If the circulation currents are to penetrate the CN and ON shells, the molecular weight gradients in the vicinity of these must be small. In metal-poor stars ($Z \approx 10^{-4}$) Sweigart and Mengel find this to be the case, and the products of both shells can be brought to the surface. However, as the metal abundance is increased, the ON and CN shells move closer to the hydrogen burning shell, thereby increasing the molecular weight gradient across the ON region. The result is that for all metallicities the CN shell is sufficiently removed from the hydrogen burning shell to always permit dredge-up of its material, but for Population I abundances the mixing of ON cycled material should be prohibited.

This theory has a number of observable consequences.

1) In Population II giants it permits ON processed material to contribute to the surface $^{14}$N abundance, in agreement with the large overabundances observed in the CN-rich stars. Another result of this could be to remove a strict 1:1 C,N abundance anticorrelation, since the $^{14}$N abundance could be increased without further carbon depletion. Carbon et al. (1982) do in fact find large nitrogen and carbon variations among the giants in the metal-poor cluster M92, but no evidence for a 1:1 C,N anticorrelation.

2) The Sweigart and Mengel theory predicts a critical luminosity for the onset of CN and CH variations. With the cluster M92 ([Fe/H] = -2.2; Zinn 1980b) the theoretical onset is at $M_v = -0.5$. Bell, Dickens and Gustafsson (1979) find for this cluster and
NGC 6397 that carbon depletions set in above $M_V = -0.7$. The work of Carbon et al. (1982) has shown, however, that CH variations in M92 exist down to $M_V = 1.7$, in conflict with the Sweigart and Mengel theory. Nonetheless, both studies find that carbon depletion is a function of luminosity on the giant branch, which strongly suggests a mixing origin.

Support for the Sweigart and Mengel theory comes from Suntzeff's (1981) study of M3. He finds that subgiants below $M_V = -0.4$ have carbon and nitrogen abundances of $[\text{C/Fe}] \sim -0.3$ and $[\text{N/Fe}] \sim -0.2$, whereas the more evolved giants (with $B-V_0 > 0.8$) have $[\text{C/Fe}] \sim -0.6$ and $[\text{N/Fe}] \sim 0.3$. In other clusters the meridional circulation theory does not fare well. Cyanogen variations have been found among faint subgiants and/or main sequence turn-off stars in 47 Tuc (Hesser 1978, Hesser and Bell 1980) and ωCen (Bell et al. 1981). In addition, nitrogen-rich stars have been identified in NGC 6752 (Da Costa 1979, Norris et al. 1981) and M13 (Suntzeff 1981) at magnitudes $M_V > 0$.

3) The Sweigart and Mengel theory indicates that no mixing of ON processed material should occur to the surfaces of Population I giants; only CN-cycled material should be brought up. When this result is coupled with the calculations of Deming (1978) which show that the presence of CN-processed material in a stellar atmosphere should not significantly increase the λ4216 CN band strength, and may in fact decrease it if mixing is extensive enough, it offers an explanation for why few giants with anomalously large C(41-42) colors are found in open clusters.

The existence of CH stars in the clusters ωCen (Harding 1962, Stock and Wroblewski 1972, Dickens 1972, Bond 1975), M22 (McClure and Norris 1977), M55 (Lloyd Evans; see McClure 1979) and
M2 (Zinn 1981) is further evidence for the occurrence of mixing within globular cluster stars. These giants show strong features of the \( \lambda 4216 \) CN and \( \lambda 4310 \) G bands, as well as the presence of a \( C_2 \) band at \( \lambda 4737 \). Bell and Dickens (1974) found abundances for two \( \omega \)Cen CH stars of \([C/\text{A}] \sim 0.4 - 0.5\), \([^{12}\text{C}/^{13}\text{C}] \sim 10\), and \([\text{N}/\text{A}] \sim 1.3\) (assuming \([\text{O}/\text{A}] = 0\) with \([\text{A}/\text{H}] = -1.3\)). The low \([^{12}\text{C}/^{13}\text{C}]\) ratio indicates substantial exposure of the material now in the atmosphere to CN-processing, while the carbon overabundances may indicate that primary carbon, produced by helium burning, has been brought to the surface.

Another category of stars that are important to the mixing theory are the weak-G-band stars. These have been found in M92 (Zinn 1973), M13 and M15 (Norris and Zinn 1977), NGC 6397 (Mallia 1975, Norris and Zinn 1977), \( \omega \)Cen (Norris and Bessell 1977), M5 (Zinn 1977) and NGC 6752 (Mallia 1977). Spectrum synthesis analyses (Mallia 1977; Bell, Dickens and Gustafsson 1979; Suntzeff 1981; Carbon et al. 1982) have revealed substantial carbon depletions e.g. \([\text{C}/\text{Fe}] \lesssim -0.7\), which are more extreme than those seen among the CN-rich stars in clusters such as NGC 6752, and so possibly reflect the occurrence of a more extreme mixing event.

IV. THE EVIDENCE FOR PRIMORDIAL ENRICHMENT WITHIN GLOBULAR CLUSTERS

The primordial explanation for the C,N abundance variations within globular clusters assumes that the star-to-star inhomogeneities existed in the gas from which the stars formed. There are two possible ways in which this might have come about.

Firstly, the original protocluster gas clouds may have been chemically inhomogeneous prior to any cluster star formation. A second scenario envisages the formation of massive stars within a
collapsing gas cloud. Such stars produce heavy elements which are ejected into, and mixed with, the surrounding gas within the protocluster. Subsequent generations of stars are therefore more metal-rich than the first. This possibility will be referred to as the 'self-enrichment' picture, since it proposes that globular clusters, by virtue of the star formation occurring within them, actively increase their mean abundance. In the previous hypothesis, the clusters are merely reflecting inhomogeneities that were established during an earlier period of star formation.

Evidence for the self-enrichment scenario is the existence of B-V and U-B gradients within 47 Tuc (Gascoigne and Burr 1956, Chun and Freeman 1979). This appears to result from an excess of bright red giants per unit luminosity toward the cluster centre (Lloyd Evans 1974, Chun 1976, Freeman 1980).

Good evidence is thus available for the existence of a color gradient in 47 Tuc. In addition, Chun and Freeman (1979) from a survey of 24 clusters, find color gradients in 8 of them. Apart from 47 Tuc, the most convincing evidence is in NGC 2808, where the B-V and U-B gradient extends over the entire core radius. The largest gradient found was in the cluster M5, however Da Costa (1979) and Buonanno et al. (1981) have shown that this result is due to the contaminating effects of a few bright giants on the colors measured through the smallest apertures. These authors argue that many of the color gradients found by Chun and Freeman could be the result of centering their apertures on bright giants.

Parallel to these investigations are searches for radial abundance variations. Norris and Freeman (1979) find that the proportion of CN-strong giants in 47 Tuc is higher within r=2' of
the cluster center than for the region $r>6'$. This result has been questioned by Hartwick and McClure (1980), although Norris and Smith (1981) still find evidence for a CN gradient when the stars are divided into groups with $r<3'$, $6'<r<15'$, and $r<15'$. Smith, H.A. (1979), from spectra of regions devoid of bright giants, finds evidence for slight gradients in the abundances of CH, Ca and Mg within 47 Tuc.

In ω Cen, Norris, Freeman and Seitzer (as reported in Freeman and Norris 1981) find a radial CN gradient among a sample of giants which extend almost to the tidal radius. Da Costa (1979) finds that the mean [Fe/H] abundance is essentially constant within 8' (4 core radii) of the cluster center, a result which is still consistent with Norris, Freeman and Seitzer, since the CN gradient is only apparent among a sample of giants which extend to greater than 15' from cluster center. There is little evidence for a CN gradient within 8'. Freeman (1980) and Smith, H.A. (1981) find evidence for a calcium abundance gradient among the RR Lyraes.

These color and line strength gradients are reminiscent of those found in elliptical galaxies (cf. Faber 1977), which points to them having been established during the era of star formation within the clusters (Chun 1976, Freeman 1980, Larson 1974).

The Globular Cluster ω Centauri

The most striking evidence for primordial enrichment within a globular cluster is provided by ω Centauri. The broad giant branch in the $(V, B-V)$ diagram (Woolley et al. 1966, Cannon and Stobie 1973, and Bessell and Norris 1976), suggests the presence of heavy element variations (Iben 1974); the width of the giant branch being $\Delta(B-V) \approx 0.24$ (Butler, Dickens and Epps 1978) for $V>13.0$, increasing to $\Delta(B-V) \approx 0.40$ for $V<12.5$ (Bessell and Norris 1976).
Variations in $Z_{\text{Fe}}$ were discovered by Freeman and Rodgers (1975) who found large calcium abundance variations among the RR Lyraes. This work was extended by Butler, Dickens and Epps (1978) and Manduca and Bell (1978). It is now well established that a calcium abundance spread of $-1.9 \leq [\text{Ca/H}] \leq -1.1$ exists among the RR Lyraes in $\omega$Cen. This result is in agreement with the $[\text{Ca/H}]$ and $[\text{Fe/H}]$ abundance spreads found among the red giants (Rodgers et al. 1979, Norris 1980, Mallia and Pagel 1981, Cohen 1981). It is these Ca and Fe variations that are indicative of primordial enrichment, since low mass globular cluster stars do not manufacture these elements within their interiors, and so the surface abundances should not be affected by mixing.

In addition, $\omega$Cen giants display large variations in the strengths of the CN, CH and CO bands. Dickens and Bell (1976) find nitrogen enhanced by up to a factor of 40 in some giants. Bessell and Norris (1976) and Norris and Bessell (1977) found large variations in the CN and CH band strengths among giants of comparable luminosity. While the strong CH stars also have strong CN, those with less extreme G-bands show a variety of CN strengths. This lack of a CN, CH correlation is consistent with the infrared photometry of Persson et al. (1980), who find no strict correlation between the incidence of strong CO and CN bands, and the spectrum synthesis calculations of Mallia and Pagel (1981) who find carbon enhancements $[\text{C/Fe}] \leq 0.4$ for two of the CO-strong giants.

Thus $\omega$Cen, apart from showing variations in $Z_{\text{Fe}}$, for which a primordial origin seems necessary, also has variations in $Z_{\text{CNO}}$, which might be thought to have a mixing origin. However, Norris (1980) and Norris and Bessell (1977) have shown that a correlation exists between the CaII H+K absorption and the strength
of the $\lambda 3883$ CN band. This result is supported by the observation that the CN absorption increases upon moving across the giant branch, from the blue to the red side (Bessell and Norris 1976). These facts indicate that the cyanogen abundance shares in the primordial manufacture of the heavy elements, and so raises the possibility that the CN variations in other clusters may have a primordial origin.

$\omega$Cen-like Anomalies in Other Globular Clusters

A large scatter in the C(41-42) DDO color, and hence the $\lambda 4216$ CN band strength was found among the giants in M22 by Hesser, Hartwick and McClure (1977). The existence of a CN variation has been confirmed by the spectroscopic work of Lloyd Evans (1978) and Hesser and Harris (1979). On the basis of a wide giant branch ($\Delta(B-V) \approx 0.06$) seen in their $V, B-V$ photometry for this cluster, Hesser, Hartwick and McClure (1977) suggested that it might possess, although to a milder degree some of the $Z_{Fe}$ inhomogeneities characteristic of $\omega$Cen. The data relevant to this question are conflicting. Lloyd Evans (1978) has shown that the width of the giant branch can be explained in terms of observational errors and the inclusion of field stars in the color-magnitude diagram of Hesser, Hartwick and McClure (1977). In addition, no evidence has been found for a calcium abundance variation among the RR Lyraes (Butler et al. 1973, Butler 1975, Manduca and Bell 1978). Cohen (1981), from a detailed abundance analysis of three giants, finds no evidence for variations in any elements other than sodium, and perhaps barium. On the other hand, Hesser and Harris (1979) report the possible existence of Ca I and II line strength variations, although they consider that repeat observations are necessary. Peterson (1980b) has reported a variation of 0.6 dex in the $[Fe/H]$
abundance among four M22 red giants. Norris and Freeman (1982b) have recently completed a comprehensive survey of M22 giants, and their work clearly shows a number of the ωCen anomalies. Correlated variations of the λ3883 CN band and CaII H+K lines are apparent among giants of comparable luminosity. In addition the G-band equivalent width correlates with the H+K strength, and the AlII lines at λλ3944 and 3961 appear to be enhanced in the CN-rich giants.

Apart from M22, evidence for variations of elements heavier than oxygen exists for other clusters. Peterson (1980a) finds a [Na/Fe] variation of ~1 dex among giants in M13. Sodium line variations have also been found in the more metal rich cluster 47 Tuc (Cottrell and Da Costa 1981; Da Costa 1981; Lloyd Evans, Smith and Menzies 1981). It is apparent in the 47 Tuc studies that the Na overabundances are found in giants which also have cyanogen enhancements. Norris et al. (1981) and Cottrell and Da Costa (1981) find correlations between the strengths of Na and Al lines and the λ3883 CN band for giants in NGC 6752. These results for 47 Tuc and NGC 6752 are reminiscent of ωCen, and taken by themselves, would imply a primordial origin for the cyanogen inhomogeneities.

V. THESIS OUTLINE

At the time of commencing the research reported in this thesis (mid-1979) it was apparent from the literature that cyanogen inhomogeneities were widespread among the globular clusters of the Galaxy (§II). However, detailed information on the form of the CN distributions within individual clusters was only available for the massive systems of 47 Tuc and ωCen, as well as for NGC 6752. In view of the possibility that the form of this distribution might
prove to be a distinctive signature of the mechanism responsible for the CN variations, a program was undertaken to determine the cyanogen distributions among giants within stellar systems having a wide variety of masses and morphologies. To cover as wide a range of these parameters as possible, open clusters and dwarf spheroidal galaxies were also considered for observation along with globular clusters. It was decided to concentrate on cyanogen inhomogeneities because the CN bands at $\lambda\lambda$ 3883 and 4216 can be observed in spectra of intermediate dispersion ($\sim$50 - 100 $\AA$ mm$^{-1}$) and resolution ($\sim$3-10 $\AA$). Work reported in a number of the papers cited above has shown that the inhomogeneities typically found in globular clusters with [Fe/H] $\sim$ -1.9 can be identified with such spectra.

The thesis layout is as follows: In Chapters 2, 3 and 4 observations of the cyanogen distributions in the globular clusters M55, M71, NGC 3201, M5 and NGC 362 are presented. Most of the data consists of spectroscopic measurements of the strength of either the $\lambda$4216 or $\lambda$3883 CN bands. For some clusters, estimates of the G-band strength will be presented, while for others data on the 2.3 $\mu$m CO band strength have been obtained from the literature.

The aims of this work are as follows:

i) To provide further information concerning the frequency of bimodal CN distributions within globular clusters. Such bimodalities have been found in 47 Tuc, NGC 6752 and M4 by Norris and Freeman (1979), Norris et al. (1981), and Norris (1981), and this high incidence may suggest that distributions of this nature are the ones preferred by globular clusters.

ii) The work of Norris and Cottrell (1979) on 47 Tuc, and Da Costa and Cottrell (1980) and Norris et al. (1981) on NGC 6752, indicates that the carbon and nitrogen abundances are anticorrelated
between the CN-rich and CN-normal giants in these clusters. In addition, Norris (1981) finds evidence for a CN, CH band strength anticorrelation between two giants within M4. This may be hinting that a C,N anticorrelation is a characteristic of clusters with bimodal CN distributions. The CN,CH and CO data given in Chapters 2 and 3 will provide additional information with which to weigh this suggestion.

iii) By substantially increasing the number of clusters for which CN distributions are known, it may be possible to assess whether the form of these distributions correlate with the mass or metallicity of the globular clusters. A mass dependence might be expected for instance if the CN anomalies owe their existence to primordial enrichment. To this end, the low mass clusters M71 and M55 were included in the observing program.

iv) In Chapter 4 a panoramic photometry technique, utilising narrow-band filters and a direct imaging detector, has been developed to measure the strength of the $\lambda$3883 CN band. This system has been used to determine the cyanogen distribution among the subgiants in NGC 362, down to magnitudes much fainter than the Sweigart-Mengel critical luminosity for the onset of mixing driven by meridional circulation.

As outlined in §III one of the most important observations pertaining to the origin of globular cluster CN variations is that of a carbon, nitrogen abundance anticorrelation. In Chapter 5, the implications of this anticorrelation for both the mixing and primordial theories are discussed. Within the context of the primordial scenario, it is interesting to investigate whether this observation can be used to put constraints on the mass function required for the enriching stars.
Open clusters differ substantially from the globulars with respect to both their total mass and metal abundance. It is therefore valuable to ascertain whether they exhibit any globular cluster type cyanogen variations. The low incidence of CN enhanced giants in open clusters has been mentioned above, and is reviewed in Chapter 6. The main aim of this Chapter is to present a DDO photometric investigation of giants in the open cluster IC 4651. One of the giants is found to exhibit an enhanced $\lambda 4216$ CN band when compared with the other cluster giants. The nature of this cyanogen anomaly is contrasted spectroscopically to that of the globular cluster giants in Chapter 7. High resolution spectra are presented of the $\lambda 4216$ CN and $\lambda 4310$ G-bands for the CN-enhanced giant and a comparison cluster star of similar $T_{\text{eff}}$ and $\log g$. A spectrum synthesis analysis is then used to determine the carbon and nitrogen abundance differences between these two stars.

As described in §II, there is now conclusive evidence that the dwarf spheroidal galaxies are inhomogeneous in $Z_{\text{Fe}}$. Less substantial data, reviewed in Chapter 8, suggests that variations in $Z_{\text{CNO}}$ may also be present (e.g. Norris and Bessell 1978; Kinman et al. 1981). These diffuse systems may therefore have undergone a primordial self-enrichment similar to that hypothesised for $\omega$Cen. As reviewed above, one of the characteristics of the $\omega$Cen inhomogeneities is a correlation between the calcium and cyanogen abundances. A survey of the CaII H+K line and $\lambda 3883$ CN band absorption is presented in Chapter 8 for a sample of giants in the Sculptor dwarf spheroidal, and compared with the inhomogeneities seen in $\omega$Cen, with a view to assessing whether a similar form of enrichment has occurred within these two systems. The data needed for such a survey were obtained by using the same panoramic
photometry technique with which the cyanogen data were obtained of NGC 362. With the Sculptor observations however, two additional filters were used to obtain a measurement of the strengths of the CaII H and K lines, in addition to CN.

In summary then, the broad aims of this thesis are twofold. Firstly, to more extensively define the nature of the cyanogen inhomogeneities found within globular clusters, and secondly, to see whether such inhomogeneities exist within stellar systems which formed in different environments, namely the open clusters and the dwarf spheroidal galaxies. By identifying those types of stellar systems within which globular cluster type CN variations exist, it is hoped to provide constraints for theories concerning the origin of such abundance anomalies.
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CHAPTER 2

THE CYANOGEN DISTRIBUTIONS IN NGC 3201, M55 AND M71

Graeme H. Smith and John Norris

ABSTRACT

Observations have been made of the cyanogen distributions in the globular clusters NGC 3201, M55, and M71. The latter two clusters were chosen for study because they have heavy element abundances similar to those of ωCen and 47 Tuc respectively, but considerably smaller masses. No cyanogen enhancements (apart from one CH star) were detected in M55, in marked contrast to the inhomogeneities seen in ωCen. On the other hand, M71 was found to have a range in cyanogen strength very similar to that seen in 47 Tuc. For NGC 3201 we find a bimodal cyanogen distribution, though the difference between the CN-weak and CN-strong stars is not as marked as that found in NGC 6752 and M4 (which have a heavy element abundance similar to that of NGC 3201).

These results, and other available data on CH, CO and Na are discussed within the contexts of both the primordial and mixing enrichment hypotheses. The main conclusions are:

(1) M71 is similar to 47 Tuc not only in its CN distribution, but also in that it possesses a CO/CN anticorrelation, and a positive Na/CN correlation. As noted by others the Na/CN
correlation is very difficult to explain within the framework of mixing. The large mass difference between these clusters also indicates that the driving mechanism of the abundance patterns is independent of present day globular cluster mass. In particular, if primordial variations are responsible, they are required to have acted in systems which give rise to clusters of present day mass as low as \( \sim 4 \times 10^4 M_\odot \).

(2) M55 is the first cluster having \([\text{Fe/H}] > -1.9\) to be thoroughly searched and yet show no substantial cyanogen variations. Since M55 (with \( M \sim 10^5 M_\odot \)) is somewhat more massive than M71 this indicates, from a primordial viewpoint, that enrichment is a process dependent on at least two parameters.
Over the past decade an extensive literature has built up concerning the behaviour of the $\lambda 3883$ and $\lambda 4216$ bands of cyanogen in the spectra of globular cluster red giants. A large number of the clusters which have been investigated are found to contain band strength variations among stars with similar temperatures and surface gravities. Among those clusters showing the most marked CN variations are $\omega$Cen (Dickens and Bell 1976; Bessell and Norris 1976; Norris 1980) and 47 Tuc (McClure and Osborn 1974; Hesser, Hartwick, and McClure 1977; Hesser 1978; Norris and Freeman 1979; and Hesser and Bell 1980). These are two of the most massive clusters known in the Galaxy. Norris and Freeman (1979) have found that the distribution of the $\lambda 4216$ CN-band strengths among the 47 Tuc giants is bimodal. The results of surveys of the $\lambda 3883$ band-strengths in the clusters NGC 6752 (Norris et al. 1981) and M4 (Norris 1981) have recently become available, and in both cases the distributions have been found to be bimodal. The CN distribution found in $\omega$Cen by Norris (1980) is quite different in form, being very broad and much more featureless. This cluster is known to be anomalous in also having a range of heavy element abundances among its stars (Freeman and Rodgers 1975; Butler, Dickens, and Epps 1978; Rodgers et al. 1979; Mallia and Pagel 1981; Cohen 1981). It is impossible within the space of this introduction to discuss all of the work contributed in this field. Comprehensive summaries can be found in the reviews by Kraft (1979), McClure (1979), and Freeman and Norris (1981).

Complementing the CN surveys are a number of spectroscopic abundance analyses which have shown that these cyanogen band variations are due to real variations of the atmospheric nitrogen
abundances in the red giants. These are often accompanied by carbon abundance variations. In the globular clusters NGC 6752 (Da Costa and Cottrell 1980; Norris et al. 1981) and 47 Tuc (Norris and Cottrell 1979) the spectroscopically determined carbon and nitrogen abundances are found to be anticorrelated, the CN-strong stars having lower carbon abundances than their CN-weak counterparts. Such a situation however, does not prevail in every cluster. From analysis of the 3360 Å band of NH in the spectra of the M92 giants, Carbon et al. 1982, have found that the nitrogen abundance is variable, but that it does not anticorrelate in a one-to-one manner with carbon. It can be noted from their Fig.24 however, that those giants with the highest surface nitrogen abundances, show a tendency to also have low carbon abundances.

In the present paper surveys of the cyanogen distributions within globular clusters are extended to include several low mass systems. The aims of this investigation are twofold.

1) To see whether the nature of the CN variations is correlated with cluster morphology. This might be expected if the nitrogen enhancements were produced as a result of an early generation of massive stars returning enriched ejecta to the globular cluster proto-cloud while star formation was in an active phase. The degree to which the proto-cloud could sustain (and survive) supernova induced enrichment should be dependent on the cluster mass and mass distribution.

2) To search for evidence of possible carbon and nitrogen abundance anticorrelations in other globular clusters. Two approaches can be used here. The behaviour of the G-band at 4300 Å can be used as an indicator of any carbon variations. As well, two clusters have been observed for which there is infrared photometry
of the 2.3 μ CO band available. The work of Frogel, Persson and Cohen (1981) on the metal rich cluster 47 Tuc has shown that their observed CO index is anticorrelated with the λ4216 CN-band strength measurements of Norris and Freeman (1979).

The clusters which have been observed are M55, NGC 3201 and M71. A list of some of the properties of both these and other clusters with which they will be compared is given in Table 1. Significant revisions to the cluster metal abundance scale have recently been proposed by Cohen (1980), and Pilachowski, Canterna and Wallerstein (1980), and so included in Table 1 are the metallicities derived by Zinn (1980a, b) using calibrations based on both the old and new scales ([Fe/H]_I and [Fe/H]_II’, respectively). Both of these scales employ the abundances of Cohen (1978, 1979) for M3, M13, M15 and M92, but differ in that scale I uses a value of [Fe/H] = -0.4 for M71, as taken from Frogel, Persson, and Cohen (1979), while scale II is based on [Fe/H] = -1.29 for this cluster (Cohen 1980).

To provide a comparison with ωCen and M22, a cluster with similar metallicity and low central mass concentration was chosen. Such a system is M55. Note that while it has a metallicity lower than the mean given for ωCen in Table 1, the abundance in the latter ranges from -1.8 < [Fe/H] < -0.8 (see e.g., Butler, Dickens and Epps 1978, Rodgers et al. 1979) and so approaches that of M55. The cluster M71 has an abundance similar to that of 47 Tuc, but a much lower mass and central concentration. Finally, NGC 3201 is intermediate between M4 and NGC 6752 as regards both M_v and c, and is of similar metallicity. Data on the cyanogen variations in all of the comparison clusters mentioned are available in the literature, and most of these have already been mentioned. Cyanogen
### TABLE 1

PROPERTIES OF GLOBULAR CLUSTERS FOR WHICH CN DISTRIBUTIONS ARE AVAILABLE

<table>
<thead>
<tr>
<th>NGC</th>
<th>Name</th>
<th>$M_V$</th>
<th>$c$</th>
<th>$R$</th>
<th>$r_t$</th>
<th>$(B-V)_{o,g}$</th>
<th>$[\text{Fe/H}]_I$</th>
<th>$[\text{Fe/H}]_{II}$</th>
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<tr>
<td>104</td>
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<td>-9.43</td>
<td>2.03</td>
<td>8.2</td>
<td>71.1</td>
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<td>-1.29</td>
</tr>
<tr>
<td>3201</td>
<td></td>
<td>-7.40</td>
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<td>9.7</td>
<td>45.7</td>
<td>0.79</td>
<td>-1.40</td>
<td>-1.51</td>
</tr>
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<td>$\omega$ Cen</td>
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<td>86.7</td>
<td>0.81</td>
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<td>-1.60</td>
</tr>
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</tr>
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<td>0.94</td>
<td>-0.40</td>
<td>-1.22</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

- $M_V$: absolute visual integrated magnitude
- $R$: galactocentric distances in kpc
- $r_t$: tidal radius in pc
- $c$: concentration parameter; $c = \log r_t / r_c$, where $r_c$ is the core radius
- $(B-V)_{o,g}$: unreddened color of the giant branch at the luminosity of the horizontal branch.

**References**

- $M_V$, $c$, $R$ from Harris and Racine (1979)
- $r_t$ from Philip, Cullen, and White (1976)
- $(B-V)_{o,g}$ from Butler (1975) for M71 and Lee (1976) for the other clusters
- $[\text{Fe/H}]_I$ from Zinn (1980a)
- $[\text{Fe/H}]_{II}$ from Zinn (1980b)
variations have been observed in M22 by Hesser, Hartwick and McClure (1977), Hesser and Harris (1979), and Norris and Freeman (1982).

II. THE OBSERVATIONS

Spectra of the region $\lambda\lambda3600-4600$ Å were obtained using the AAT 3.9m and the Mt Stromlo 1.9m telescopes, allowing analysis of both the $\lambda3883$ and $\lambda4216$ cyanogen bands.

The AAT spectra were obtained by using the IPCS-RGO spectrograph combination, with the 25cm camera. The 1200 1/mm⁻¹ B and V gratings were used over a series of observing runs in 1979 and 1980. The blaze to collimator configuration was generally used, producing a dispersion of 33 Å mm⁻¹ with a resolution of $\sim 1.2$ Å. Some observations were made working blaze to camera, which gives a nominal dispersion of 25 Å mm⁻¹ and a resolution of $\sim 0.9$ Å.

All of the Mt Stromlo data were obtained in 1979 and 1980 with the Boller and Chivens Cassegrain spectrograph. A second generation Carnegie image tube (IT) was used with a 600 1/mm⁻¹ grating worked in second order, and centered at 4100 Å. Coupled with a 6 inch camera, this produces a dispersion of 50 Å mm⁻¹ at a resolution of $\sim 3.7$ Å. Apertures at the spectrograph slit of 9.8 and 19.6 sq arcsec were used. The spectra, which were widened to 0.6mm using an oscillating quartz block, were recorded on hydrogen sensitized IIaO plates. The (density, intensity) - calibration of these plates was determined by using a similar Carnegie image tube with the coude spectrograph of the 1.9m telescope, exposed to a uniformly illuminated triangular aperture placed at the coude focus. A continuum source provides the illumination, and the triangular aperture ensures that the intensity of the light which is incident on the photographic plate varies linearly with the distance.
across the spectrum (i.e. in the direction perpendicular to the dispersion). A scan across the spectrum can then be used to derive a density, relative intensity calibration. The image tube plates were scanned with the Mount Stromlo PDS microdensitometer. A scanning aperture of 400µ x 10µ was used, with a step size of 10µ.

During these runs spectra were obtained from among the stars ROA 252, 287 and 253 in ωCen (Woolley et al. 1966) and A3 and A68 in NGC 6752 (Alcaino 1972). This enabled measurements from different runs to be transformed onto a standard system.

In the case of the M55 and NGC 3201 spectra, a cyanogen strength based on the λ3883 band was calculated according to the index of Norris et al. (1981):

\[ S(3839) = -2.5 \log_{10} \frac{\int F_\lambda d\lambda}{\int F_\lambda d\lambda} \]

where \( F_\lambda \) is the recorded intensity at wavelength \( \lambda \). As mentioned above, measurements made of ωCen and NGC 6752 giants were used to transform the instrumental \( S(3839) \) indices onto a standard system described by Norris, Freeman, and Seitzer (1981).

For the more metal rich cluster M71, the cyanogen measurements were based on the λ4216 band, adopting the parameter of Norris and Freeman (1979):

\[ S(4142) = -2.5 \log_{10} \frac{\int F_\lambda d\lambda}{\int F_\lambda d\lambda} \]

These results were transformed onto the DDO C(4142) system using observations of stars in ωCen (Bessell and Norris 1976), M71 (Hesser, Hartwick, and McClure 1977) and NGC 2477 (Hartwick, Hesser, and McClure 1972). Air mass corrections were applied to both indices using an extinction coefficient of 0.02.
The technique of transforming the CN indices onto a standard system will partly compensate for errors made in the wavelength calibration of the spectra, since the same calibrations were applied to the standards. Once a calibration had been derived for a template spectrum, it was applied to the others after first aligning them using cross-correlation techniques. The effect of errors in the cross-correlation upon the CH indices were found to be less than \( \approx 0.01 \text{ mag.} \) Separate wavelength calibrations were determined for each run, and were derived from the positions of the absorption lines in the spectrum of the template star.

The differences in the M55 S(3839) values found when using two different photographic plate calibrations was \( \approx 0.01 \). Since the same calibrations were again applied to the program and standard spectra, it is considered that uncertainties from this aspect of the reduction are not significant.

### III. THE RESULTS

**a) M55**

The data for this cluster are given in Table 2, where the star names are taken from Lee (1977b). As indicated in the table most of the CN measurements are derived from IT spectra, with only a small sample of IPCS material. For the image tube spectra the standard deviation of a single measurement is \( \approx 0.06 \text{ mag.} \) This estimate is based on stars for which repeated observations are available, and from past experience with the system (Norris et al. 1981; Norris 1981). The results from the IPCS data are less well calibrated, being transformed via only two standards (A3 and A68). For the three stars observed both at Stromlo and on the AAT, there
<table>
<thead>
<tr>
<th>Star</th>
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<th>$V_r$</th>
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<td>M</td>
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<td>1.37</td>
<td>0.28</td>
<td>10</td>
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<td>4522</td>
<td>12.65</td>
<td>1.08</td>
<td>0.17</td>
<td>10</td>
<td>179</td>
</tr>
</tbody>
</table>

a: First (second) digit gives number of 1.9 m (3.9 m) observations.
appears to be a systematic difference of \( \sim 0.18 \) mag between the two systems. No correction has been applied to the AAT data however, since they comprise only 20% of the sample, and their inclusion does not seriously affect the form of the resultant cyanogen distribution.

A radial velocity of 170 km s\(^{-1}\) for M55 (Kinman 1959), permits cluster membership to be assessed from the image tube material. Cross-correlation techniques (Da Costa et al. 1977), were used to determine radial velocities, and these are given in Table 2. No radial velocity standards were observed, since the data were not obtained specifically for this purpose. Instead it was assumed that the average velocity of the sample was equal to the cluster systemic velocity, and the measurements were made relative to this mean. The IT data were obtained in two runs, in June and July of 1979, and the data from these were reduced independently. The standard deviation of the velocities relative to the mean of each run is \( \sim 23 \) km s\(^{-1}\), which mostly reflects the measurement errors, since the velocity dispersion within the cluster is \( \sim 5 \) km s\(^{-1}\) (Peterson and King 1975). All stars in the IT sample are found to have velocities within \( \sim 2\sigma \) of the systemic velocity, and so are considered to be cluster members. Membership from the AAT material was judged on the basis of the velocity shifts between the spectra of the program stars. All velocities were found to lie within 35 km s\(^{-1}\) of the mean of the sample. Consequently, all of the stars with only AAT spectra are taken to be cluster members, and are designated by 'M' in Table 2.

We note at this point that the star L2406 appears to be a CH star. We assume that this is the object first discovered by Lloyd Evans and Menzies (1980, private communication). Since these
FIG. 1 - This figure shows the $V, (B-V)$ diagram for the M55 program stars. Also shown are the observational loci for the subgiant, asymptotic giant, and horizontal branches. The photometry is from Lee (1977b).
FIG. 2 - The $S(3839)$ cyanogen index for the M55 giants is here plotted against $V$. The solid line is the estimated lower envelope to the data, and is used as the reference level from which to measure the cyanogen excess $\delta S(3839)$.

FIG. 3 - The generalised histogram of the cyanogen excess $\delta S(3839)$ for the M55 program stars. The width of the distribution is consistent with the observational errors, indicating that there is little intrinsic scatter among the CN bands in these stars.
objects possess peculiarities quite distinct from those of the more common CN-strong stars found in globular clusters we shall not consider L2406 in the discussion of the cyanogen distribution of this system.

The V, B-V diagram for the program stars is presented in Figure 1, along with the mean loci for the various evolutionary phases, as determined from the data of Lee (1977b). A plot of S(3839) against V is shown in Figure 2. The majority of the data fall above a baseline which is marked on the diagram, and has the equation

\[ S_\circ(3839) = -0.083 V + 1.029 \]

The vertical height of each point above this line is used to define a cyanogen excess \( \delta S(3839) = S(3839) - S_\circ(3839) \). A generalized histogram (see Searle and Zinn 1978) showing the distribution of \( \delta S(3839) \) is presented in Figure 3. The half-width of the gaussian smoothing function used was 0.06. The resultant distribution is much narrower than that obtained for \( \omega \) Cen by Norris (1980), and is quite unlike the bimodality seen in 47 Tuc (Norris and Freeman 1979), NGC 6752 (Norris et al. 1981) or M4 (Norris 1981). Indeed, the half-width of the distribution (~0.10) probably reflects mainly the observational errors, although an intrinsic spread in \( \delta S(3839) \) of ~0.08 among the M55 giants cannot be ruled out.

It is appreciated that there is a degree of arbitrariness attached to the adopted baseline. The S(3839) data of Norris et al. (1981) for NGC 6752 falls above a sloping baseline, and the authors show that this is consistent with model atmosphere calculations. The magnitude of the slope adopted for the M55 data is similar to that found for M4 by Norris (1981), and also with that of NGC 3201 given below. Most importantly though, a change in the slope to zero
say, would have no significant effect on the cyanogen distribution.

To our knowledge M55 thus becomes the first cluster with an abundance greater than \([\text{Fe/H}] = -1.9\) to show no evidence for substantial cyanogen variations upon close inspection. By comparison, M22 (which as indicated in Table 1 has a metallicity similar to that of M55) exhibits a range in \(\Delta S(3839)\) of \(\approx 0.9\) (Norris and Freeman 1982).

b) NGC 3201

The observational data for the program stars in this cluster are presented in Table 3, and the accompanying color-magnitude diagram is shown in Figure 4, where the photometry is from Lee (1977a). Treating the AAT and 1.9m observations separately, it was found from repeated observations that the standard deviation of a single AAT measurement of \(S(3839)\) was 0.04, and that for a 1.9m index was 0.07. Consequently the AAT material was given double weight in forming the final \(S(3839)\) indices. From those stars for which both AAT and image tube observations exist, it was found that there is a systematic difference of 0.05 between the two data sets. This has no significant effect on the final cyanogen distribution and so was not corrected for.

The high radial velocity of 493 km s\(^{-1}\) for this cluster (Kinman 1959) is very convenient for membership determination. Velocities were derived from most of the AAT spectra, and were measured relative to the stars for which Da Costa, Frogel and Cohen (1981) have given data. The results are given in Table 3, the standard deviation of a single observation being 16 km s\(^{-1}\). For the remaining 9 stars, the displacements of their spectra relative to those of other stars of known velocity observed on the same night
<table>
<thead>
<tr>
<th>Star</th>
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<th>B-V</th>
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<th>W(G)</th>
<th>a</th>
<th>V_r</th>
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a: First (second) digit gives number of 1.9 m (3.9 m) observations.

b: Indicates a $\delta S(3839)$ measurement obtained by transforming Da Costa et al.'s (1981) (CN) index, or velocity from Da Costa et al.
FIG. 4 - The $V, (B-V)$ diagram of the NGC 3201 program stars, along with the major stellar evolutionary sequences. The data are taken from Lee (1977a).
were used to assess membership, a procedure which is quite adequate in view of the high cluster velocity. Velocities accurate to 30 km s\(^{-1}\) were thus obtained. For these stars, a probable membership is denoted by 'M' in Table 3.

The \(S(3839), V\) diagram for this cluster is presented in Figure 5. The lower envelope to the data is chosen to be

\[
S_0(3839) = -0.081 V + 1.088
\]

The generalized distribution of the \(\delta S(3839)\) indices is shown in Figure 6, where a gaussian kernel of 0.05 has been used. A bimodality is apparent from this diagram, although the difference in \(\delta S(3839)\) between the CN-strong and CN-weak giants is not as great as was found for NGC 6752 and M4 by Norris et al. (1981) and Norris (1981) respectively. In Figure 5, those stars which are considered to be CN enhanced are represented by filled circles, a convention which is adopted in our figures.

Da Costa, Frogel and Cohen (1981), have obtained infrared photometry and spectroscopic data for a sample of NGC 3201 giants. Their spectra lead them to conclude that there is no variation in the \(\lambda 3883\) band at a given \((V-K)\)_0, a result which is at odds with the present investigation. The reason for this apparent discrepancy can be found by examining the data for those stars in common between the two investigations. Figure 7 shows a plot of the present CN indices against those of Da Costa, Frogel and Cohen along with the adopted transformation line. The two stars in the Da Costa, Frogel and Cohen

1. The comments made by Norris (1981) with regard to defining \(\delta S(3839)\) relative to a lower bound are relevant here. In particular, it must be recognised that lines of constant nitrogen abundance may not be everywhere parallel to this lower bound.
FIG. 5 - The S(3839), V diagram for the NGC 3201 program stars. The estimated lower envelope to the data is shown. Filled and open symbols are used to define the CN-strong and CN-weak groups respectively, a convention which is also adopted in Figs. 8, 9 and 10. Circles refer to the present data, some of which is common with the Da Costa et al. study. A square marks the point for L1312, the data for which was transformed from Da Costa et al. The point for the other such star, L2405, is coincident with that for L4620.
This diagram shows the generalised histogram of the $\delta S(3839)$ cyanogen excess for the NGC 3201 giants. A bimodality is apparent, although it is not as striking as those found by Norris et al. (1981) for NGC 6752, or Norris (1981) for M4.

The $S(CN)$ index of Da Costa et al. is plotted against the present $S(3839)$ for those stars common to both investigations. An estimated best fit line is also shown. It is this line which is used to transform the $S(CN)$ measurements for stars L1312 and L2405 onto the present $S(3839)$ system.
sample for which there are no present data (L1312 and L2405) can be transformed onto the present system via Figure 7, and are included in Table 3 and Figure 5. The resultant data indicate that three of the stars observed by Da Costa, Frogel and Cohen (L1410, L117 and L1312) have strong CN. The existence of an enhanced λ3883 band in L1410 was noted by them, but they have misinterpreted stars L1117 and L1312 (which are among the cooler stars in the sample) as having weak CN for two reasons. First, as may be seen from Figure 5, the CN indices appear to converge for the cooler stars. Second, Da Costa, Frogel and Cohen have relatively few cool stars in their sample making the definition of the lower bound of the cyanogen index as a function of V-K difficult. Our larger sample allows us to say that relative to other stars of similar magnitude and color, L1117 and L1312 do, in fact, possess enhanced CN. It should also be pointed out that when the Da Costa, Frogel and Cohen data are transformed via Figure 7 into the [S(3839), V] plane, they fall along a sequence whose slope is much steeper than found for the CN-weak stars in NGC 6752 by Norris et al. (1981). This further suggests that there is an admixture of CN-weak and CN-strong stars in the Da Costa, Frogel and Cohen sample.

In an effort to investigate the behaviour of carbon, the G-band strength was estimated from the AAT spectra, in the form of an 'equivalent width' measured over the interval λλ4290 – 4318 Å. Since it is difficult to reliably place the continuum in spectra of the present dispersion, a pseudo-continuum has been adopted. This has been defined by the mean of the five greatest flux points in the interval λλ4314 – 4322 Å, and as such gives a completely objective method of setting the continuum. The standard deviation of a single measurement, as determined from repeated observations, is 0.8 Å.
These widths $W(G)$ are plotted against the CO data of Da Costa, Frogel and Cohen in Figure 8. The resulting correlation is very tight, and strengthens their claim that the anomalous CO strengths seen in several of their program stars are the result of a carbon depletion. In Figure 9, $W(G)$ is plotted against $V$. There appears to be a marginal anticorrelation between CN and CH, but the effect is not as marked as that found in NGC 6752 by Norris et al. (1981). One may determine the statistical significance of the difference between the CN-strong and CN-weak groups as follows. First, the least squares line through the entire sample is $W(G) = 18.89 - 0.668 V$. The average deviation of the CN-weak stars from this line is $0.44 \pm 0.22$ (s.e.). For the CN-strong group it is $-0.54 \pm 0.21$ (s.e.). We may conclude therefore that, on average, the difference between the G-band strength of the two groups is significant at the 3$\sigma$ level. One must resort to statistical arguments for the CH material in this cluster because the scatter in $W(G)$ at a given $V$ magnitude is comparable to the uncertainties of measurement. (It is perhaps relevant to note that the smaller spread in CH in NGC 3201 relative to NGC 6752 is what one would have naively expected from the smaller CN spread in the former, if there is a strict anticorrelation of C and N.) It is clear, however, that there are some stars in NGC 3201 which do not share in a general CN, CH anticorrelation. As pointed out by Da Costa, Frogel and Cohen, star L4319 has weak CN, CH and CO. The present data confirm the weakness of CN and CH. It should perhaps also be noted that this star is anomalously redder than other cluster giants of comparable luminosity. As discussed by Da Costa, Frogel and Cohen the high radial velocity of this object makes it seem unlikely that it is a field dwarf. The extent of the CN, CH anticorrelation not only in
FIG. 9 - A plot of the G-band strength $W(G)$ versus $V$ for a sample of NGC 3201 giants. The CN-strong stars are again distinguished by filled circles.

FIG. 8 - The present measurements of the G-band strength $W(G)$, are here plotted against the CO measurements of Da Costa et al. (1981) for NGC 3201. A tight correlation is seen.
NGC 3201, but also in 47 Tuc and NGC 6752, deserves further attention. Higher resolution material than currently available, or accurate photometry with an intermediate band filter situated in the region of the G-band (cf. Norris and Zinn 1977) could prove rewarding.

c) M71

The observational data concerning this cluster are presented in Table 4, the B, V photometry being taken from Arp and Hartwick (1971). Only star 77 was observed on both of the two nights for which the data were collected, all the spectra being obtained with the AAT. Also included in Table 4 is a photoelectric C(41-42) measurement for star S, which was obtained by using the 1.0 meter telescope at Siding Spring Observatory. The estimated error in the cyanogen indices is 0.04, based on the repeated observations of star 77. Where both published DDO photometry and AAT spectra are available, the tabulated C(41-42) indices are a weighted mean, with double weight being given to the photometry. The published photoelectric observations come from Hesser, Hartwick and McClure (1977) and Frogel, Persson and Cohen (1979).

Kinman (1959) gives a radial velocity for M71 of \(-80\) km s\(^{-1}\), while Cohen (1980), from echelle spectra, finds a lower value of \(-25\) km s\(^{-1}\). The latter value will be adopted here, since it is close to the values found by Jenner and Kwitter (1977), Pike and Strickland (1977), Gratton and Nesci (1978), and Hesser and Shawl (1981). Cross-correlation techniques were used to determine relative velocities for those stars observed on the AAT. The observing sequence for most stars was wavelength comparison source, star in the first of two apertures, comparison source, star in the
TABLE 4

OBSERVATIONAL DATA FOR 22 STARS IN THE FIELD OF M71

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a: First digit gives number of AAT spectra; the second indicates whether (1) or not (0) there is a published DDO color. An S denotes a DDO C(41-42) from the Siding Spring 40".

b: Non-member according to radial velocity.

c: Cluster giant according to DDO photometry.
second aperture, move to the next star. The data from each aperture were reduced separately, compensation being made for instrumental velocity drifts as indicated by the comparison source. Velocity shifts were deduced relative to an adopted standard, and averaged for the two apertures. From one star with repeated observations, and the measurements in the two apertures, the standard deviation of a single observation is estimated to be 10 km s\(^{-1}\). Three stars with velocity shifts greater than \(+20\) km s\(^{-1}\) relative to the mean of our sample are rejected as being superposed field stars. The radial velocities deduced by adopting a mean of \(-25\) km s\(^{-1}\) for the remaining stars, are given in Table 4, together with the identification of the adopted field stars. No velocities are available for four stars in Table 4. Full DDO colors have been published by Hesser, Hartwick and McClure (1977) for three of them, and these are consistent with membership, as indicated in the table.

As a result of both the low radial velocity and galactic latitude of M71 it is possible that some of the adopted cluster members may in fact be field stars superposed on the cluster. Consequently we need to estimate the number of field stars that might be found at galactic latitude \(b = -5^\circ\), in the magnitude range \(12 < V < 14\), color range \(1.2 < B-V < 1.9\), radial velocity range \(-45 < V_r < -5\), and within an area of \(20\) arcmin\(^2\) (the area covered by the adopted cluster members). From Allen (1973, §117), one would expect \(\sim 4\) stars with \(12 < V < 14\), in an area of \(20\) arcmin\(^2\) at \(b = -5^\circ\). Allowing for the solar motion of \(25\) km s\(^{-1}\) in the direction of M71, this number must be multiplied by the fraction of stars which lie in the velocity range (relative to the LSR) of \(-27\) to \(+13\) km s\(^{-1}\). With a velocity dispersion for the field stars of \(30\) km s\(^{-1}\) (see e.g., Allen 1973, §119), the required fraction is
If most of the foreground objects seen in the direction of M71 are K giants, the present sample of radial velocity members may contain $\sim 2$ field stars. This should be kept in mind throughout the following discussion.

Figure 10 shows the color-magnitude diagram of the cluster members, the data being that of Arp and Hartwick (1971). The positions of the stars in the $[C(41-42), V]$ plane are shown in Figure 11, and can be compared with the analogous figure given by Norris and Freeman (1979) for 47 Tuc. The lower bound to their data can be written as

$$C_{o}(41-42) = -0.079 M_V + 0.06$$

on taking an apparent distance modulus to 47 Tuc of 13.46 (see Harris and Racine 1979). This baseline, rewritten for an M71 apparent distance modulus of 13.90 (Harris and Racine 1979) is also shown in Figure 11.

The use of a sloping baseline in the $[C(41-42), V]$ diagram by Norris and Freeman (1979) has been questioned by Dickens, Bell and Gustafsson (1979), who claim that it implies an increase in nitrogen abundance with increasing luminosity on the giant branch. A discussion of this matter has been given by Norris (1982), and will not be elaborated upon here. We note however, that a sloping baseline also provides a suitable lower boundary to the M71 data in Figure 11, and to the 47 Tuc DDO data analyzed by Dickens, Bell and Gustafsson when plotted in the $[C_{o}(41-42), C_{o}(45-48)]$ plane (their Fig. 17).

2. After publication of this paper in Ap. J. 254, Drs J. Norris and M. Bessell (private communication) found from high resolution spectroscopy that star 78 is not a radial velocity member of M71. The velocity given in Table 4 is not inconsistent with this result, and so this star will not be considered further.
FIG. 10 - A V, (B-V) diagram for the radial velocity members of M71. The major evolutionary sequences are also marked. The data have been taken from Arp and Hartwick (1971).
FIG. 11 - The [C(41-42), V] diagram for the present sample of M71 giants. The lower envelope to the 47 Tuc data of Norris and Freeman (1979) is also shown, where a correction for the different distances to the two clusters has been applied, as discussed in the text. Only stars which appear to be radial velocity members are plotted. The filled and open circles are used to define the CN-strong and CN-weak groups respectively.
At a given V magnitude, Figure 11 reveals a range in CN strength greater than can be accounted for by the observational errors. These cyanogen variations were also noticed by Hesser, Hartwick and McClure from their smaller sample of DDO photometry. Eleven stars fall in a region close to the 47 Tuc lower bound line, and are represented by open circles. These are probably the analog of the CN-weak group in 47 Tuc. Stars 27 and 30 appear to be weaker still, whereas the remainder of the sample are identified as being CN enhanced, and are depicted with filled circles. There is a hint of bimodality in Figure 11, with the separation between the 'normal' and 'enhanced' CN stars being larger at fainter magnitudes. However, because of the small number of stars involved, no firm statements can be made about the form of the CN distribution, and no generalized histogram has been constructed.

It has been found by Frogel, Persson and Cohen (1981) that for a given \((V-K)_o\), the 2.3\(\mu\) CO index and the CN band strengths for 47 Tuc giants are anticorrelated. This was attributed to an excess blanketing by CN bands in the CO continuum filter, producing a spuriously weak CO index for those stars with strong CN. An alternative explanation is that carbon is anticorrelated with nitrogen as reported by Norris (1978) and Norris and Cottrell (1979) for horizontal branch and AGB stars in this cluster (from analyses of the CH and CN bands in the blue region). What is needed to decide between these alternatives is spectra in the vicinity of the infrared CO bands, together with spectrum synthesis calculations to determine the effects of carbon and nitrogen variations on each of the Frogel, Persson and Cohen bandpasses involved in the CO index. In either case, however, a CO, CN anticorrelation might be expected in the M71 data. The limited data at our disposal on this matter.
are shown in Figure 12, in which the CO, (V-K) data of Frogel, Persson and Cohen (1979) are plotted, with the CN-weak and CN-strong stars, as determined from the present work, being represented as in Figure 11. In view of the small number of CN-strong stars represented in this diagram, the best that can be said is that these data are not inconsistent with there being a CN, CO anticorrelation among stars with similar (V-K), with the caution that star A9 may be anomalous in having both weak CO and CN.

d) Summary

We can now summarize the facts to have emerged from the above investigations.

1) The low mass cluster M55 has little (if any) discernible cyanogen variations among its giants. This situation is in striking contrast to the large CN enhancements that exist among the wCen and M22 giants. We have an example here of a low mass system not sharing in the pronounced inhomogeneities of its high mass counterparts, even though the heavy element abundances and the mass distributions are similar.

2) A counter-example to this result is provided by the 47 Tuc - M71 comparison. The photometry of Zinn (1980a, b) again indicates that both clusters have similar metallicities. This is also verified by the infrared data of Frogel, Persson and Cohen (1981) who find that both clusters have identical giant branches in the K, (V-K)_0 diagram, and is consistent with the good agreement found between the 47 Tuc lower bound and the M71 weak CN stars in the C(41-42), V plane of Figure 11. Despite the dissimilarities in M_v (i.e. mass) and the mass distributions of the two clusters, the giants in M71 exhibit cyanogen variations comparable to those in
FIG. 12 - The CO, (V-K)$_0$ data of Frogel, Persson and Cohen (1979) are shown, where again the CN-strong stars are identified by filled circles. The CO/CN anti-correlation found by Frogel, Persson and Cohen (1981) for 47 Tuc, appears to be also present in M71. The discordant star, A9, is discussed in the text.
Similarly to NGC 4631, and M3, NGC 3601 displays a blend (V-K) distribution. The separation between the peaks of the distribution, however, is somewhat smaller than that found for the other clusters. There is also evidence for a CH/CH$_2$ anticorrelation to NGC 3601. On average, the 5-band strengths of the CH-strong and CH$_2$ stars are equal at the 1-σ level. The star (L/318) on the other definitely does not show a CH/CH$_2$ anticorrelation. Further quality data are needed to investigate this problem fully.

The distribution of galactic clusters shows a relation between the concentration (n) diagram as shown in Fig. 1b. These clusters contain at least two CH-strong stars are represented by filled circles. Also shown for comparison on the upper axis is the CCl obtained using the transformation log[M/Ag] = 0.34.
47 Tuc. The data of Norris and Freeman (1979) show that cyanogen excesses of 0.2 to 0.3 relative to the lower bound are common among the 47 Tuc giants. Inspection of Figure 11 shows that similar values of $\delta C(41-42)$ are found in M71.

3) Similarly to NGC 6752, and M4, NGC 3201 displays a bimodal $\delta S(3839)$ distribution. The separation between the peaks of the distribution, however, is somewhat smaller than that found for the other clusters. There is some evidence for a CN/CH anticorrelation in NGC 3201. On average, the G-band strengths of the CN-strong and CN-weak stars differ at the 3$\sigma$ level. One star (L4319) on the other hand, definitely does not show a CN/CH anticorrelation. Higher quality data are needed to investigate this problem further.

IV. THE MASSES OF CLUSTERS CONTAINING CYANOGEN VARIATIONS

The distribution of galactic globular clusters in the (concentration, $M_V$)-diagram is shown in Figure 13, where clusters containing at least one CN-strong star are represented by filled circles. Also shown for convenience on the upper axis is log ($M/M_\odot$) obtained using the transformation $\log M/M_\odot = -0.34 M_V +2.69$ following McClure and Norris (1977). In this diagram there seems to be no correlation between the existence of cyanogen variations and either concentration or mass. Of some significance, however, is the range of masses over which variations are seen. M71 and 47 Tuc, with similar heavy element abundances, have masses of $4 \times 10^4 M_\odot$ and $8 \times 10^5 M_\odot$ respectively, as judged from the $M_V$ values in Table 1. Dynamical masses for both of these clusters are also available, being based on observations of the internal velocity dispersions, star counts and the light distributions. Jenner and
The possibility that the incidence of CN variations within globular clusters may depend upon their morphology can be investigated with this diagram, in which the magnitude $M_V$ is plotted against the central concentration parameter $c$, the data having been obtained from Harris and Racine (1979). For convenience the upper abscissa also gives the logarithm of the cluster mass, computed from $\log (M/M_\odot) = -0.34 M_V + 2.69$. Clusters known to have CN variations are represented as filled circles. The clusters within this category which are not identified in the figure are NGC 362, M5, M10, NGC 6352, M92, NGC 7006, M15, NGC 1851, M3, M13, M2, NGC 288. Whatever the nature of the mechanism producing these anomalies, it can be seen to have operated over a wide range of cluster masses and central concentrations.
47 Tuc
NGC6752
NGC3201
M4
ω Cen
M71
M22
M55

Log (M/M_⊙)

4.5 5.0 5.5 6.0

C
2.4
2.0
1.6
1.2
0.8

-6 -8 -10 M_V
Kwitter (1977) derive $M = 7 \pm 4 \times 10^4 M_\odot$ for M71, and for 47 Tuc Da Costa (1977) gives $M > 10^6 M_\odot$ while Illingworth (1976) finds $M = 5 \pm 1 \times 10^5 M_\odot$. The mass estimates based on $M_\nu$ appear to be in reasonable agreement with these results. According to Hesser, Hartwick and McClure (1977) NGC 6352, with a similar abundance and a mass of $8 \times 10^4 M_\odot$ also shows cyanogen variations. Thus the mechanism(s) responsible for changes in cyanogen operate in clusters whose present masses may differ by a factor of $\sim 14-20$. Somewhat more surprisingly from a primordial viewpoint, is that these mechanisms are required to have operated in systems which evolve into clusters with present masses as low as $4-7 \times 10^4 M_\odot$. By comparison, the most massive open clusters contain $\sim 5 \times 10^3 M_\odot$ (Prata 1971; Michie 1963), and are relatively homogeneous, although several of them possess a small percentage of stars which exhibit cyanogen variations (see e.g., Dawson [1978] and Anthony-Twarog, Twarog and McClure [1979] on Melotte 66). More work clearly needs to be done on the relationship between the cyanogen variations in low mass globular clusters and high mass open clusters. It should be noted, however, that while it seems surprising from a primordial viewpoint to find cyanogen variations in systems with present masses as low as $\sim 4-7 \times 10^4 M_\odot$, it is the initial mass which is important for the retention of stellar ejecta, and it is quite possible that the amount of gas that was swept from the clusters by the primordial supernovae was a significant fraction of the cluster proto-cloud. The work of Zinn (1978, 1980c) on the heavy element variations among the giants in the Draco dwarf spheroidal galaxy suggests that this system may have been swept while it was still predominantly gaseous (see Stetson [1979, 1980] however, for an alternative study).
A comparison between M55 and M71 is interesting in this regard. If cyanogen variations are primordial one requires that even though M55 ($M \sim 10^5 M_\odot$) is more massive than M71 ($M \sim 4-7 \times 10^4 M_\odot$) some other factor has prevented it from undergoing substantial enrichment. Perhaps this results from the different heavy element abundances between these two systems, with the metal richer cluster being able to more efficiently transform the kinetic energy of any supernova remnants into radiation and hence delay the sweeping of its gas. On this basis we would expect the cluster NGC 6397, which has a very low mass ($8 \times 10^4 M_\odot$), and extremely low abundance ([Fe/H] $\sim -2.2$) to be homogeneous with regard to nitrogen. Observations of the NH bands near $\lambda 3360$ for the giants in this and other similar clusters may help to ascertain whether there is any interplay between the cluster mass and metallicity in determining the history of the enrichment process.

V. THE BEHAVIOUR OF SODIUM AND ALUMINIUM

As an alternative to the requirement that primordial enrichment has occurred among clusters with quite dissimilar masses and mass concentrations, it may instead be argued that bimodal CN distributions betray those clusters whose stars have undergone mixing. In support of this suggestion is the fact that the CN distribution of $\omega$Centauri (Norris 1980), a cluster which is generally accepted to have undergone primordial enrichment, is not bimodal. The most recent attempt to develop a theory for mixing within globular cluster giants is the work of Sweigart and Mengel (1979) in relation to meridional circulation.
One result which such a theory would have to accommodate is the observation of enhanced Al in NGC 6752 (Norris et al. 1981; Cottrell and Da Costa 1981), and enhanced Na in 47 Tuc (Cottrell and Da Costa 1981, Lloyd Evans, Smith and Menzies 1982). These enhancements have been found to correlate with the cyanogen strengths, implying a primordial origin for the excess nitrogen. A mechanism by which nitrogen, aluminium and sodium could have been produced primordially within intermediate mass AGB stars has been discussed by Iben (1975, 1976), and is advocated by Cottrell and Da Costa (1981). The reader is referred to these papers for details.

A similar situation may pertain to M71, for which Cohen (1980) finds that the [Na/H] ratios of the stars 45 and 46 are -0.58 and -0.92 respectively. The data in Table 4 indicate that the sodium enhanced star, 45, is also one of the CN-strong stars in this cluster, whereas 46 has weak cyanogen. The sodium overabundance in star 45 is similar to the 0.4 dex enhancement found by Cottrell and Da Costa for the CN-strong stars in 47 Tuc. This is a most important result. In all of the abundance patterns so far observed - the CN spread, the CO/CN anticorrelation, and now the CN/Na correlation - M71 may be regarded as a low mass counterpart of 47 Tuc.

Considering now a much more metal-deficient cluster, Peterson (1980) has reported finding sodium line strength variations between three stars in M13. On the basis of their spectroscopic data, Bell and Dickens (1980) find that nitrogen is "possibly enhanced" in star II-67, the one which Peterson finds to be sodium enriched. Only one of the three stars studied by Peterson is included in Suntzeff's (1981) survey of the C and N abundances of the M13 stars. This is II-76, the star with the lowest [Na/Fe]
abundance in Peterson's sample. Suntzeff finds this to have weak CN. These results however, are only suggestive, and cyanogen indices are needed for all three of the stars included in Peterson's analysis.

In order to sustain the mixing hypothesis in the face of these observations, it might be argued that the enhancements of these lines are artifacts of a lowered stellar boundary temperature, produced perhaps as the result of blanketing by CN and/or CO molecular lines. Such a possibility has been proposed by Strom, Strom and Carbon (1971) and Peterson (1976) to explain the anomalously strong sodium lines found in the 'super-metal-rich' (SMR) stars.

Arguing against this possibility for the globular cluster stars is the fact that both Cottrell and Da Costa's, and Peterson's observations pertain to weak Na lines, and the sensitivity of their derived abundances to temperature errors should be quite small. Peterson claims that for her data a temperature error of $T_{\text{eff}} = 100^\circ K$ will produce an error of only 0.09 dex in [Na/H].

In relation to the super-metal-rich (SMR) phenomenon, Hartwick and McClure (1980) have suggested that the SMR giants may be low-velocity disk population counterparts of the globular cluster CN-strong stars. In this context it is interesting that Oinas (1974) finds sodium to be the only element which is consistently enhanced by a factor of three or more among his sample of SMR giants. This behaviour is also apparent in the available globular cluster data. However it is uncertain at present whether the SMR stars also have an overabundance of the heavier elements such as Ca
or Fe (see e.g. Deming 1980, and references therein). This situation needs to be clarified before the analogy between these objects and the globular cluster CN-strong giants can be fully assessed.
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CHAPTER 3

THE CYANOGEN DISTRIBUTION OF THE RED GIANTS IN M5

Graeme H. Smith and John Norris

ABSTRACT

A spectroscopic survey of 29 red giants in the globular cluster M5 shows that the distribution of cyanogen is strongly bimodal in the magnitude range $-1.7 < M_V < -0.5$. The ratio of CN-strong to CN-weak stars is 2.6:1. The strength of the G band appears to anticorrelate with that of cyanogen, suggestive of an anticorrelation in the abundances of carbon and nitrogen. The implications of these results for the mixing and primordial hypotheses of abundance anomalies are discussed.
I. INTRODUCTION

The distribution of cyanogen band strengths among red giants in globular clusters is commonly seen to be bimodal (i.e., many clusters seem to possess two distinct populations of stars). Such distributions occur in 47 Tuc (Norris and Freeman 1979), NGC 6752 (Norris et al. 1981), M4 (Norris 1981), NGC 3201 and possibly M71 (Smith and Norris 1982a), and so it seems worthwhile to assess the frequency with which these occur within globular clusters. As part of such a study, the present paper reports the results of an investigation concerning the CN differences among giants in M5.

Several previous investigations of cyanogen in this cluster exist in the literature. It was known from the DDO photometry of Osborn (1971) that it contains giants with anomalously strong λ4216 CN bands. This result was confirmed and extended by the work of Zinn (1973, 1977) who qualitatively described the strengths of the $\lambda\lambda$3883 and 4216 CN bands and the $\lambda4300$ G band for a sample of red giant branch (RGB) and asymptotic giant branch (AGB) stars. One of Zinn's most interesting discoveries was the presence of relatively weak G bands in the spectra of many AGB stars. Due to limitations of observing time, the attention of this chapter is concentrated on the RGB stars in M5, for which intermediate resolution spectra have been obtained. Quantitative measurements of the strength of the $\lambda3883\text{Å}$ CN band are presented in §II, and their distribution is derived in §III. In the magnitude range $-1.7 < M_V < -0.5$ this distribution is bimodal. The strength of the G-band at $\lambda4300$ is also assessed. Implications of the present data for the mixing and primordial theories for the origin of CN variations within globular clusters are discussed in §IV.
II. OBSERVATIONS

Spectra were obtained in 1980 June and 1981 April and August with the 3.9m Anglo Australian Telescope, the RGO spectrograph and the UCL Image Photon Counting System (IPCS) detector. The 1980 spectra were obtained with the 25 cm camera, and the 1200 1/ mm\(^{-1}\) B grating of the AAT (first order, blaze to camera). The spectra have a (reciprocal) dispersion of either 26 or 33 \(\AA\) mm\(^{-1}\), and resolution of \(\sim 1 \AA\) [FWHM], while covering the region of both the 3883 \(\AA\) CN and 4300 \(\AA\) G bands. During the 1981 runs the 82 cm camera was used working blaze to collimator, with the AAT 1200 1/ mm\(^{-1}\) R grating in August, and a Mt Stromlo 600 1/ mm\(^{-1}\) grating in April. Used in 2nd and 4th orders respectively these give dispersions of 5 \(\AA\) mm\(^{-1}\). Blocking filters were used to remove the overlapping orders. Only data on the 3883 \(\AA\) CN band were obtained on these two runs. In April and August projected slit widths of 0.7 \(\AA\) and 1.2 \(\AA\) respectively, were used. During these runs, sky and star signals were recorded simultaneously, thereby permitting the subtraction of the sky background from the spectra.

From the spectra, the S(3839) cyanogen index of Norris et al. (1981) was measured:

\[
S(3839) = -2.5 \log_{10} \frac{\int F_\lambda d\lambda}{\int F_\lambda d\lambda} \frac{3883}{3916}
\]

where \(F_\lambda\) is the recorded intensity. This index compares the intensity in the 3883 \(\AA\) CN band with that in a redward, pseudo-continuum region. On each night observations were obtained of stars from the sample of \(\omega\)Cen ROA 252, 253 and 287 (Woolley et al. 1966) and NGC 6752 A3 and A68 (Alcaino 1972). The S(3839) indices measured for these stars enabled transformation of the
instrumental indices for each run onto a standard system defined by the observations of Norris, Freeman and Seitzer (1982). The present data are consequently on the same system as the M4 results of Norris (1981) and the M55 and NGC 3201 results of Smith and Norris (1982a).

A G-band equivalent width, \( W(G) \), over the wavelength range \( \lambda\lambda 4290-4318 \) was measured from the 1980 spectra as described by Smith and Norris (1982a). A pseudo-continuum was set by adopting the mean of the five maximal points within the wavelength range \( \lambda\lambda 4315-4322 \) (each pixel represents increments of either 0.4 or 0.5 Å). This procedure gives an objective method of determining the G-band strength.

The results of this work are presented in Table 1. The designations are those of Arp (1955) and Buonanno, Corsi, and Fusi Pecci (1981), while the V, B-V data come (except where noted) from the latter authors. The \( S(3839) \) and \( W(G) \) values, together with the number of observations, are given in columns (4) - (6) respectively. Finally, for comparison purposes, the G-band and \( \lambda 3883 \) CN band strength assessments of Zinn (1977) are indicated in columns (7) and (8), where N refers to 'normal' band strengths, S to a 'strong' CN band, and W to a 'weak' G-band. There is some evidence that the \( S(3839) \) indices obtained from the 5 Å mm\(^{-1}\) data are systematically higher by \( \sim 0.12 \) mag than those measured from the lower dispersion material. However, in view of the small number of stars (3) on which this difference is based, no attempt was made to correct for this effect, which has no influence on the conclusions. There are very few repeated observations from which to determine the uncertainties in the data. Past experience with this system (Norris 1981; Smith and Norris 1982a) suggests errors of \( \sim 0.06 \) mag in \( S(3839) \) and 0.8 Å in \( W(G) \).
### TABLE 1

Observational Data for 30 Giants in M5

<table>
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<th>Star (1)</th>
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<th>B-V (3)</th>
<th>S(3839) (4)</th>
<th>W(G) (5)</th>
<th>n (6)</th>
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\(^a\)First (second) digit gives number of 26/33 and (5) \(\Delta_{\text{mm}}^{-1}\) spectra respectively.

\(^b\)\(V, B-V\) derived from Arp (1955) and a (CI, B-V) relation determined from the data of Arp (1955) and Buonanno et al. (1981).

\(^c\)From Simoda (1980), whose data show this star to lie on the giant branch. (We suspect that the Buonanno et al. [1981] values for this star are in error).
Most of the stars in Table 1 have a 99% probability for cluster membership, as determined from the proper motion survey of Cudworth (1979). Membership of the remaining stars was judged by the cross-correlation of their spectra with those of known cluster members. For III-94, III-96, III-99, and III-147, which were observed at 5 Å mm\(^{-1}\), velocities agreed with those of other cluster members to within 10 km s\(^{-1}\). For III-52, III-67, IV-12, and IV-82, observed at lower resolution, the agreement was better than 15 km s\(^{-1}\). Taking the radial velocity of M5 to be +49 km s\(^{-1}\) (Kinman 1959), it is concluded that all of these stars have a high probability of being cluster members.

III. RESULTS

The V, B-V color magnitude diagram of the program stars is shown in Figure 1, on which has been superposed schematic RGB, AGB, and horizontal branch sequences based on the data of Buonanno, Corsi and Fusi Pecci (1981). With one exception (the AGB star III-50) all stars appear to lie on the well defined red giant branch.

a) The Cyanogen Distribution

The M5 cyanogen data are shown in Figure 2 in the S(3839), V plane. It is apparent that there are two preferred values of S(3839). A reference line with the equation \(S_o(3839) = -0.074 V + 1.108\) has been included in the figure, and the height of each point above it has been measured and denoted by \(\delta S(3839)\).

The slope of the reference line is very similar to those of the analogous baselines adopted by Smith and Norris (1982a) for their M55 (-0.083) and NGC 3201 (-0.084) S(3839) data, although it is larger than that used by Norris (1981) in his investigation of
FIG. 1 - The V, B-V color magnitude diagram for the M5 program stars. Also shown are the RGB, AGB and horizontal branch sequences as derived from the photometry of Buonanno, Corsi and Fusi Pecci (1981).
FIG. 2 - A plot of the cyanogen index $S(3839)$ versus V. Two groups of stars are clearly evident. Those with strong $\lambda 3883$ CN bands are depicted as filled circles, while those with weak CN bands are represented by open circles. A reference line is also shown, relative to which the CN excess parameter $\delta S(3839)$ is measured. The only AGB star in the present data is depicted by a filled triangle.
the squared distribution of residuals, the residuals in Figure 3, in the form of a normalized

Another aspect to consider is the distribution of the residuals. Typically, a difference between the points of 0.1 is

discrepancy between the peaks of 0.2 in

decay of the residuals. This indicates that there is a significant difference in the

To assess whether a significant variation exists between the residuals, a plot was drawn as shown in Figure 3. The residuals

The residuals were then plotted against the normalized variance. This was done to determine the significance of the
differences in the residuals. It is concluded that there is a difference in the normalized variance between the residuals.
the cyanogen distribution of M4 (-0.127). The distribution of \( \delta S(3839) \) values is shown in Figure 3, in the form of a generalised histogram, (Searle 1977) in which each measurement is represented as a gaussian distribution of half width 0.06. This histogram is clearly bimodal with a separation between the peaks of 0.4 in \( \delta S(3839) \), a difference typical of clusters such as NGC 6752 (Norris et al. 1981) and M4 (Norris 1981). What is atypical about M5 is that the ratio of CN-strong to CN-weak giants is 2.6, whereas in other clusters it is more nearly unity. It is apparent from Figure 2 that these conclusions will hold for any reasonable choice of the reference line, because the separation in \( S(3839) \) between the CN-rich and CN-poor giants is so marked.

b) The G-band Equivalent Widths

To assess whether a CN,CH anticorrelation exists among the M5 program stars, a plot of \( W(G) \) vs. \( V \) is shown in Figure 4. The CN-weak stars are represented by open symbols, and the CN-strong giants by filled ones. It is apparent from this diagram that in the mean, the CN-weak stars have stronger G bands than those with strong CN. However, since the separation in \( W(G) \) between the two groups is comparable to the uncertainty of a single \( W(G) \) measurement, no attempt will be made to discuss the evidence for a CN,CH anticorrelation on a star-to-star basis. It is possible nonetheless to investigate whether there is a significant difference in the mean G-band widths, \( W(G)_m \), of the CN-weak and CN-strong groups of giants (excluding the asymptotic branch star III-50). There are 6 CN-weak RGB stars in the present sample, for which \( W(G)_m = 11.37 \) (mean error = 0.22), while for the 15 CN-rich RGB stars \( W(G)_m = 10.47 \) (m.e. = 0.19). It is concluded that a difference of 0.9 Å in the mean G-band width exists between the CN-rich and CN-weak group
FIG. 3 - The generalised histogram of the cyanogen excess $\delta S(3839)$. 
FIG. 4 - A plot of the $\lambda4300$ G-band strength, $W(G)$, versus $V$.

The CN-strong and CN-weak stars are again represented by filled and open symbols respectively. This diagram shows that, on average, the CN-weak stars possess stronger G-bands than the CN-rich stars, i.e., a CN, CH anticorrelation appears to exist among the M5 giants.
of stars, a result which is significant at the 3σ level. A similar
difference was found between the CN-rich and CN-weak giants in NGC
3201 by Smith and Norris (1982a).

By analogy with the results for NGC 6752, the most likely
explanation for the mean CN,CH anticorrelation is the existence of a
general carbon, nitrogen abundance anticorrelation in M5 (Norris
et al. 1981). Higher resolution spectra combined with a spectrum
synthesis analysis are needed to confirm this result.

c) Comparison with the Investigation of Zinn

There are twelve stars in the present sample for which Zinn
(1977) gives qualitative assessments of the λ3883 CN strengths (see
Table 1). Eight of these are in accord with present S(3839) values,
leaving four discrepancies (I-2, I-50, II-59 and II-74). Dr Zinn
kindly allowed one of us (J.N.) to inspect his plate material. The
spectrum of II-59 appeared comparable to that of IV-74, a star which
both Zinn and ourselves find to have strong CN. This assessment
(with which Zinn agrees) supports the present data for II-59, rather
than his previous assignment of it to the CN-weak class. However,
Zinn's spectra for both III-59 and I-50 showed that these stars have
clearly weaker CN than IV-74, whereas the present data indicate them
to have comparable S(3839). This suggests the need for a re-
examination of these stars. 1 We did not inspect Zinn's plate of
I-2.

The only one of Zinn's weak-G-band stars in Table 1 is
III-50. The W(G) measurement shows its G band to be one of the
weakest in the sample, although there are several other giants with

1. Our data for I-50 consisted of two spectra, both of which showed
this star to have strong CN.
similar W(G) values (e.g., III-36, which has a comparable V magnitude) for which Zinn classifies the G-band strength as normal. Unfortunately, III-SO is the only AGB star in our sample and so we are unable to make a quantitative assessment of the G-band strength at which a star appears G-band-weak in this cluster. W(G) measurements, or their equivalent, are needed for more AGB stars in M5 for this purpose.

IV. DISCUSSION

M5 appears to be similar to several other clusters in possessing a bimodal CN distribution. Two theories have been discussed in the literature concerning the origin of such CN variations. One is that the red giants have mixed $^{14}N$ to their surfaces via an extensive convective envelope, having first produced it as a by-product of CN-cycle hydrogen burning within their interiors (the mixing theory). The alternative is that the globular clusters were enriched by an early generation of massive stars, which manufactured $^{14}N$ and returned it to the cluster while it was still gaseous and forming stars (the primordial theory). Each of these possibilities will be discussed in turn.

a) The Mixing Theory

One observation which can be cited as implying a mixing origin for the M5 CN variations is the probable existence of a C, N anticorrelation, implying that relative to the CN-weak group the CN-strong stars have enhanced $^{14}N$ and depleted $^{12}C$ surface abundances (analogous to NGC 6752; Da Costa and Cottrell, 1980; and Norris et al. 1981).
Norris et al. (1981) first pointed out that the C,N anti-correlated abundances in NGC 6752 present a difficulty for the primordial theory, and this matter has been addressed in some detail by Smith and Norris (1982b). Basically the problem is that in order to explain an anticorrelation in two populations of roughly equal size, one requires that if the CN-rich stars were formed from material which had been enriched in the CN-cycle processed ejecta of an early generation of massive stars, then the mass of this ejecta must have been comparable to that eventually incorporated into the enriched stars. Such a requirement can only be met if the progenitor stars follow an inverted mass function with \( x < -10 \) (where \( x \) is defined by the proportionality \( dN \propto m^{-(1+x)}dm; \) \( dN \) being the number of stars contained within the mass limits \( m \) to \( m+dm \)). In view of these difficulties, the C,N anticorrelation taken by itself would seem to favour a mixing origin for the M5 cyanogen variations.

Within the context of a mixing scenario, a strict C,N anticorrelation would be expected if only CN processed, and not ON processed material was being brought to the surface. Inspection of Figure 4 indicates that some CN-rich and CN-poor giants may have comparable G-band widths, although the uncertainties in our \( W(G) \) measurements are such that caution must be used in comparing data for individual stars. An answer to the question of whether a strict C,N abundance anticorrelation exists among the M5 giants must await the acquisition of higher resolution data.

In NGC 6752, Norris et al. (1981) found that all of the AGB stars were CN-weak. They advocated that this might occur if the CN-strong stars, after their horizontal branch phase, did not evolve back to the AGB. This was suggested by the fact that the distribution of stars along the blue horizontal branch (BHB) of
NGC 6752 is distinctly bimodal (Newell and Sadler 1978). Using the evolutionary tracks of Gingold (1976), Norris et al. (1981) found that the hotter group of BHB stars would not return to the AGB, so that if such stars had evolved from the CN-rich giants (for reasons discussed by Norris et al. 1981 and Norris 1981) their AGB observations would follow.

The situation in M5 should be different. Almost all of its horizontal branch stars should evolve onto the AGB. This follows from a comparison of the maximum temperature on the BHB of log $T_{\text{eff}} = 4.33$ (Buonanno, Corsi, and Fusi Pecci 1981), and the models of Gingold (1976). This temperature is only slightly hotter than the limit at which a star (with $Y = 0.30$ and $Z = 0.001$) will return to the AGB. We would expect therefore to find some CN-strong stars on the AGB of M5. The fact that our one AGB star, III-50, is CN-strong is consistent with this interpretation.

In view of the fact that we have data for only a single AGB star, we cannot conclude that its properties are representative of the AGB stars as a whole. More data are clearly needed to investigate the composition of these stars fully.

b) The Primordial Theory

It might be thought that the large proportion of CN-strong stars in this cluster presents a challenge to the primordial theory, regardless of the presence of a carbon depletion. This, however, is not necessarily so. The calculations of Smith and Norris (1982b) showed that a generation of CN-weak, 5-10 $M_\odot$, asymptotic giant branch stars in NGC 6752 could have produced the excess nitrogen seen in the CN-strong stars. This conclusion would be unaltered even if the ratio of CN-strong to CN-weak stars in NGC 6752 was 3:1,
and so would also apply to M5 provided that the nitrogen abundance
difference between its CN-strong and CN-weak stars is similar to
that in NGC 6752 (the [Fe/H] abundances of the two clusters being
similar [cf. Zinn 1980]).

Within the context of both the primordial and mixing
theories one further point can be made. In M5 (and also NGC 6752)
almost all of the spread in S(3839) among the CN-strong stars is
accountable for by the errors of measurement. As far as the present
data are concerned the CN-strong stars appear to be a homogeneous
group, although high resolution spectroscopic C and N abundances are
needed to test this suggestion. How could this have arisen by
primordial enrichment, a process which ought to be quite
inhomogeneous, since the level of nitrogen overabundance in a star
would depend on the proximity of $^{14}\text{N}$ producing massive stars, and
the extent of the interaction between the ejecta of these and the
surrounding inter-cluster medium? This would seem to require that
the nitrogen was well mixed throughout the proto-cluster cloud
before formation of the M5 CN-rich stars took place. On the other
hand, the situation in a cluster such as $\omega$Cen seems to be different
since a continuous CN distribution is observed (Norris 1980). Here
it might be suggested that star formation occurred while mixing of
nitrogen with the proto-cloud was still occurring.

The similarities of the S(3839) values among the CN-rich
stars also has implications for the mixing theory. It would seem
that whatever mechanism is driving the mixing in CN-rich giants
(e.g., rotation induced meridional circulation currents in the work
of Sweigart and Mengel 1979) it must reflect a quantity (denoted as
$X$, e.g., rotational velocity) which is distributed over a small
range of values in the CN-rich stars, and is different to that
characterising the CN-weak stars. The alternative to this suggestion is that the mixing is a threshold process, which is always present to the same extent, regardless of the magnitude of X, or else not at all if X is below a limiting value.
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CHAPTER 4

THE CYANOGEN INHOMOGENEITY OF NGC 362

Graeme H. Smith

ABSTRACT

The cyanogen distribution among the subgiants in NGC 362 has been investigated by using a panoramic photometry technique employing narrow band filters designed to measure the strength of the $\lambda$3883 CN band. This distribution is found to be bimodal, with a heavy preference towards CN-rich stars. The cyanogen variations are found among giants two magnitudes fainter than the Sweigart and Mengel critical luminosity at which CN surface abundance variations are predicted to first appear.
The globular cluster NGC 362 is of interest for several reasons.

1) It is a key object in the present controversy over the cluster metal abundance scale. Its metal abundance as derived from echelle spectra (Pilachowski, Sneden and Wallerstein 1982) is higher than that of 47 Tuc (Pilachowski, Canterna and Wallerstein 1980), whereas the reverse ordering is indicated by the colors of their giant branches, and the strength of the blue spectral lines (Zinn 1981; Canterna, Harris and Ferrall, 1982).

2) This cluster has been considered an example of the 'second parameter' phenomenon, with its horizontal branch being redder than those of clusters with similar giant branch morphologies (Menzies 1967, Harris 1982).

Horizontal branch morphology is sensitive to a number of parameters such as the cluster age, helium abundance, total C+N+O abundance, and the extent of stellar mass loss on the giant branch (cf. Rood 1973, Renzini 1977, Rood and Seitzer 1981). Therefore, since some properties of the stars in NGC 362 may be different from those in other clusters, it was considered worthwhile to examine its cyanogen distribution. The DDO photometry of McClure and Norris (1974), and the spectroscopy of Zinn (1981), and Canterna, Harris and Ferrall (1982) have shown that cyanogen variations exist among the NGC 362 red giants. In the present paper a panoramic photometry investigation of this cluster is described, the observations being made through narrow band filters designed to measure the strength of the λ3883 CN band. The observations are described in §II, and the data reduction in §III. The results are presented in §IV, and discussed in §V.
II. OBSERVATIONS

a) The Panoramic Narrow-Band Filter Observations.

The aim of this project was to obtain images of a field in NGC 362 through two narrow band filters designed to duplicate the $S(3839)$ spectroscopic index of Norris et al. (1981), where

$$ S(3839) = -2.5 \log_{10} \frac{\int F_{\lambda} d\lambda}{\int F_{\lambda} d\lambda^{'}} $$

and $F_{\lambda}$ is the intensity recorded at wavelength $\lambda$. The transmission curves for the two filters are shown in Figure 1, along with the bandpass intervals (dashed lines) used in $S(3839)$. The filters have peak wavelengths of 3868Å and 3905Å, with FWHM bandpasses of 36Å and 31Å respectively. They are three inches in diameter, and were manufactured by Spectrofilm Inc. The bluest transmission filter is centered on the 3883Å ($\Delta v=0$) violet band of cyanogen, whereas the 3905Å filter measures a pseudo-continuum between this bandhead and the CaII H+K lines.

The observations were made in November 1980 by using the 3.9 meter Anglo-Australian Telescope with the Image Photon Counting System (IPCS) operated in direct imaging mode at the f/8 cassegrain focus. Each observation acquired a 440x440 pixel$^2$ image array, with a scale of 0.5" pixel$^{-1}$ in both the E-W and N-S directions. The telescope was stopped down to a 2 meter aperture to avoid excessive count rates (>1 Hz pixel$^{-1}$) at the centers of the brightest stars. Two 1000 second exposures were made through each filter. Typical count rates obtained at the centers of the brightest stars, through the $\lambda$3905 filter, were 0.4 - 0.5 Hz pixel$^{-1}$, while sky counts varied from $7 \times 10^{-3}$ to 0.02 Hz pixel$^{-1}$, depending on the severity of stellar crowding.
FIG. 1 - The transmission curves for the narrow band interference filters used in this investigation. Also indicated by dashed lines are the end-wavelengths used in calculating the spectroscopic $S(3839)$ parameter. A spectrum of the CN-rich giant $\omega$Cen 253, kindly provided by Dr J. Norris, is also superimposed.
Observations were also obtained of the dawn and dusk skies. These frames were smoothed with a 6 pixel x 6 pixel FWHM gaussian filter, normalised with the average pixel count, and divided into the NGC 362 frames, to effect a flat-fielding which corrects for any coarse variations in detector response and filter transmission which may have been present. No attempt was made to correct for small scale pixel-to-pixel instrumental variations.

The field observed was centered at
\[ (\text{r.a.}, \text{dec.})_{1950} = (01:01:08, -71:06:52), \]
which lies west of the cluster center, near the star designated IV-67 by Menzies (1967). The observations were obtained at hour angles of \(< 1\frac{1}{4}\) hours. A typical segment of one of the \(\lambda 3905\) frames is shown in Figure 2.

b) The Spectroscopic Observations.

Spectra of eight of the brightest stars in the direct images were obtained by using the Mt Stromlo 1.9m telescope in conjunction with a Boller and Chivens cassegrain spectrograph and a Carnegie image tube, during observing runs in 1979 and 1980. The spectra, which were recorded on 2 inch square IIaO plates, had a dispersion of 50 \(\AA\) mm\(^{-1}\), resolution \(\approx 3.7 \, \AA\), and were widened to 600\(\mu\) by a rocking quartz block. A plate calibration was obtained by uniformly illuminating a triangular aperture placed at the 1.9m coude focus with a continuum source, and recording a spectrum, which was also intensified with a Carnegie image tube, on a IIaO plate at the focus of the coude spectrograph. The triangular aperture ensures that the intensity increases linearly with distance across the spectrum (i.e. in the direction perpendicular to the spectrograph dispersion). A scan across the spectrum therefore
FIG. 2 - A $180 \times 180$ pixel$^2$ portion of one of the λ3905 images.
gives a relative intensity, density calibration. All spectra were traced and digitised with the Mt Stromlo PDS microdensitometer. Wavelength calibrations were determined from the stellar absorption lines in one of the spectra, and applied to all other spectra obtained on the same observing run, after shifting them by amounts determined by cross-correlating them with the wavelength calibrated spectrum. The CN index S(3839) was then measured by adding the relative intensities of all channels within the appropriate bandpasses.

Only a single aperture dekker was used with the Mt Stromlo 1.9m spectrograph, so that the spectra were not sky corrected. With entrance apertures of 9.8 arcsec², a dark Stromlo sky of B=20.5 would cause a systematic error of ~0.04 in the S(3839) value measured for a giant with B=14.3 and an intrinsic S(3839) index of 0.3 (this being typical of the NGC 362 giants for which spectra were obtained). This error is not large enough to be of significance to the present work.

Supplementary spectra were also obtained with the AAT and the IPCS-RGO spectrograph combination during June 1980. A 1200 l mm⁻¹ grating was used to give spectra of 33 or 25 Å mm⁻¹ dispersion, and resolution ~1 Å. The use of two apertures permitted the simultaneous recording of star and sky spectra, so that sky subtracted spectra could be determined.

During both Mt Stromlo and AAT observing runs, spectra were obtained of giants in ω Cen, NGC 6752 and M22, so that the instrumental S(3839) values could be transformed onto the system used by Norris (1981), Smith and Norris (1982a, b) and Norris and Freeman (1982b).
Magnitudes $m(3868)$ and $m(3905)$ were obtained by using the APEX panoramic photometry program written by Dr E.B. Newell, with some additional options due to Dr W.J. Couch. The algorithms used in this software have been fully described by Newell (1979). The reductions were carried out on the Mt Stromlo VAX 11/780 computer.

The first step in the reduction is to extract 31x31 pixel$^2$ sub-arrays around the visually estimated centers of each of the program stars. A sample of stars with well-defined images are then used to obtain an analytic fit to the image profile, which is of the form (normalised to unit height)

$$\psi(r) = (1-Q) \exp \left( -\ln \left[ 2\beta \right] \right) + Q/(\beta + 1)$$

where $\beta = (2r/\Gamma)^2$. The image full-width at half-height $\Gamma$, and the wing parameter $Q$ were determined for each 440x440 pixel$^2$ frame. The values of $\Gamma$, which is the parameter that controls all size dependent routines in APEX, were from 3.0 to 4.0. Precise centers $(x_c', y_c')$ for the stars within their sub-arrays were derived from the peaks in the cross-correlation functions obtained by cross-correlating $\psi$ with the intensity profiles measured through the centers of the stars in both $x$ and $y$ directions (see Newell 1979 for a full discussion). The computed centers could be inspected by displaying the individual sub-arrays on a RAMTEK grey-scale monitor, and altered manually if desired.

The stellar magnitudes were calculated using a modal photometry algorithm. This has been fully described by Newell (1979), and so only a brief summary will be given here. A series of ten concentric annuli, each of width $\Gamma/4$ were centered on each star; these will be referred to as the star-zones. Another two annuli
further out (typically \( r > 2.5 \sigma \)) were used as sky-zones. Pixels are assigned to a ring according to whether their radial distance \( r = \sqrt{(x-x_c)^2 + (y-y_c)^2} \) from the image center lies within its boundaries. The intensity distributions \( \eta_j(I_k) \), where \( k \) refers to an individual pixel in zone \( j \), were then determined for all twelve zones, with the qualification that for the star-zones \( I_k \) is interpolated (using the profile \( \psi(r) \) multiplied by the central height of the star), to the value that it would have if \( k \) were located at the effective radius \( r_e \) of the annulus \( j \).

The sky intensity \( I_s \) is derived from the sky zones via a modal algorithm. This consists of searching for the mode of the function obtained by cross-correlating the sky-zone \( \eta \)-functions with a data noise distribution, which for computational ease is represented by a unit-height gaussian profile with a half-width determined by the standard deviation of intensities within several defect-free sky patches. Isophotal intensities \( I_j(r_e) \) are similarly determined from the \( \eta_j \)-functions for each of the 10 star-zones. The magnitude of the stellar image enclosed within zone \( n \) is then calculated from

\[
m_n = 25 - 2.5 \log_{10} \left[ \sum_{j=1}^{n} (I_j - I_s) N_j \right]
\]

where \( N_j \) is the number of points within zone \( j \).

Ten magnitudes, calculated through concentric apertures of different size, are therefore calculated for each star. For convenience, the images obtained through the \( \lambda 3905 \) filter will be designated frames A and B, while those through the \( \lambda 3868 \) filter will be referred to as frames C and D. It was found that the best agreement between frame A and B magnitudes was obtained for aperture
5, while the aperture 4 magnitudes repeated best between frames C and D. (As an example of the use of intermediate size apertures to maximise the signal-to-noise ratio, see Newell and O'Neill 1974). It was decided therefore to average the aperture 4 and 5 magnitudes for each frame. The program star $m(3868)$ magnitudes were obtained by averaging the frame A and B magnitudes, while $m(3905)$ magnitudes were similarly calculated from frames C and D. The $\lambda 3883$ cyanogen index is then given by

$$ S_{CN} = m(3868) - m(3905). $$

Many of the program stars are located in crowded fields, and so it is necessary to be certain that the sky intensities $I_s$ are not adversely affected by starlight contamination. To check this the data were also reduced using an additional option in APEX called DECON. This works by examining the intensities recorded in pixels diametrically opposite each other with respect to the star center, and if the difference exceeds a preset error allowance the lower of the intensities is assigned to both pixels. The resulting sky $n$-function is subjected to a 2σ clipping, and the intensity $I_s$ again determined by a modal algorithm. An example of the use of DECON is given by Couch (1981), who has undertaken stellar photometry from PDS scans of photographic plates. He finds that unless this decontamination procedure is operated on all pixels more removed than $0.3\Gamma$ from the star center (his image sizes being $\sim 10$ pixels) the artificial lowering of the sky causes the faint stars to be measured too bright. However, because the present images are so small, it is impractical to run DECON so close to the image center. Instead, reductions were made using DECON to within a distance $\Gamma$. A plot of magnitudes obtained with and without DECON should
nevertheless permit an assessment of how well the modal algorithm by itself is handling sky contamination.

An example of this comparison is given in Figure 3, which shows the relation between magnitudes calculated from frame A both with, \( m_w(A) \), and without, \( m_{wo}(A) \), the application of DECON. Prior to the data reduction, each of the 70 sub-arrays was inspected visually. The open circles in Figure 3 give the magnitudes of stars which were found to be in fields containing either no other stars or only one or two faint ones, and which should give sky \( \eta \)-distributions little affected by bright star contamination. Stars in the remaining, more crowded, fields are represented by filled circles. The magnitudes used were calculated through aperture 4 (radius = \( r \)), so that DECON has not been applied to the relevant star-pixels. This diagram illustrates two points:

1) The magnitudes obtained with DECON are well correlated with those obtained without using it. Except perhaps for the very faintest stars, \( m(A) > 17.5 \), the correlation is just as tightly defined by the stars in crowded regions as by those which are not. There is little or no evidence for scatter in this diagram being caused by incorrect sky measurements in the case of the magnitudes obtained without using DECON. These non-DECON magnitudes are therefore used throughout the remainder of this work. Figure 3 illustrates the success of the modal algorithm in handling sky contamination. The level of repeatability of the aperture 4 and 5 magnitudes is essentially identical, irrespective of whether or not DECON is used. It is important to state here that the conclusions of this work are independent of whether non-DECON or DECON magnitudes are used.
FIG. 3 - A comparison between the $m(3905)$ magnitudes obtained by reducing the data of frame A both with and without the DECON routine, denoted $m_w(A)$ and $m_{\text{wo}}(A)$ respectively. The filled and open circles depict those stars which are situated in crowded and uncrowded regions respectively.
Frame A \( \lambda 3905 \)
2) The slope of the relation in Figure 3 is \( \frac{\text{dm}_w(A)}{\text{dm}_w(A)} = 1.022 \). Consequently, while \( m_w(A) \) and \( m_{wo}(A) \) agree to within \( \approx 0.01 \) mag for the brightest stars, at faint levels \( m_{wo}(A) \approx 17.6 \), the DECON magnitudes are too bright by \( \approx 0.05 \) mag. This is the effect described by Couch (1981). It was also found that the slopes \( \frac{\text{dm}_w}{\text{dm}_w} \) varied from frame to frame, leading for example, to

\[
[m_{wo}(C) - m_w(C)] - [m_{wo}(D) - m_w(D)] = 0.03, 0.02 \text{ and } 0.00
\]

for \( m_w(C, D) = 17.60, 17.20 \text{ and } 16.0 \) respectively. The DECON-ed \( m_w(C) \) and \( m_w(D) \) magnitudes are therefore not on exactly the same photometric system, although the differences between them are less than the observational errors (which are discussed in § IV). It is apparent from this result, that in badly crowded fields, DECON could be used with little penalty.

IV. RESULTS

The photometric data for seventy program stars are presented in Table 1. Columns 1 and 2 give the Menzies (1967) and Harris (1982) numbers respectively. The next three columns give \( V \), \( B-V \) and \( U-B \). These are taken from Harris (1982) when available; in the remaining 8 instances the \( V \), \( B-V \) photometry of Menzies (1967) is listed. The photometric cyanogen color \( s_{CN} \) is given in column 5. The evolutionary state of the stars is listed in column 6. The spectroscopic \( S(3839) \) indices are given in Table 2, which also lists the number of spectra obtained, both image tube and IPCS.

The uncertainty in the \( s_{CN} \) indices can be estimated in two ways. Firstly, the average absolute values, \( \Delta m' \), of the magnitude differences between frames \( A \) and \( B \), and \( C \) and \( D \) can be
### Table 1

<table>
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<th>Star Designation</th>
<th>$M_1$</th>
<th>$H^2$</th>
<th>$V$</th>
<th>B-V</th>
<th>U-B</th>
<th>$s_{CN}$</th>
<th>$M_1$</th>
<th>$H^2$</th>
<th>$V$</th>
<th>B-V</th>
<th>U-B</th>
<th>$s_{CN}$</th>
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<td>BHB</td>
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<td>0.42</td>
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<td>AGB</td>
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1,2 Star designations from Menzies (1967), Harris (1992) respectively.
### Table 2

Spectroscopic Data for 8 NGC 362 Stars

<table>
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<th>Star designation from Menzies (1967)</th>
<th>Star designation from Harris (1982)</th>
<th>First (second) digit gives number of image tube and (IPCS) spectra respectively</th>
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combined to give

\[ \varepsilon (s_{\text{CN}}) = 0.63 \left[ \Delta_{A-B}^2 + \Delta_{C-D}^2 \right]^{1/2} \]

where the \( \Delta_m \)'s have been corrected for systematic magnitude differences between frames. This gives \( \varepsilon (s_{\text{CN}}) = 0.05 \) for both aperture 4 and 5 colors. Secondly, the \( s_{\text{CN}} \) values for the red horizontal branch stars are plotted versus B-V in Figure 4. There appears to be little evidence for a systematic trend with color, and the standard deviation of the \( s_{\text{CN}} \) indices is \( \sigma (s_{\text{CN}}) = 0.04 \). This may be treated as an upper limit on the observational errors, in view of the possibility that \( \lambda 3883 \) CN spectral variations may still be discernible among these relatively hot stars, as well as the likelihood of there being a slight dependence of \( s_{\text{CN}} \) on B-V. The standard deviation in a single spectroscopic measurement of \( s(3839) \), as evaluated from repeated observations of several stars is 0.08, and so the uncertainties in the colors given in Table 2 are 0.08 \( n^{-1/2} \).

The V, B-V color-magnitude diagram of the program stars is shown in Figure 5. Also included are the mean giant (GB) and asymptotic branch (AGB) sequences as given by Harris (1982). The dashed line is used to distinguish between these two branches, although it should be mentioned that the classification of I-9 and IV-49 as AGB stars is perhaps not too secure.

A plot of the spectroscopic \( s(3839) \) index versus the photometric \( s_{\text{CN}} \) for the stars of Table 2 is shown in Figure 6. Both indices give a consistent ranking of stars as either CN-poor (IV-47 and IV-61) or CN-rich (I-23, I-44, IV-49, IV-67, IV-70, IV-84), although apparently the photometric index is not as sensitive as the spectroscopic one (\( ds_{\text{CN}}/dS(3839) \approx 0.8 \)), which
FIG. 4 - The $s_{\text{CN}}$ indices of the red horizontal branch stars plotted versus B-V.
FIG. 5 - The color-magnitude diagram of the NGC 362 program stars. The photometry is taken from Harris (1982) or Menzies (1967). The mean sequences of Harris (1982) are also shown. The dashed line is adopted as the boundary between the first giant branch (GB) and the asymptotic giant branch (AGB).
FIG. 6 - A plot of the photometric cyanogen index $s_{\text{CN}}$ versus the spectroscopic index $S(3839)$, for the 8 stars listed in Table 2.

FIG. 9 - The two-color (U-B, B-V) diagram for the NGC 362 giant branch (GB) stars of Table 1. The photometry is taken from Harris (1982). The CN-poor and CN-rich giants are represented by open and filled circles respectively.
Fig. 6

Fig. 9
may partly be a consequence of the overlapping in wavelength of the filter transmissions.

The $s_{CN}$ indices of giants with $V>13.5$ is plotted against $V$ in Figure 7; the GB stars are depicted as circles, and the AGB stars as triangles. It appears that the giant branch stars can be divided into a CN-poor (open circles) and a CN-rich group (filled circles) as indicated in the figure. The statistical significance of this division can be demonstrated as follows. A hand-drawn baseline has been fitted to the CN-weak group as shown in Figure 7. This has the equation

$$s_o = -0.088V + 1.582$$

Relative to this, the cyanogen excess $\delta s = s_{CN}(V) - s_o(V)$ parameter has been measured. A generalised histogram of $\delta s$ is shown in Figure 8. Two main peaks are evident, with a third, smaller peak corresponding to star IV-46. A gaussian kernel of 0.04 mag dispersion has been used to obtain Figure 8. The ratio of CN-rich to CN-poor giants is 3:1. For the 18 CN-rich giants the mean value of $\delta s$ is $\delta s_M = 0.241 \pm 0.023$ (mean error), while for the 6 CN-poor giants $\delta s_M = 0.002 \pm 0.022$ (m.e.). The difference of 0.24 between the mean $\delta s$ values of the two groups is therefore significant at the $7.5\sigma$ level.

The division of the AGB stars into CN-rich and CN-poor groups is not as straightforward, since it might be claimed that they all fall along a single $s_{CN}$, $V$ sequence which is highly inclined to that of the CN-poor GB stars, rather than following two sequences parallel to it. The observations of Norris et al. (1981) can be used as a guide here. They find in the cluster NGC 6752, which has a metallicity $\sim 0.2-0.4$ dex lower than NGC 362 (Zinn 1980a, b), that the AGB stars fall on a sequence of similar slope in the
FIG. 7 - A plot of $s_{CN}$ vs. $V$ for stars on the giant branch (GB; circles) and asymptotic giant branch (AGB; triangles). Those stars taken to have strong cyanogen bands are represented by filled symbols, and those with weak CN by open symbols.
FIG. 8 - The generalised distribution of $\delta$s for the NGC 362 subgiants of Table 1.
S(3839), V plane to that of the CN-weak GB stars, there being no CN-rich AGB stars found in NGC 6752 by Norris et al. Assuming this implies that stars of constant CN abundance define closely parallel loci in the S(3839), V diagram irrespective of whether they are in the GB or AGB phase of evolution, it can be concluded that a variation in CN abundance exists among the AGB stars in NGC 362. Under this assumption the AGB stars can be separated into two groups, one (containing 3 stars) with $\Delta s_M = 0.001 \pm 0.016$ (m.e.), and a second (containing 7 stars) with $\Delta s_M = 0.140 \pm 0.016$ (m.e.). These are significantly different by 6σ. The ratio of CN-rich to CN-poor AGB stars in this interpretation is consistent with the CN distribution among the subgiants. It would be valuable to check these conclusions with observations of a larger sample of AGB stars.

It is known that the CN-poor giants in 47 Tuc (Hartwick and McClure 1980) and NGC 6752 (Norris et al. 1981) exhibit an ultraviolet excess of $\delta(U-B) \sim 0.07$ (at constant B-V) relative to their CN-rich counterparts. The NGC 362 giants behave similarly, as indicated in Figure 9 which shows the U-B, B-V diagram for the CN-weak (open circles) and CN-rich (filled circles) subgiants. The Population I giant locus of Fitzgerald (1970) is also shown. The CN-weak stars have an ultraviolet excess of $\sim 0.05$ relative to the CN-rich ones. As discussed by Norris and Freeman (1982a) in relation to 47 Tuc, this probably results from the effect of the cyanogen bands on B-V and U-B.

Before concluding this section it is necessary to discuss the possibility of field star contamination of the present sample of stars. The present data offer no way of identifying non-cluster stars in Table 1. It is nonetheless possible to estimate how many
such stars might be present, in order to assess whether field star contamination is an important uncertainty in this work. The data of Allen (1973) indicate that a density of \( \approx 790 \) field stars per square degree will be seen in the direction of NGC 362, and in the magnitude range \( 14.0 < V < 16.5 \). Therefore, within the field observed in NGC 362 (\( \approx 13.4 \) sq.arc min), a total of 3 field stars is expected.

The contribution of halo giants to this sample is probably negligible. A calculation similar to that described by Carbon et al. (1982) indicates that only 0.04 halo giants with \([\text{Fe/H}] > -1.5\) would be expected in the IPCS direct image. It is only necessary to consider contamination by Population I dwarfs and giants. Confining attention to such stars in the color range \( 0.75 < B-V < 1.10 \), typical disk giants and dwarfs would have magnitudes \( M_V = +0.5 \) and +6 respectively. To be seen with an apparent magnitude of \( V=15 \), such giants and dwarfs would be at distances of \( r_G = 7.9 \times 10^3 \) pc and \( r_D = 630 \) pc respectively. Hence the volume of space over which the giants with \( 14.0 < V < 16.5 \) are sampled is larger than that from which the dwarfs are seen by a factor of \( \approx (r_G/r_D)^3 = 2 \times 10^3. \)

However, assuming that the Population I star density declines exponentially with distance perpendicular to the disk, the density in the region containing the observed giants will be lower by a factor exp \( (-r_G/r_D) \) than in the region containing the dwarfs. The expected ratio of disk dwarfs to giants contaminating the NGC 362 giant sample is then

\[
100(r_D/r_G)^3 \exp[r_G/r_D] = 1.5 \times 10^4,
\]

on adopting the luminosity function for the solar neighbourhood tabulated by Jones et al. (1981), which indicates that the local ratio of dwarfs to giants is \( \approx 100 \).
Hence, all 3 non-cluster stars predicted to lie within the present NGC 362 field, with $14.0 < V < 16.5$, are expected to be disk dwarfs. Of these, the luminosity function given by Jones et al. (1981) indicates that only one of these is expected to have a color $0.75 < B-V < 1.15$. Such a level of field star contamination is not high enough to significantly alter the conclusions of this work.

V. DISCUSSION

NGC 362 is similar to a number of other globular clusters e.g. 47 Tuc (Norris and Freeman 1979), NGC 6752 (Norris et al. 1981), M4 (Norris 1981) and M5 (Smith and Norris 1982b), in possessing two relatively distinct populations of giants with regard to their cyanogen band strengths. The CN-rich giants predominate in NGC 362, which appears to be more like M5 in this regard than either 47 Tuc, NGC 6752 or M4, which have roughly equal numbers of CN-rich and CN-poor giants. The anomalous nature of the color-magnitude diagram of NGC 362 does not appear to be accompanied by an anomaly in the form of the cyanogen distribution.

The present data give no support for the meridional circulation theory of Sweigart and Mengel (1979). In this scenario, surface CN anomalies can only be produced after the hydrogen-burning shell has burnt through the molecular weight gradient that exists at the composition discontinuity marking the innermost extent of the convective envelope. The discussion by Harris (1982) indicates that the metallicity of NGC 362 is $[\text{Fe/H}] \sim -1.2$, and if $Y=0.3$, cyanogen anomalies should appear at $\log(L/L_\odot) = 2.1$ (see Table 3 of Sweigart and Mengel 1979, or Figure 6 of Kraft, 1979) or $M_V = -0.1$, which gives $V \sim 14.7$ upon taking $V-M_V = 14.83$. 
(Harris 1982). The observations indicate however that CN anomalies are found in stars ~1.7 magnitudes fainter than this. Observations of CN anomalies among giants this faint or fainter have been reported for other globular clusters e.g. 47 Tuc (Hesser 1978, Hesser and Bell 1980), M92 (Carbon et al. 1982), ω Cen (Bell et al. 1981), NGC 6752 (Da Costa 1981), and indicate the need for a main sequence site for any meridional circulation.
REFERENCES


CHAPTER 5

COMMENTS ON THE ORIGIN OF THE CARBON AND NITROGEN VARIATIONS WITHIN NGC 6752 AND 47 TUCANAE

I. INTRODUCTION

When the DDO photometric system was applied to the observation of globular cluster giants (see e.g. Hesser, Hartwick and McClure 1977, and references therein), a number of stars were found which had anomalously strong $\lambda 4216$ cyanogen bands. These stars were typical globular cluster giants as regards their temperatures and gravities, and so it seemed that the strong bands had to be attributed to an enhanced atmospheric CN abundance. Comprehensive reviews of the literature concerned with these anomalies can be found in the articles by Kraft (1979), and Freeman and Norris (1981).

There are two popular explanations of the origin of the CN enhanced stars.

1) The mixing hypothesis

This postulates that the atmospheres of the cluster giants have been enriched in material which has undergone CN cycle processing in the stellar interior and has then been brought to the surface by convection.

2) The primordial hypothesis

In this theory it is thought that nitrogen and carbon abundance variations already existed in the material out of which
the stars formed. This could mean that the proto-cluster cloud was initially heterogeneous, or that an early generation of massive stars had returned enriched material to it by means of supernovae events or stellar winds.

In this chapter a semi-quantitative investigation will be conducted into the consequences of the available carbon and nitrogen abundance measurements for both the mixing and primordial hypotheses. Most of the discussion will be concerned with NGC 6752 and 47 Tuc, since for these two clusters there is a considerable amount of published material.

To begin with, the relevant data are summarized, and similarities with other clusters are also pointed out.

1) The work of Norris and Freeman (1979) and Norris et al. (1981) has shown that both 47 Tuc and NGC 6752 possess a bimodal cyanogen distribution among the giants. This is a property which is also common to M4 (Norris 1981), NGC 3201 and possibly M71 (Smith and Norris 1982a), M5 (Smith and Norris 1982b), and NGC 362 (Smith 1982).

2) Da Costa and Cottrell (1980) and Norris et al. (1981) have found from a spectrum synthesis analysis of four giants in NGC 6752 that the carbon and nitrogen abundances are anti-correlated. Relative to the CN-weak stars, the CN-strong members appear to have nitrogen enhanced by a factor of 7 or 8, while the carbon is depleted by a factor of 2. Measurement of the $\lambda$4300 G band strength by Norris et al. (1981) indicates that this C,N anticorrelation is common throughout a majority of the giants which they have sampled. Bell and Dickens (1980), from a spectrum synthesis analysis of four giants in NGC 6752, find a range of 0.5 dex in carbon abundance, with three stars having $[C/A] = -0.5$ and one with $[C/A] = 0$. They do not give any quantitative nitrogen abundances.
The situation in 47 Tuc is not as well documented. Norris and Cottrell (1979) found that carbon and nitrogen were anticorrelated in two asymptotic giant-branch stars. The only sizeable survey of G band strengths among the 47 Tuc giants is that due to Norris (1978). He found a clear CH,CN anticorrelation among the horizontal branch and asymptotic branch giants, but this was not apparent among his sample of first giant branch stars. From an analysis of low resolution spectra of the G bands in a sample of 9 47 Tuc giants, Dickens, Bell and Gustafsson (1979) concluded that carbon depletions of between 0 and 3, and nitrogen enhancements of between 3 and 10 are common. However their data give little information concerning a possible C,N anticorrelation. The infrared photometry of Frogel, Persson and Cohen (1981) demonstrates that for a constant \((V-K)_0\) on the giant branch, their CO index anticorrelates with the cyanogen measurements of Norris and Freeman (1979). The cause of this anticorrelation cannot yet be unambiguously identified, and could be due to either a real C,N abundance effect or just excess blanketing of the continuum filter by CN bands (see Frogel, Persson and Cohen, and Smith and Norris 1982a).

3) Da Costa (1977) has fitted multi-mass models to the observed stellar distributions of 47 Tuc and NGC 6752. From such an analysis both the present day cluster mass, \(M_p\), and the slope of the mass function, \(x\) (as defined below) can be determined. Da Costa's results are:

\[
M_p \sim 1.22 \times 10^5 \, M_\odot \\
1.0 < x < 2.1 \\
M_p \sim 1.3 \times 10^6 \, M_\odot \\
2.4 < x < 3.4
\]

NGC 6752
47 Tuc
The results obtained for 47 Tuc are the most uncertain, because it is unclear as to what the dynamical state of this cluster is. The value of $x$ determined by Salpeter (1955) for the solar neighborhood is 1.35, so that the results of Da Costa show that star formation in 47 Tuc (at least for the present day main sequence stars) was heavily weighted to the low end of the mass spectrum.

4) Observations by Hesser (1978) and Hesser and Bell (1980) have revealed that CN variations between 47 Tuc stars are found at the main sequence turn-off. This is considered by many authors to be convincing evidence for a primordial origin of the C and N variations. If the mixing hypothesis is still to be accepted it requires that the mixing mechanism must be able to operate at the turn-off, or on the main sequence.

5) The CN-strong stars in both 47 Tuc and NGC 6752 exhibit aluminium overabundances (Norris et al. 1981, Cottrell and Da Costa 1981), while those in NGC 6752 also show sodium enhancements (Cottrell and Da Costa 1981).

The mechanism by which nitrogen, aluminium, and sodium could be produced primordially within an intermediate mass AGB star has been discussed by Iben (1975, 1976) and is advocated by Cottrell and Da Costa (1981) as the origin of the observed Na and Al anomalies. During each thermal pulse of such stars, a convective shell extends inward from just below the hydrogen-helium interface at the base of the H-burning shell to the region of maximum energy production. The composition of this shell is characteristic of helium-burning material, and contains $^{12}\text{C}$, $^{16}\text{O}$, $^4\text{He}$ and $^{22}\text{Ne}$. The temperature within this shell increases with each successive pulse, until eventually the lifetime of the $^{22}\text{Ne}$ nucleus against the $^{22}\text{Ne} (\alpha, \text{n}) ^{25}\text{Mg}$ reaction becomes shorter.
than the pulse duration. This reaction can now act as a source of free neutrons, which will be captured predominantly by $^{22}\text{Ne}$, $^{25}\text{Mg}$, and their progeny. It is these neutron capture reactions which can lead to the production of $^{23}\text{Na}$, $^{25,26}\text{Mg}$, and $^{27}\text{Al}$ within the shell. After the pulse, the shell disappears and a convective envelope extends inward in mass, and may eventually overlap the mass shell corresponding to the greatest outward extent of the convective shell. Newly formed $^{12}\text{C}$, $^{22}\text{Ne}$ and an assortment of s-process elements, including $^{23}\text{Na}$ and $^{27}\text{Al}$ can then be transported to the surface of the star. If the temperature is hot enough at the base of the convective envelope during the interpulse phase, some of the $^{12}\text{C}$ may be converted to $^{14}\text{N}$ through CN cycle hydrogen burning. In this way, the elements $^{14}\text{N}$, $^{23}\text{Na}$, and $^{27}\text{Al}$ can be brought to the surface of the star and released back to the environment via a stellar wind.

These observations will now be discussed.

II. THE NITROGEN EXCESS

a) The Mixing Hypothesis

For the solar composition the number fractions of $^{12}\text{C}$ and $^{14}\text{N}$ relative to hydrogen are $4.67 \times 10^{-4}$ and $9.77 \times 10^{-5}$ respectively (Lambert 1978). If this ratio were applicable to globular clusters, and if all of the available carbon were converted to nitrogen by the CN cycle, the nitrogen would be enhanced by a factor of $5^{1/2}$. This may be compared with the factor of seven found by Da Costa and Cottrell (1980) and Norris et al. (1981) for the nitrogen enhancements of the cyanogen strong giants in NGC 6752. If the ON cycle has only processed a small amount of O to
N in the cluster giants, and recognizing that not all of the C is processed to N (as these stars have observable CN and CH bands), it seems unlikely that this factor of 5 1/2 would be achieved. In addition, Da Costa and Demarque (1982) have described the evolution of a $0.9 M_\odot$ metal-poor star. A metal abundance of $Z = 0.004$ was used to give compatibility with 47 Tuc. The standard evolution of this star was found to lead to only a factor of 1.3 enhancement in the surface nitrogen abundance, which as expected, is less than the maximum value of 5 1/2 which would be obtained from a complete carbon-to-nitrogen conversion. This gives greater support to the argument that the standard evolution of a metal-poor star with a solar C/N/O abundance ratio cannot account for the observed nitrogen enhancements.

In order to account for the nitrogen enhancements by means of a mixing scenario either of the following two possibilities may be invoked.

1) A significant amount of ON-cycle processing has occurred within the interiors of the observed stars, the products of which are subsequently mixed to the surface.

2) The initial C/N/O ratio was different from solar.

The first alternative has been discussed by Deming (1978) and Sweigart and Mengel (1979). These latter authors find that in giants of metal-poor clusters such as ωCen significant ON processing occurs in regions which may be mixed to the surface by meridional circulation currents. They find that a factor of ten increase in the surface nitrogen abundance may result, which would be sufficient to explain the size of the enhancements observed in NGC 6752. It still remains to be explained why there should be so sharp a contrast between the mixed and unmixed stars. Why is there no
gradation in nitrogen overabundance? (This of course presents a challenge to the primordial hypothesis as well.)

It is not clear yet whether a similar mixing scenario can explain the nitrogen overabundances in 47 Tuc, since the higher metal abundance should lead to a reduction in the extent to which oxygen is involved in the CNO processing of the envelope. In addition, the existence of cyanogen enhancements among the main sequence turn-off stars in this cluster presents a further difficulty for the mixing hypothesis, even if extensive meridional circulation can occur at this evolutionary stage. Da Costa and Demarque (1982) have analysed the effects of non-standard evolution when deep mixing is artificially introduced into a model star throughout its main sequence lifetime, and find that such stars evolve into blue stragglers. They conclude that this sort of evolution cannot be common in 47 Tuc because of its small blue straggler population.

Keeping this point in mind, we turn to the second alternative mentioned above, namely that of having an initially non-solar C/N/O abundance ratio. Deming (1978) has suggested that the factor of 40 nitrogen overabundance observed by Dickens and Bell (1976) in some ω Cen giants may require ON-processing in stars which formed from gas with an above-solar [O/Fe] abundance. Sweigart and Mengel (1979) point out that a low initial [N/C] abundance coupled with CN-cycle processing may account for the nitrogen enhancements observed in metal-rich globular clusters.

Consider then a star whose composition is initially characterized by [C/A] = 0. (Here and in what follows A is used to refer to the heavy elements). If a factor of seven enhancement in the nitrogen abundance is to be required by the CN cycle processing
of 1/2 of the available carbon as indicated by the results of Da Costa and Cottrell (1980) and Norris et al. (1981) (and assuming no sources of carbon production such as helium burning, and no CN cycling), then the initial nitrogen abundance must be \([N/A] = -0.4\), a result that is independent of the heavy element abundance \([A/H]\). Such an initial nitrogen deficiency seems compatible with Norris et al's (1981) abundance of \([N/A] = -0.6\) for star A3 (NGC 6752), and with Da Costa and Cottrell's value of \([N/A] = -0.2\) for CL25. For 47 Tuc, the work of Norris and Cottrell (1979), and Dickens, Bell and Gustafsson (1979) indicates that nitrogen enhancements of from 5 to 10 are present in the CN-strong population, requiring that the initial \([N/A]\) ratio must be between about -0.2 and -0.6 dex if the mixing theory is to be adequate. Norris and Cottrell derive \([N/H] = -1.4\) for the weak CN star L1518. However, this analysis is based on a cluster metallicity of \([A/H] = -0.4\) which is now known to be too high. Dickens, Bell and Gustafsson give \([N/A] = 0\) for this star on the basis of DDO photometry, assuming that \([A/H] = -0.5\). If instead \([A/H] = -1.0\) for 47 Tuc (Dickens, Bell and Gustafsson find \([A/H] = -0.8\)), then the Figure 17 of Dickens, Bell and Gustafsson implies \([N/A] = 0.2\) for L1518. These observations do not appear to be compatible with the requirements of a theory involving the dredge-up of only CN-processed material. However, more accurate measurements for a larger sample of 47 Tuc giants are needed before such a theory can be fairly assessed.

b) The Primordial Hypothesis

The possibility that the excess nitrogen has been produced by primordial events will now be considered. The nitrogen abundances for the CN-weak and CN-strong stars in NGC 6752 are taken
to be \([N/A] = -0.4\) and 0.5 respectively, these being averages of the Da Costa and Cottrell (1980) and Norris et al. (1981) analyses. The consequences of taking \([N/A] = 0\) and 0.7 (giving a factor of 5 enhancement) in the case of 47 Tuc will also be investigated. The metallicities of the clusters are chosen to be \([A/H] = -1.0\) for 47 Tuc (see Pilachowski, Canterna and Wallerstein 1980; Dickens, Bell and Gustafsson 1979; Cottrell and Da Costa 1981) and \(-1.5\) for NGC 6752 (see e.g. Zinn 1980; Norris et al. 1981).

It is assumed that star formation followed a mass function of the form

\[
\frac{dN}{dm} = K m^{-(1 + x)} \tag{1}
\]

where \(dN\) is the number of stars in the mass range \(m\) to \(m + dm\). The upper and lower mass limits for the stars formed are denoted by \(m_u\) and \(m_u\) respectively. Once the total number of stars to be considered is specified, or equivalently, the total mass locked up in them is known, the value of the proportionality constant \(K\) can be determined. The values of the index \(x\) which will be adopted here, in accordance with the results of Da Costa (1977) given above, are 1.35 and 2.6 for NGC 6752 and 47 Tuc respectively.

Within the globular clusters all of those stars formed with masses in the range \(0.9 < m < m_u\) will have evolved into remnants, while shedding part of their mass in the process. This gas will be stripped from the cluster by passages through the galactic plane. Thus by virtue of stellar evolution processes, the present masses of the clusters determined by Da Costa will be less than the original stellar masses. Assuming \(m_u = 50 M_\odot\) and taking \(m_z = 0.2 M_\odot\), Da Costa (1977) has estimated the amount of mass that has been lost
from the clusters in this way. Using his results it is found that
the initial total stellar masses, $M_t$, for NGC 6752 and 47 Tuc
respectively were $2.2 \times 10^5 M_\odot$ and $1.35 \times 10^6 M_\odot$. Only a
small percentage of mass has been lost from 47 Tuc in this way,
because the $x = 2.6$ mass function is heavily biased toward low mass
star formation, as noted above. No other form of mass loss from
globular clusters will be considered in this paper. Taking these
masses in conjunction with the adopted abundances, one finds that
the excess mass of nitrogen, $\Delta m_N$, in the CN-strong stars relative
to the CN-weak group (assuming that both comprise 50% of $M_t$, as
inferred from the roughly equal areas under the two peaks in the CN
distributions obtained by Norris et al. (1981) for NGC 6752, and
Norris and Freeman (1979) for the outer regions of 47 Tuc) is $10$
$M_\odot$ in NGC 6752 and $270 M_\odot$ in 47 Tuc. These numbers were
obtained from the relation

$$m_N = \frac{1}{14} \times 10^{[A/H]} \times 10^{[N/A]_2} - 10^{[N/A]_1} M_t$$

where $x_{14}^{14}$ (=1.01 $\times 10^{-3}$) is the solar $^{14}N$ mass fraction,
and $[N/A]_2$ and $[N/A]_1$ specify respectively the nitrogen
abundances in the CN-strong and CN-weak groups. The heavy element
metallicity $[A/H]$ is taken to be the same in both groups.

The first fact which follows from these constraints is that
a primary rather than a secondary source of nitrogen is required.
Again adopting $m_\mu = 50 M_\odot$ and $m_\gamma = 0.2 M_\odot$, one finds that for
NGC 6752 ($x=1.35$) the fraction of mass tied up in the 5-50 $M_\odot$
stars is 21 percent. Assuming that the enriching generation had a
mass of $2.2 \times 10^5 M_\odot$ (an apparent overestimate), that $[O/A] = 0$,
and that all of the $^{12}C$ and $^{16}O$ in these stars was converted to
$^{14}N$ by CNO cycle processing, approximately $20 M_\odot$ of $^{14}N$ would
result. The fact that such extreme assumptions lead to the production of only twice as much nitrogen as required indicates the need for a primary source of this element. The situation in 47 Tuc will be even more extreme, because of the steeper mass function.

The most promising source of primary nitrogen is the intermediate mass AGB stars, as discussed by Cottrell and Da Costa (1981). In their picture the CN-weak populations in 47 Tuc and NGC 6752 represent the pristine stars which gave rise to the CN-strong group by the incorporation of their enriched ejecta into the gas which formed the second generation. Working within this context, it is assumed that one half of all the stars formed did so from enriched gas. It is further postulated that only the CN-weak generation of 5-10 $M_\odot$ stars were able to return nitrogen to the cluster proto-cloud for incorporation into further star formation. That is, the CN-strong stars are assumed to result from only one nitrogen enrichment event. This $^{14}$N is taken to be a primary element in that it is synthesised from triple-$\alpha$ $^{12}$C made in the helium burning shell of the AGB stars, and as such is independent of the $^{12}$C abundance in the proto-cloud. Following the calculations of Renzini and Voli (1981) it is assumed that each CN-weak star in the mass range 5-10 $M_\odot$ is capable of expelling 0.1 $M_\odot$ of primary nitrogen. The number, $N$, of such intermediate mass stars in the unenriched generation will be

$$N = \frac{M_\odot}{2 \times (m_\odot - m^1_{-x}) \times (5^{-x} - 10^{-x})}$$

The mass of the primary nitrogen made available is then 0.1 N ($M_\odot$). Taking $m_\odot = 0.2$ and $m^1_{-x} = 50$, it follows that the 'first
epoch' stars can produce $130 \, M_\odot$ of nitrogen in NGC 6752, but only $40 \, M_\odot$ in 47 Tuc, due to the steepness of the mass function. A primordial explanation for the enriched CN stars in NGC 6752 may seem plausible, but the case for 47 Tuc (where $270 \, M_\odot$ of nitrogen is required) presents a problem.

There are several possible reasons for this apparent shortcoming, one being that the amount of primary nitrogen available may have been underestimated. The work of Iben (1975) and Paczynski (1977) illustrate the problems encountered here. Calculations of the nitrogen production within intermediate mass stars depend on how much triple-$^12$C can be brought from the region of previous helium burning into the convective envelope. As well, the depth of the convective envelope, and hence the temperature at its base, are dependent on the mixing length chosen. Iben (1975) finds that reducing the ratio of the mixing length to the pressure scale height from 1.0 to 0.7 in a $7 \, M_\odot$ model is sufficient to prevent the CN-cycle burning of $^12$C. Nevertheless, removal of the problem of the 47 Tuc nitrogen deficiency requires $0.7 \, M_\odot$ of $^{14}$N to be produced by each 5-10 $M_\odot$ star. Also, it has been implicitly assumed that all of the ejected nitrogen is further incorporated into stars, and any departure from this assumption makes it even more unlikely that an underestimate of the nitrogen production is the entire solution to the present discrepancy.

Alternatively, the choice of $[\text{N/A}] = 0$ may be too high, leading to an overestimate of the mass of $^{14}$N required. $40 \, M_\odot$ of nitrogen would be sufficient to explain a 0.7 dex enhancement if the initial $[\text{N/A}]$ were $-0.8$ dex. This seems too low to be admitted by the available abundance estimates (see §IIa).
Finally, agreement could be achieved by relaxing the condition that \( x=2.6 \) in 47 Tuc. This could come about in either of two ways. Firstly, sufficient nitrogen could be produced for \( x < 1.7 \). Alternatively the intermediate mass stars may have formed with a mass function of slope different from that of the low mass stars. As an example, suppose that the \( 0.2 - 0.9 \, M_\odot \) stars formed according to a mass function with \( x=2.6 \), while the more massive stars followed a slope of \( x=1.35 \). By demanding that the mass function be continuous at \( m=0.9 \, M_\odot \), it follows that the number of CN-weak stars formed in the 5-10 \( M_\odot \) range was \( 3.85 \times 10^{-3} \, M_{\text{ms}} \), where \( M_{\text{ms}} \) is the mass locked up in the \( 0.2 - 0.9 \, M_\odot \) stars. Taking \( M_{\text{ms}} = 10^6 \, M_\odot \), it is found that 385 \( M_\odot \) of primary nitrogen may have been available, which is larger than the required amount.

The problem encountered with 47 Tuc will be common to metal-rich clusters of any mass which show large cyanogen enhancements and steep mass functions. To illustrate this point suppose that a cluster possesses a bimodal CN distribution, that the nitrogen abundances in the two groups are \([N/A]_1=0\), \([N/A]_2=0.7\), and that each group comprises half of the total mass \( M_t \). The mass of excess N in the CN-strong stars, as calculated from equation (2), will total

\[
\Delta m_N = 2.03 \times 10^{-3} \, M_t \, 10^{[A/H]} 
\]  
(4)

The mass of nitrogen \( m_N^e \) produced by the 5-10 \( M_\odot \) stars, as derived from equation (3), (for \( m_u = 50 \, M_\odot \) and \( m_\gamma = 0.2 \, M_\odot \)) will be

\[
m_N^e = 5.97 \times 10^{-4} \, M_t \quad x = 1.35
\]  
(5)
If the primordial theory is to be successful it requires that $m_N^e > \Delta m_N$. Equations (4) and (5) then imply that this theory will only be adequate in those clusters with $\text{[A/H]} < -0.5$ for $x=1.35$, and $\text{[A/H]} < -1.8$ for $x=2.6$. This result illustrates the difficulty encountered by invoking primordial enrichment to explain cyanogen variations if they are found in clusters with steep mass functions. It also demonstrates the necessity for further work in measuring these mass functions, particularly among high metallicity clusters, since the results of Hesser, Hartwick, and McClure (1977), and Smith and Norris (1982a) show that these can have cyanogen enhancements comparable to those in 47 Tuc. On the basis of the mass functions obtained by Da Costa (1977) for 47 Tuc, NGC 6752 and NGC 6397, it has been suggested by Da Costa, and also Freeman (1977), that there may be a correlation between the cluster metallicity and $x$, with the more metal-rich systems having steeper mass functions. In view of the above discussion it will be very interesting to see whether work on other high metallicity clusters confirms this suggestion.

III. THE CARBON DEFICIENCY

Consider now the carbon abundance measurements of Da Costa and Cottrell (1980), who found that for NGC 6752, carbon is depleted by 0.3 dex in the strong CN star CL166 relative to CL25. A comparable carbon depletion was found by Norris et al. (1981), who studied the stars A3 and A68 within this cluster. It is this $C,N$ anticorrelation that is suggestive of CN cycle processing.
a) The Mixing Hypothesis

In view of this anticorrelation, the calculations presented at the end of §IIa were based on an implicit requirement that 1/2 of the carbon throughout the convective envelope of a cluster giant could be converted to nitrogen. It is not at all certain that such a feat could in fact be accomplished. To illustrate this point, consider a star with an initial mass of $0.85 \, M_\odot$. At the end of its main sequence phase, carbon will have been converted to nitrogen over an inner mass of $m_{CN}$. After dredge-up on the ascent of the giant branch, the envelope carbon mass fraction, $Z_{12}^e$, will be related to the original mass fraction, $Z_{12}^0$, by the equation

$$Z_{12}^e = \left(\frac{m - m_{CN}}{m_{CN}}\right) \frac{Z_{12}^0}{m_{ce}}$$

Here $m_{ce}$ is the mass contained within the convective envelope at the time of its greatest inward extent, and $m$ is the mass of the star at this time, which can be written as $m = 0.85 - \Delta m$, where $\Delta m$ is the amount of mass-loss which has occurred prior to this time. Using $m_{CN} = 0.28 \, M_\odot$ (the value pertaining to a $0.85 \, M_\odot$ star, Iben 1977) and requiring that $Z_{12}^e = Z_{12}^0/2$, the above equation becomes

$$m_{ce} = 1.14 - 2 \, \Delta m$$

When this equation is coupled with the constraint that

$$m_{ce} < 0.85 - \Delta m$$

it implies that $m_{ce} < 0.56$ and $\Delta m > 0.29$. This indicates that considerable mass-loss and very extensive mixing would have been required if the carbon depletions in the CN-rich stars were to have been established during the sub-giant branch phase. In particular, the requirement of substantial mass-loss ($>0.29 \, M_\odot$) during the early subgiant evolution is a very unpleasant aspect of the mixing theory.
During main sequence evolution, which is presumably unaccompanied by any significant mass-loss, carbon-to-nitrogen conversion has gone to completion over the inner 33\% by mass of the cluster stars. Therefore, even if they were subjected to a complete homogenisation by some unidentified process, the surface carbon abundance would only drop to 2/3 of its original value. Although the available data are not sufficiently precise to rule out such a depletion, the lack of a large blue straggler population in 47 Tuc would seem to rule out the existence of deep mixing during the main sequence phase (Da Costa and Demarque 1982).

This analysis indicates that a mixing theory requires active CN-processing of the convective envelope material. It is inadequate for this envelope merely to dredge up part of the CN-burning shell, instead what is required is that the convection zone be capable of continuously cycling the envelope material through the CN-shell, and that during this passage significant carbon-to-nitrogen conversion must occur. It is for this reason that theories such as the meridional circulation model of Sweigart and Mengel (1979) are necessary.

b) The Primordial Hypothesis.

In the primordial scenario of Cottrell and Da Costa (1981), the existence of a C,N anticorrelation demands that the ejecta from the intermediate mass stars be deficient in carbon, which is not unlikely if the carbon is undergoing CN cycle H-burning at the base of the convective envelope. Assuming that each CN-weak star in the mass range 5-10 M\(_\odot\) leaves a 1.4 M\(_\odot\) remnant, the mass M\(_{\text{ej}}\) ejected back into the protocloud by these stars is given by

\[
\frac{M_{\text{ej}}}{M_1} = \frac{1}{(m_{l1}^{1-x} - m_{l1}^{1-x})} \left\{ (5^{1-x} - 10^{1-x}) - 1.4 \frac{x-1}{x} (5^{-x} - 10^{-x}) \right\}
\] (6)
where $M_1$ is the mass involved in the unenriched population of stars. In §II we set $M_1 = 1/2 M_t$, but this assumption can now be relaxed.

Now define the following parameters:

$\zeta = \frac{\text{mass of enriched stars}}{\text{mass of unenriched stars}}$

$c = \frac{\text{carbon mass fraction in the N enriched stars}}{\text{carbon mass fraction in the N unenriched stars}}$

$\epsilon = \text{the fraction of mass ejected by the 5-10 } M_0 \text{ stars that is incorporated into further star formation}$

$j = \frac{C \text{ mass fraction in the stellar ejecta}}{C \text{ mass fraction in the unenriched stars}}$

$M = \text{the mass of proto-cloud gas with which the enriched stellar ejecta is mixed.}$

From these definitions the following equations can be written:

$$\epsilon M_{ej} + \zeta M = \zeta M_1$$  \hspace{1cm} (7)

$$\epsilon_j M_{ej} + M = c\zeta M_1$$  \hspace{1cm} (8)

These relations give the mass and the carbon abundance involved in the CN-strong stars, and from them it can be shown that

$$\frac{M_{ej}}{M_1} = \frac{\zeta (1-c)}{\epsilon (1-j)}$$  \hspace{1cm} (9)

The two relations (6) and (9) can be used together to provide strong constraints on the slope of the mass function. The right hand side of equation (6) is plotted in Figure 1 as a function of $x$, and for several choices of $m_e$ and $m_\mu$. Taking $\zeta = 1$, $c = 1/2$ from the Norris et al. (1981) observations, and (optimistically) $\epsilon = 1$ and $j = 0$, gives $M_{ej}/M_1 = 1/2$ (via equation 9), leading to $x < -0.4$. 

FIG. 1 - This graph shows the dependence of the mass fraction
\( M_{\text{ej}} / M_1 \) on the slope \( x \) of the mass function. Here \( M_{\text{ej}} \)
is the mass ejected from the 5–10 \( M_\odot \) CN-weak stars, and \( M_1 \) is the total mass that has been incorporated
into CN-weak stars of all masses. Several curves are
given for various values of the upper mass limit \( m_u \),
the lower limit being kept constant at \( m_l = 0.2 M_\odot \).
(see Fig. 1). This implies a much flatter mass function than found for the main sequence stars of either NGC 6752 or 47 Tuc by Da Costa (1977). Taking more realistic estimates for $e$ and $j$ will only make $M_{ej}/M_1$ larger, which in turn will imply a smaller $x$. This problem, which was recognised by Norris et al. (1981) arises because in order to produce a generation of stars in which $C$ is depleted by a factor of 2 relative to the initial proto-cloud material, the mass of gas released by the 5-10 $M_\odot$ stars must be comparable to that incorporated into the depleted generation. If the scenario of Cottrell and Da Costa is to survive this difficulty it may again indicate that the mass function for the intermediate mass stars had to be shallower in slope than for the main sequence stars. It is of interest to recall here that Da Costa (1977) required an enhanced remnant population in his multi-mass models of 47 Tuc when complete equipartition of energy was assumed, although with the relaxation of this assumption the need for such a remnant population vanished.

The mass functions needed to explain the carbon depletion in the CN-strong stars are much flatter than any which have been observed to date. The initial mass function for the field stars derived by Miller and Scalo (1977) has a variable index $x$, but it is flattest at the low mass end, the opposite to that which is required for the globular clusters. The value of $x$ was found to be of the form $(1 + \log m/M_\odot)$, and so goes to zero for $m=0.1 M_\odot$. The work of Taff (1974) indicates that for the open clusters, $x \sim 1.7$ in the mass range 1-10 $M_\odot$. The observations of Freeman (1977) may be of greatest importance in the present context. From a sample of six young LMC clusters, $x$ was found to vary in the range $0.2 < x < 2.5$, with three clusters having $x < 0.5$. In the light of these facts, the existence of flat mass functions in the primordial globular clusters
cannot be ruled out. The reader is referred to the review by Scalo (1978) for an extensive discussion concerning the observations of stellar mass functions.

Keeping these points in mind, an interesting feature of this model follows from setting \( \frac{M_{ej}}{M_1} = \frac{1}{2} \) in equation (6) and plotting the resultant \((m_\mu, x)\) locus for \( m_\gamma = 0.2 \) in Figure 2. For \( m_\mu > 11.4 \, M_\odot \) it is not possible to obtain the desired \( \frac{M_{ej}}{M_1} \) ratio, and hence the necessary C depletion, for any reasonable values of \( x \). In order to produce primordial C depletions low values of \( m_\mu \) are implied. The greater the depletion, the smaller is \( c \), and the greater is the required \( \frac{M_{ej}}{M_1} \). This in turn reduces the value \( m_\mu \) may take. On this basis, clusters with large carbon depletions and nitrogen enhancements should show little or no evidence for heavy element enrichment. This is exactly what is observed, since NGC 6752 and 47 Tuc show evidence for Al and Na enhancements, (which conceivably come from the stars that also produced the nitrogen), but not for substantial Ca or Fe-peak element variations, which on the basis of Arnett's (1978) models would require stars of \( > 10 \, M_\odot \) to be present. In the case of \( \omega \) Cen, where such heavy element variations are found, it is expected that the C/N anticorrelation would not be maintained, since only a small percentage of the total ejecta would consist of C depleted material. Partial support for this hypothesis comes from the work of Persson et al. (1980) on \( \omega \) Cen, who find that the CO and CN are decoupled.
FIG. 2 - For fixed $M_{ej}/M_1$ and $m_7$ equation (3) determines the relationship between $m_7$ and $x$. This figure shows the relationship for $m_7 = 0.2 M_\odot$ and $M_{ej}/M_1 = 0.5$ and $0.25$. The important fact to notice is that increasing $m_7$ decreases the highest value of $M_{ej}/M_1$ that can be attained. Hence if $M_{ej}/M_1$ can be constrained from observations of the carbon abundance, estimates of the upper limit to the mass function can be made within the context of the primordial theory.
IV. THE CARBON AND NITROGEN ANTICORRELATION

It shall now be asked whether it is at all possible for the primordial hypothesis to explain simultaneously the observed C and N mass fractions.

In the following, let $m_{14}$ denote the mass fraction of nitrogen in the enriched stars, as determined by observations. The mass of nitrogen in the ejecta will be represented as $M_N$. A relation between $M_N$ and $m_{14}$ can now be written using the definitions of §III. This is:

$$\frac{\varepsilon M_N}{\varepsilon M_{ej} + M} = m_{14}$$

(10)

where it is assumed that $m_{14}$ is much greater than the nitrogen mass fraction in the primordial material. Both $M_N$ and $M_{ej}$ can be expressed in terms of $x$ as follows:

$$M_N = 0.1 N = M_1 f(x)$$

(11)

$$M_{ej} = M_1 h(x)$$

(12)

where $N$ is as given by equation (3), upon replacing $M_{t/2}$ by $M_1$, and $h(x)$ is given by equation (6). The solution of equations (7), (8), (10), (11) and (12) is

$$g(x) = \frac{f(x)}{h(x)} = \frac{(1-j)}{(1-c)^{m_{14}}}$$

(13)

A plot of $g(x)$ as a function of $x$ is shown in Figure 3, so that once $c, j$ and $m_{14}$ are chosen, the required $x$ can be read off. Note that $f(x)/h(x)$ is independent of $m_j$ and $m_u$, and so no information about them can be obtained from this analysis. Taking $j=0$ and $c = 1/2$, the right side of equation (13) gives $2.0 \times 10^{-4}$ for NGC 6752 and $10^{-3}$ for 47 Tuc. However $f(x)/h(x) > 0.01$ for $-10 < x < 10$, so that
FIG. 3 - A plot of the function $g(x)$ is shown for $-10 \leq x \leq 10$. This range for $x$ greatly exceeds those which would be expected to have occurred during the formation of a globular cluster.
no realistic mass function can explain the observations. This problem arises because the observed nitrogen and carbon mass fractions are seemingly incompatible. The carbon depleted material from the intermediate mass stars can only be diluted with a comparable mass of primordial gas if the observations of a $^{12}\text{C}$ depletion in the CN-strong stars are to be satisfied. On the other hand, an explanation of the nitrogen mass fraction requires that the ejecta, which is also $^{14}\text{N}$ enriched, be diluted with a much larger mass of gas. Given that the nitrogen abundance observations are reliable, then in order to make the right side of equation (13) compatible with $g(x)$ for any reasonable value of $x$, it is necessary to have $j$ as small as possible (it has already been assumed that $j=0$) and $c$ only slightly less than one. This means that if the ejecta is diluted with the C-richer primordial gas to the degree required by the nitrogen observations, then the original carbon depletion within it will be reduced to an insignificant level, which is in conflict with the observations.

This difficulty cannot readily be explained away as due to uncertainty in the $^{14}\text{N}$ production of the enriching stars. Increasing this production only makes matters worse by increasing $f(x)/h(x)$ in direct proportion. Decreasing the production to $10^{-2} M_\odot$ per star would satisfy the 47 Tuc C/N anticorrelation (although not that for NGC 6752), but would only compound the problem of the underproduction of nitrogen for this cluster (see §11). Note that the mass function which results from the solution of equation (13) is the one which will explain only the observed mass fractions, it does not guarantee that a sufficient total mass of nitrogen will be produced.
From the above analysis it appears that a major difficulty to be overcome by a primordial hypothesis is the observation of a carbon depletion in the strong CN stars. In the Cottrell and Da Costa (1981) scenario the CN-weak stars derive from "the first occurrence of star formation in the proto-cluster gas cloud", and as such their composition reflects the initial cloud composition. The carbon depletion must then be a result of a carbon underabundance in the mass lost from the 5-10 M_☉ stars - which leads to the problems mentioned above. One way to avoid this is to assume that the two populations observed (the CN-weak and the CN-strong groups) are both the progeny of an initial population which had a nitrogen abundance characteristic of the CN-weak stars, and a carbon abundance characteristic of the CN-strong stars. In this picture the CN-strong stars have been enriched in nitrogen, but only little in carbon, while the CN-weak stars have been enriched in carbon but not in nitrogen. Intermediate mass AGB stars are again the proposed sites of element synthesis, but now they need to be of two distinct groups, namely those which do and those which do not process their triple-α carbon through the CN cycle. The distinction between these two groups may be one of mass, a concept which has been discussed by Scalo, Despain and Ulrich (1975). In the more massive stars the base of the convective envelope may reach sufficiently high temperatures to burn triple-α carbon into nitrogen via the CN cycle. This nitrogen is then mixed throughout the convective envelope and may be returned to the cluster proto-cloud by a stellar wind or by the later supernova explosion. In the less massive stars the temperature at the base of the envelope may not be high enough.
to permit CN cycle processing, and a carbon-rich envelope may result if the carbon produced in the helium burning shell can still be mixed into the envelope. In order to explain the enhanced Na and Al lines in the CN-strong stars, it would have to be required that only in those stars with convective envelopes hot enough to permit CN cycle $^{14}\text{N}$ production does the lifetime of $^{22}\text{Ne}$ against $\alpha$-particle reactions become sufficiently short to give rise to a free neutron excess.

It is necessary to this hypothesis that both the C enriched and the N enriched gas lost from the intermediate mass stars remain separate prior to being involved in further star formation, otherwise material would be produced which had both enhanced carbon and nitrogen. The greater the extent of mixing between these two groups of stellar ejecta, the more complete would be the eradication of the initial anticorrelation. The CO data of Persson et al. (1980) indicate that such partial mixing may have occurred in $\omega$Cen, whereas in NGC 6752 it would be concluded that mixing did not become very important.

One consequence of this picture is that there should be a primordial generation of stars with weak CN and weak G bands. Examples of such stars may be L4319 in NGC 3201 and A9 in M71 (Smith and Norris 1982a). An estimate of just how many primordial stars might be seen can be made for the case of NGC 6752. If each star responsible for nitrogen enrichment produces $0.1\ M_\odot$ of $\text{N}$, then 100 such stars are required. It is assumed that star formation was restricted to the mass limits of $0.2 < m < 10$, more massive stars being excluded on the basis of the observed absence of Fe-peak element variations within this cluster. It is also assumed that nitrogen producing stars constitute one half of the $5-10\ M_\odot$ stars,
the other half being needed to produce carbon enhancements. Taking $2.2 \times 10^5 M_\odot$ as the total mass that was formed into stars, and (again optimistically) requiring that $\varepsilon=1$, it can be shown that the ratio $r$ of the number of primordial (CN and CH weak) stars to the number of observed stars, in the mass range $m$ to $m+dm$ is

$$r = \frac{2 \times N_{REQ} (0.2^{1-x} - 10^{1-x})}{M_t (x-1)(5^{-x} - 10^{-x})}$$

(14)

where $N_{REQ}$ is the number of nitrogen producing stars required (=100), and $M_t$ as before is the total mass that has formed into stars ($= 2.2 \times 10^5 M_\odot$). This leads to $r=0.06$ for $x=1.35$, so that there may be as few as 3 unenriched stars in the survey of Norris et al. (1981). Should the mass function for the 5-10 $M_\odot$ stars be flatter than for the present main-sequence stars, then this expected number would be decreased.

A similar calculation for 47 Tuc, using $N_{REQ} = 2.7 \times 10^3$, $M_t = 1.35 \times 10^6 M_\odot$, and $x=2.6$, leads to $r > 1$, which is unphysical. This is just another reflection of the fact that if all of the stars which formed within 47 Tuc did so according to a mass function with $x=2.6$, then there would be insufficient nitrogen produced by the intermediate mass stars. The inability to explain the mass of enriched nitrogen in 47 Tuc without postulating a change in $x$ at higher masses still remains. It is perhaps worth noting in conclusion, however, that for $x=1.35$ the ratio decreases to $r = 0.3$.

The question to be addressed next is whether this primordial generation of stars can produce enough carbon to explain the enrichment of the CN-weak stars. Assuming that $[C/A]=0$ in these stars, and that $[C/A]=-0.3$ in the CN-enhanced group, it follows from
an analogous relation to equation (2), that the excess mass of $^{12}\text{C}$ in the CN-weak group amounts to $7\, M_\odot$. Hence, if there are 100 of these stars (the same as postulated for the nitrogen enrichment) then each of them needs to produce $0.07\, M_\odot$ of carbon. This seems feasible in view of the results of Iben and Truran (1978).

Within the context of the Cottrell and Da Costa scenario, it was found above that low values of $m$ are the most favourable for the production of C-depleted material. Does a similar situation pertain to this new picture? Equations (6) and (9) will still be pertinent here, with the difference that $c$ must be redefined as the ratio of the carbon mass fraction in the CN-weak, C-enhanced stars to that in the primordial material. Both $c$ and $j$ are now greater than unity. With $\xi=1$, $\zeta=1$ and $c=2$, it follows that $M_{ej}/M_1=(j-1)^{-1}$. Once $M_{ej}/M_1$ is determined by specifying $j$, equation (6) still indicates that there will be an upper limit which $m$ may have in order for the observations to be satisfied. The smaller is the degree of $^{12}\text{C}$ enrichment in the ejecta (that is, the smaller is $j$) the lower is the value that $m$ may take. Therefore, in order to make conclusions concerning $m$, one must first know $j$, a problem which is recommended to theoreticians. All that can be said here is that it is necessary for $j > 2$ in order to satisfy the physical requirement that $M_{ej}/M_1 < 1$. By way of example, for $j=3$ one finds $M_{ej}/M_1 = 1/2$, and hence $m < 11\, M_\odot$ (analogous to the example considered in §III), which is consistent with the lack of iron-peak element variations found in these clusters.
VI. CONCLUSIONS

The foremost conclusion to be had from the above work is that observations of a bimodal CN distribution coupled with the existence of a carbon, nitrogen abundance anticorrelation within a globular cluster are difficult to reconcile with a scenario in which primordial enrichment of a proto-cluster gas cloud has been produced by a generation of intermediate-mass stars with a composition identical to that of the present CN-weak giants. Although some of the assumptions made in the above analysis are admittedly unsubstantiated, this work does emphasize the importance of understanding the origin of the C,N anticorrelation. One important assumption which has been made is that this anticorrelation exists in all of the CN-strong stars within a cluster. At present NGC 6752 is the only cluster in which the available data is extensive enough to give credence to this assumption. In view of the crucial constraint which this puts on the theory it seems worthwhile documenting the extent of the C,N anticorrelation in other clusters, particularly those displaying bimodal CN distributions.

Another important ingredient in the above study is the assumption that the only source of primary nitrogen available is that which operates within 5-10 $M_\odot$ asymptotic giant branch stars. It is consequently important that further theoretical investigations be made into the quantity of nitrogen produced by these stars before the deficiency of primary $^{14}$N found above in the case of 47 Tuc can be deemed as being a serious obstacle to the primordial theory. As well the possibility that primary $^{14}$N might be formed within super-massive stars may prove to be a fruitful alternative to production within 5-10 $M_\odot$ stars. Nonetheless, one general
conclusion which would seem to hold despite the source of the nitrogen, is that in order to produce a factor of two carbon depletion in the CN-enhanced stars the mass of ejecta from the enriching stars must be comparable to the mass of stars in the enriched generation.

Taken by itself, the C,N anticorrelation would seem to testify to the action of a mixing mechanism within the observed red giants. However the observations of a radial cyanogen gradient in 47 Tuc (Morris and Freeman 1979), the occurrence of CN-enhanced stars on the main sequence turn-off of this cluster, and the CN, sodium correlation seen among the 47 Tuc and NGC 6752 giants (see §I) at present defy explanation in terms of such a theory, and seem instead to suggest a primordial origin. The possibility of a mixing origin cannot properly be assessed until the physical attribute(s) of a star which drives the mixing can be identified, such as the role of interior rotation in the theory of Sweigart and Mengel (1979). As well as this, it will be necessary to know how these attributes are distributed among the stars within a cluster. For instance, why are there two distinct populations in many clusters, one which is presumably mixed and the other which is not?

At present it would seem that there is no satisfactory single explanation for the observed carbon and nitrogen abundance patterns within globular clusters, and it is feasible, as argued by Kraft (1979), that both mixing and primordial contributions are required.
REFERENCES


C H A P T E R 6

DDO PHOTOMETRY OF GIANTS IN THE OPEN CLUSTER

IC 4651.

Graeme H. Smith

ABSTRACT

DDO photometry has been obtained for 14 stars in the open cluster IC 4651. The reddening and distance modulus derived from these data are in good agreement with the results obtained from UBV photometry by Eggen. The cluster appears to have a heavy element abundance slightly less than that of the Hyades, although one giant shows an anomalously strong λ4216 CN band comparable to those seen in the SMR giants. A comparison is made between this star and CN-enhanced giants in 8 other open clusters. It is suggested that the CN-strong phenomenon among open cluster giants is the result of non-standard stellar evolution, the occurrence of which is supported by the presence of blue stragglers in 5 out of the 8 comparison clusters, as well as in IC 4651 itself.
I. INTRODUCTION

It is well known that variations in cyanogen band strengths are not common among the giants within the disk open clusters, a situation which is in marked contrast to that seen in the globular clusters, many of which possess an almost equal proportion of giants with weak and strong CN bands (see e.g., Norris and Freeman, 1979, Norris et al. 1981). There is evidence for cyanogen anomalies in a few open clusters, such as NGC 188 (McClure 1974), NGC 2420 (McClure, Forrester and Gibson 1974), Melotte 66 (Dawson 1979), and NGC 2204 (Dawson 1981), but these enhanced CN bands appear to be confined to one or two stars. Other old disk clusters such as NGC 2360 (McClure 1972) and NGC 2506 (McClure, Twarog and Forrester 1981) appear to be quite homogeneous. The work of Roman (1952), Schmitt (1971), Janes and McClure (1971), and Janes (1975) has shown that stars with cyanogen strengths greater than that found in the Hyades giants do exist in the field, and include those stars classified as super-metal-rich (SMR) by Spinrad and Taylor (1969). Nevertheless, the few CN-enhanced stars found amongst the open clusters do not have cyanogen bands as strong as those seen in the SMR stars (see §V below).

This chapter reports the results of a photometric survey of the giants in the open cluster IC 4651, employing the DDO filter system. It is known from the UBV photometry of Eggen (1971a), that this cluster has a heavy element abundance similar to that of the Hyades. Consequently, if it contains giants with anomalously enhanced cyanogen, then it is quite possible that they would exhibit CN bands as strong as those seen in the SMR giants. It is to the search for such stars that the present chapter is addressed.
II. THE OBSERVATIONS

The data were obtained during May, June and July of 1980 by using the 1.0 m and 0.6 m telescopes at Siding Spring Observatory. Observations were made utilizing two different refrigerated photomultipliers, namely an RCA 1P21 photocell in May and June, and an RCA C31034A GaAs cell in July, together with the DDO filter set of the Anglo-Australian Observatory. Single-channel pulse-counting photometers were used, in conjunction with the Mt Stromlo GPS/ETS system, which provides for the encoding of the total number of accumulated counts, the filter used, the sidereal time and the telescope position. Subsequent output of these data were via a PDP/11 computer to a teletype printer and cassette tape. The data were reduced using mean extinction coefficients for Siding Spring (Dr J. Norris, private communication) of 0.07, 0.07 and 0.03 for C(45-48), C(42-45) and C(41-42) respectively. To enable transformation of the data onto the DDO system, equatorial standards from the list of McClure (1976) were observed, separate transformations being obtained for each night.

The data for the cluster program stars are given in Table 1. Columns 1, 2 and 3 give the star name and the B-V, U-B colors respectively, the data being obtained from Eggen (1971a, b). The remaining columns give the DDO colors and the number n of observations. The average standard deviations for single measurements of C(45-48), C(42-45) and C(41-42) are 0.005, 0.008, 0.010 respectively. To obtain the mean errors in the tabulated colors, these numbers should be multiplied by $n^{-1/2}$. More than one observation was obtained for most of the stars except 8 and 12. Both of these have nearby stars and observations were only obtained
on one night of good seeing using the 0.6 m telescope.

**TABLE 1**

Photometry for the IC 4651 Program stars

<table>
<thead>
<tr>
<th>Star</th>
<th>B-V</th>
<th>U-B</th>
<th>C(45-48)</th>
<th>C(42-45)</th>
<th>C(41-42)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1.11</td>
<td>0.82</td>
<td>1.207</td>
<td>0.856</td>
<td>0.238</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>1.105</td>
<td>0.90</td>
<td>1.221</td>
<td>0.876</td>
<td>0.267</td>
<td>4</td>
</tr>
<tr>
<td>22</td>
<td>1.14</td>
<td>0.915</td>
<td>1.216</td>
<td>0.897</td>
<td>0.249</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>1.125</td>
<td>0.89</td>
<td>1.234</td>
<td>0.897</td>
<td>0.348</td>
<td>2</td>
</tr>
<tr>
<td>27a</td>
<td>1.04</td>
<td>0.75</td>
<td>1.185</td>
<td>0.800</td>
<td>0.244</td>
<td>4</td>
</tr>
<tr>
<td>58</td>
<td>1.23</td>
<td>1.19</td>
<td>1.250</td>
<td>0.980</td>
<td>0.268</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>1.13</td>
<td>1.04</td>
<td>1.233</td>
<td>0.906</td>
<td>0.262</td>
<td>4</td>
</tr>
<tr>
<td>65</td>
<td>1.275</td>
<td>1.185</td>
<td>1.253</td>
<td>0.989</td>
<td>0.289</td>
<td>4</td>
</tr>
<tr>
<td>78</td>
<td>1.255</td>
<td>1.23</td>
<td>0.970</td>
<td>0.472</td>
<td>0.087</td>
<td>2</td>
</tr>
<tr>
<td>83</td>
<td>1.14</td>
<td>0.94</td>
<td>1.234</td>
<td>0.910</td>
<td>0.283</td>
<td>2</td>
</tr>
<tr>
<td>91</td>
<td>1.01</td>
<td>0.69</td>
<td>1.179</td>
<td>0.798</td>
<td>0.206</td>
<td>4</td>
</tr>
<tr>
<td>93</td>
<td>1.68</td>
<td>2.01</td>
<td>1.433</td>
<td>1.418</td>
<td>0.196</td>
<td>3</td>
</tr>
<tr>
<td>96</td>
<td>1.33</td>
<td>1.285</td>
<td>1.289</td>
<td>1.039</td>
<td>0.297</td>
<td>3</td>
</tr>
<tr>
<td>98</td>
<td>1.175</td>
<td>1.025</td>
<td>1.227</td>
<td>0.913</td>
<td>0.287</td>
<td>3</td>
</tr>
</tbody>
</table>

*Eggen (1971a) gives (B-V) = 0.04, while Eggen (1971b) lists (B-V) = 1.04. The former is presumably a typographical error.*

Yoss, Karman and Hartkopf (1981) found from DDO observations made with a red-sensitive GaAs cell that the C(42-45), C(41-42) colors of standards with C(42-45) > 1.2 deviated systematically from the transformations obtained for hotter stars. In the present program, not more than 5 such standards were observed each night, and it can be seen from Table 1, that with the exception of star 93, the giants in this program have C(42-45) < 1.1. Consequently, significant differences in the colors obtained with the 1P21 and GaAs photocells are not expected. To check this, the
mean colors for the cluster giants, as obtained separately with the red and blue tubes, were calculated. The differences in the sense of \((\text{GaAs} - 1\text{P21})\) were found to be \(3 \times 10^{-4}\), \(2 \times 10^{-4}\), and 0.003 for \(C(45-48)\), \(C(42-45)\) and \(C(41-42)\) respectively. Only for the \(C(41-42)\) color is there perhaps some evidence for a systematic difference, although it is less than the mean error in this color. On the other hand there is no indication that the \(C(42-45)\) colors obtained with the two tubes are discrepant. Only star 93 is red enough to show the type of effect described by Yoss et al. The three measurements from which the DDO colors of this star are derived were obtained in May and June of 1980 with a 1P21 cell, so there should be no difficulties here.

III. ANALYSIS OF THE DATA

a) The Dereddened Colors

The reddening \(E(B-V)\) can be estimated for each star using the \((B-V)\), \(C(45-48)\), \(C(42-45)\) colors and the technique of Janes (1977b), which is an iterative procedure whereby the unreddened \(B-V\) color is obtained from \(C(45-48)\) and \(C(42-45)\). The reddening derived for each star is given in Table 2. The mean of these determinations, based on those stars with 3 or 4 measurements is \(E(B-V) = 0.15 \pm 0.02\), which agrees with the value given by Eggen (1971a). This value will therefore be adopted throughout this work. (A straight mean of the reddening determinations from all the observed cluster giants produces \(E(B-V) = 0.14\)). The DDO colors are dereddened using the present value of \(E(B-V)\) and the reddening coefficients of Janes (1979):
The dereddened colors are plotted in the $C_0(45-48)$, $C_0(42-45)$ plane of Figure 1, and the $C_0(41-42)$, $C_0(45-48)$ plane of Figure 2, along with the mean sequences of Osborn (1979) for solar neighborhood stars of luminosity classes III and V.

TABLE 2
Derived Quantities from DDO Photometry

<table>
<thead>
<tr>
<th>Star</th>
<th>E(B-V)</th>
<th>$\delta$CN</th>
<th>$M_V$</th>
<th>(V-$M_V$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.17</td>
<td>0.061</td>
<td>0.92</td>
<td>9.86</td>
</tr>
<tr>
<td>12</td>
<td>0.10</td>
<td>0.071</td>
<td>0.62</td>
<td>9.78</td>
</tr>
<tr>
<td>22</td>
<td>0.14</td>
<td>0.067</td>
<td>1.29</td>
<td>9.65</td>
</tr>
<tr>
<td>23</td>
<td>0.10</td>
<td>0.134</td>
<td>0.47</td>
<td>10.21</td>
</tr>
<tr>
<td>27</td>
<td>0.15</td>
<td>0.086</td>
<td>0.99</td>
<td>9.22</td>
</tr>
<tr>
<td>58</td>
<td>0.14</td>
<td>0.045</td>
<td>1.44</td>
<td>9.42</td>
</tr>
<tr>
<td>60</td>
<td>0.09</td>
<td>0.051</td>
<td>0.71</td>
<td>10.19</td>
</tr>
<tr>
<td>65</td>
<td>0.23</td>
<td>0.062</td>
<td>1.47</td>
<td>9.41</td>
</tr>
<tr>
<td>83</td>
<td>0.10</td>
<td>0.072</td>
<td>0.79</td>
<td>10.15</td>
</tr>
<tr>
<td>91</td>
<td>0.10</td>
<td>0.058</td>
<td>1.07</td>
<td>9.54</td>
</tr>
<tr>
<td>96</td>
<td>0.18</td>
<td>0.027</td>
<td>0.98</td>
<td>9.43</td>
</tr>
<tr>
<td>98</td>
<td>0.18</td>
<td>0.089</td>
<td>1.16</td>
<td>9.78</td>
</tr>
</tbody>
</table>

Figure 1 can be used to check for field dwarfs interloping in the region of the cluster, since it produces a separation of stars on the basis of their temperatures and surface gravities (measured by $C(42-45)$ and $C(45-48)$ respectively). It can be seen that star 78, for which the plotted colors have been dereddened using the cluster E(B-V), is a dwarf whose $C_0(42-45)$ color of 0.44 implies a (B-V) ~ 0.38 and a spectral type earlier than ~F5 V (by reference to Figure 3.1 of Osborn 1971). This conclusion still
FIG. 1 - The $[\text{C}(45-48), \text{C}(42-45)]_o$ gravity, temperature diagram for the IC4651 program stars. The solid lines are Osborn's (1979) solar neighborhood field lines for luminosity classes V and III. Only number 78 appears not to be a giant, and may be either an interloping field dwarf or a main-sequence turn-off star.
FIG. 2. The \( [\text{C}\ii-\text{I}], [\text{O}\ii-\text{I}] \) diagram comparing the positions of late-type stars in the solar neighborhood (depicted by the solid line) obtained from Table 3.9. The fact that most of the cluster stars lie above the field sequence indicates that they have near-solar abundances.
FIG. 2 - The \([C(41-42), C(45-48)]\) diagram comparing the cyanogen band strengths of the IC4651 giants with giants in the solar neighborhood (as depicted by the solid line obtained from Osborn, 1979). The fact that most of the cluster stars lie above the field sequence indicates that they have above-solar abundances.
follows from consideration of its reddened colors. Eggen (1971a) however gives $B - V = 1.255$ and $B = 11.72$. A misidentification of this star on Eggen's finding chart seems the most likely cause of this discrepancy, since his data give $B = 11.62, 12.08, 11.81$ for stars 91, 22 and 23, while an inspection of the Hogg and Hunt (1965) plate for IC 4651, which was obtained using a blue-sensitive Eastman Kodak 103-a-0 emulsion, shows that all three of these stars are clearly brighter than 78 (see also Eggen 1971a, Figure 1, which is a reproduction of this plate). Should this star be a cluster member rather than a field dwarf, its color would place it as a main-sequence turn-off star with $B \sim 13 - 14$.

b) The Cyanogen Excess.

The DDO C(41-42) color measures the strength of the $\lambda 4216$ band of cyanogen, such that the larger the index the greater is the absorption by this band (McClure and van den Bergh 1968). Figure 2 therefore indicates that the IC 4651 giants have stronger CN in the mean than solar composition giants. This comparison can be quantified using the $\delta CN$ parameter of Janes (1975), which is the difference between the observed $C_0 (41-42)$ and that of a typical solar neighborhood star with identical $C_0 (45-48)$ and $C_0 (42-45)$. This latter color has been tabulated by Janes (1975). The $\delta CN$ excesses reveal the similarity between the metallicity of this cluster and that of the Hyades, for which $\delta CN = 0.074$ (McClure 1976, 1979). On excluding the determinations for stars 23 and 96, which appear to have anomalously strong and weak CN respectively, the average value of the cyanogen excess is $\delta CN = 0.066 \pm 0.004$ (including star 96 gives $0.063 \pm 0.006$).
Star 93 is much redder than the rest of the giants and shows a low cyanogen strength. The dereddened \((R-I)_{K,0}\) color for this star (on the Kron-Eggen system), as determined from the photometry of Eggen (1971b) is 0.66, which using the transformation of Bessell (1979) converts to \((R-I)_{C,0} = 0.86\) on the Cousins system. This corresponds to a temperature of \(T = 3870^\circ\)K (Bessell 1979) and a spectral type of \(\sim M0\) (Ridgway et al. 1980).

The low \(C_{O}(41-42)\) color for IC 4651/93 is probably due in large part, if not entirely, to its relatively low temperature (as compared to the other cluster giants). A \(\delta CN\) index cannot be determined since the \(C_{O}(45-48), C_{O}(42-45)\) colors lie outside the range of Jane's calibration, and so this star will not be considered in the following discussions.

c) The Iron Abundance.

Janes (1975) found that a correlation existed between \(\delta CN\) and \([Fe/H]\) for a sample of Population I field giants. This was represented by the equation

\[
[Fe/H] = 4.5 \delta CN - 0.2
\]

where

\[
[Fe/H] = \log_{10} (Fe/H)_{\text{star}} - \log_{10} (Fe/H)_{\text{sun}}
\]

This relationship was derived from spectroscopic abundance data tabulated by Osborn (1971) for a sample of 44 stars. For the Hyades this calibration produces \([Fe/H] = 0.13\), while for the typical field K giant (\(\delta CN\)-O by definition) it gives \([Fe/H] = -0.2\), implying that the sun is overabundant with respect to the general field. Deming, Olson and Yoss (1977) and McClure (1979) have argued for a revision in the zero point of this calibration. Setting \([Fe/H] = 0.2\) for the
Hyades, McClure gives

\[ [\text{Fe}/\text{H}] = 4.5 \delta \text{CN} - 0.13 \] (2)
on adopting the slope found by Janes. This smaller zero point will be adopted here, since support for it comes from the work of Deming, Olson and Yoss (1977) who find from uvby and DDO photometry that it gives consistency between their observed \( \delta m_1 \), \( \delta \text{CN} \) relation for binary systems containing an early and a late type component (for which \( \delta m_1 \) and \( \delta \text{CN} \) are measured respectively), and the \( \delta m_1 \), [Fe/H] correlation of Crawford (1975). Twarog (1981) has determined the \( \delta \text{CN} \) distribution for a complete sample of giants from the data of Janes (1972). On comparison of this observed distribution with several theoretical models, he concluded that the zero point is 

\[-0.10 \pm 0.05.\]

Adopting equation (2) gives \([\text{Fe}/\text{H}] = 0.17 \pm 0.02\) for IC 4651, which therefore appears to be slightly metal deficient relative to the Hyades, a result which is consistent with the U-B, B-V colors obtained by Eggen (1971a). The \( \delta \text{CN} \) excess of star 23 would imply an abundance of \([\text{Fe}/\text{H}] = 0.47\) if equation (2) was taken to be applicable.

d) The Distance Modulus.

The dereddened DDO colors also provide a means of deriving the absolute magnitude \( M_v \) for the cluster giants by using the \([M_v, C_0(45-48), C_0(42-45)]\) calibration given by Janes (1975). Once \( M_v \) has been obtained in this way a metallicity correction factor of the form

\[ \Delta M_v = 0.4 - 4 \delta \text{CN} \] (3)

must be added. The values of \( M_v \) obtained from the present DDO photometry are given in Table 2.
From $M_V^{(DDO)}$ and Eggen's UBV photometry, the apparent distance modulus $V-M_V$ can be obtained. This is also listed for each cluster giant in Table 2. The mean value of $V-M_V = 9.72 \pm 0.10$, which gives $(m-M)_0 = 9.27$ for $E(B-V) = 0.15$. This is in good agreement with the value of $(m-M)_0 = 9.5$ obtained by Eggen (1971a).

IV. THE SPECTROSCOPIC DATA

As mentioned above, star 23 is found to have enhanced cyanogen, as indicated by the large value of $\delta$CN shown in Table 2. As will be discussed below, this is quite an unusual star to be seen near an open cluster and so it is important to verify its cluster membership. To this end, spectra of the stars 22, 23 and 60 were kindly obtained for the author by Dr J. Norris. As well, a number of stars were observed from the catalogue of Bidelman and Macconnell (1973) for the purpose of measuring their radial velocities (Norris, Bessell and Pickles, in preparation). The observations were made on two nights in July 1980 by using the 32 in. camera at the coude focus of the Mt Stromlo 1.9 m telescope. The spectra were acquired with the Photon Counting Array (Stapinski et al. 1978), which has a Reticon dual array for simultaneously recording the star and nearby sky spectra. On one night stars 22 and 23 were observed in each of two apertures, while on a second night stars 23 and 60 were observed through only one aperture. All observations of the Bidelman and MacConnell stars on both nights were made through one aperture only. Spectra of a standard arc source were obtained between star observations, thus allowing the instrument drift to be ascertained.
The dispersion was 0.5 ˚A/channel or 40 ˚A/mm, and the spectral range covered was λλ3740 - 4270 ˚A. The velocities of star 23 with respect to 22 and 60, calculated by using cross-correlation techniques (Da Costa et al. 1977), were found to be -1 km/s and 4 km/s respectively. The uncertainty in these measurements, as judged by the agreement between the results obtained through the two apertures and also allowing for the small uncertainties in the system drift, is ±6 km/s.

Norris (private communication) has measured the heliocentric radial velocities of the Bidelman and Macconnell stars observed during this run. The differences in instrumental radial velocities between the Bidelman and Macconnell program stars and IC 4651/23 were calculated by cross-correlation of their spectra. These were combined with the data of Norris to obtain the heliocentric radial velocity of IC 4651/23. The result from the first night was \( V_r(\text{IC4651}) = -35 \pm 3 \) km/s (upon averaging the velocities obtained relative to 19 comparison stars), while \( V_r(\text{IC4651}) = -33 \pm 4 \) km/s was obtained from the second nights data (with 9 comparison stars). These two determinations agree to within the cited uncertainties (which are the standard errors in the mean). The radial velocity of the cluster as thus determined is significantly greater than the velocity difference between stars 22, 23 and 60, which are therefore concluded to be cluster members.
V. DISCUSSION

a) Comparison of IC 4651/23 with Other Open Cluster Giants.

As mentioned in the introduction, very few open cluster giants are known to have $\lambda 4216$ cyanogen bands that are significantly enhanced in strength above the mean for their cluster. Data for a number of such stars, obtained from the literature, are listed in Table 3, which gives their DDO colors, their cyanogen excess $\delta CN$, the mean excess $\delta CN$ of their associated cluster, references, and the number of blue stragglers $N_B$ that have been identified in each cluster (see below). Also included in Table 3 are the cluster ages as taken from Demarque (1980). An age of $1.6 \times 10^9$ years has been determined for IC 4651 by Patenaude (1978). The ages derived independently by these two authors for other clusters agree to within $\sim 0.5 \times 10^9$ years, with Patenaude's estimates being lower than Demarque's by this amount for clusters with ages of $1-2 \times 10^9$ years. Within the differences of the two analyses, it appears that IC 4651 is similar in age to clusters such as NGC 7789 and NGC 752.

All of the clusters listed by Janes (1979, Table 8) as having published DDO photometry, were included in the literature search. NGC 2477 was excluded from further consideration since it is known that there is variable reddening, on the order of 0.2 mag in E(B-V), across it (Hartwick, Hesser and McClure, 1972). NGC 188 is a possibly anomalous open cluster which is not represented in Table 3. McClure (1974) finds that the giant branch, when plotted in the $C_0(45-48)$, $C_0(42-45)$ plane, exhibits a much broader sequence than a cluster such as M67. The spread in $\delta CN$ among the giants observed by McClure is 0.13, although the most cyanogen rich star has a CN excess only 0.03 mag greater than the cluster mean,
## TABLE 3

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<th>C(45-48)</th>
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<th>C(41-42)</th>
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**Super-metal-rich Field Giants**

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*NGC2682 = M67*

References:

which is $\delta_{\text{CN}} = 0.00$. The large range in $\delta_{\text{CN}}$ is due to the presence of several CN-weak stars (e.g. III-94 with $\delta_{\text{CN}} = -0.10$). The data of Janes (1979) for 4 stars in NGC 1342 also displays a large range in $\delta_{\text{CN}}$ (~0.18), but this is not included in Table 3 because of the small number of giants concerned.

The stars in Table 3 were selected on the criterion that they have a CN excess of $\delta_{\text{CN}} > \overline{\delta_{\text{CN}}} + 0.05$. If the random error in the photometry from which the data in Table 3 is obtained is 0.01 mag, then 0.05 mag corresponds to a 3σ increase on the cluster mean (since errors of 0.01 mag in the photometry produce an error of $\sim 0.015$ in $\delta_{\text{CN}}$, Janes 1979). It can be seen that most of these giants have $\delta_{\text{CN}}$ comparable to that of the Hyades ($\delta_{\text{CN}} = 0.074$), with the exception of star 1329 in NGC 2204, which has a significantly higher excess. However none of them shows as large a $\delta_{\text{CN}}$ as that obtained above for IC 4651/23. There appears to be no age limitation on the clusters containing CN-strong giants, since they are present in systems with ages from $1 - 6 \times 10^9$ years. It should be cautioned here that radial velocity or proper motion membership data is not available for most of the stars in Table 3, a fact which should be kept in mind when discussing the incidence of CN-enhanced stars in open clusters.

Since giants such as IC 4651/23 are exceedingly rare in open clusters, it is of interest to enquire into their incidence in the general field. This can be done using the $\delta_{\text{CN}}$ distributions given by Boyle and McClure (1975), which are derived from data in McClure (1970) and Janes (1972). For a random sample of field giants their histogram indicates that only 3% of the stars have $\delta_{\text{CN}} > 0.08$. On the other hand, Spinrad (1976) finds from the work of Janes (1975), Spinrad and Taylor (1969) and Gustafsson et al. (1974)
that ~ 9% of the K giants are classified as SMR, i.e. as having metal abundances greater than the Hyades. Part of this difference is due to the fact that Spinrad takes $\delta CN > 0.06$ for the SMR giants, and another factor can no doubt be attributed to the small numbers of SMR stars in the above-mentioned samples (e.g. there are only 6 stars with $\delta CN > 0.08$ in Boyle and McClure's histogram). Perhaps of more interest is the fact that even from Boyle and McClure's $\delta CN$ distribution for Schmitt's spectroscopic sample of CN-strong giants, only 9% have $\delta CN > 0.13$. It comes as no surprise then to find that such stars are very rare in open clusters.

b) Comparison Between Open Cluster CN-strong Giants and SMR Giants.

Hartwick and McClure (1980), and Smith and Norris (1981) have discussed the possibility that the super-metal-rich field giants, as described by Spinrad and Taylor (1969) may be Population I analogs of the CN-strong stars common in globular clusters. For means of comparison with the open cluster stars, data for the SMR giants $\mu$Leo, $\alpha$Ser and HD 112127 are also included in Table 3. It is apparent that with the exception of IC 4651/23 and perhaps NGC 2204/1329, none of the open cluster giants in Table 3 have cyanogen bands as strong as those seen in the SMR giants.

It is of interest then to discover a star (IC 4651/23) in an open cluster which has a larger $\delta CN$ excess than that of $\mu$Leo. It would be expected that this star should have the same iron abundance as the other cluster members. A spectroscopic comparison between it and both the SMR giants and the globular cluster CN-strong giants could prove to be quite fruitful.
One way to compare IC 4651/23 and the SMR giants is via the (U-B)_0, (B-V)_0 two-color diagram. This is shown in Figure 3, where the IC 4651 giants are represented as open circles. The data are obtained from Eggen (1971a, b) upon using E(B-V) = 0.15 and E(U-B) = 0.14, the reddening in (U-B) having been calculated with equation (7) of Janes (1979). Also shown as filled circles are the SMR stars from Table 3. The dashed line is the mean field locus of Fitzgerald (1970) for luminosity class III, while the solid line is a fit by Boyle and McClure (1975) to the sequence defined by the Hyades moving group giants. Included in Figure 3 are a number of CN-strong stars with δC_m(41-42) > 0.11 taken from the list of McClure (1970), δC_m(41-42) being a gravity corrected cyanogen excess similar to δCN (see McClure, 1970). Both the CN-strong giants and the SMR field giants in Figure 3 show ultra-violet deficiencies relative to the field and Hyades sequences, a property that has been well documented by Spinrad and Taylor (1969), McClure (1970) and Janes and McClure (1971). The data of Eggen for IC 4651 is consistent with a slightly-below-Hyades abundance, but the interesting feature is that star 23, with its strong cyanogen, does not show any (U-B) deficiency. A confirmation of this result seems worthwhile, since it runs counter to trends shown by CN-strong stars in both the field and the halo globular clusters (see e.g. Hartwick and McClure, 1980). In contradistinction, IC 4651/60 does exhibit an ultraviolet deficiency, yet its cyanogen excess (δCN = 0.05) is marginally smaller than the cluster mean. The colors of this star are also worth checking.
The (U-B, B-V) diagram for the IC4651 giants (open circles, data from Eggen 1971), several super-metal-rich giants (filled circles), and a number of field CN-strong giants with $\delta C_{m}(41-42) > 0.11$ (crosses, data from McClure 1970). Unlike its counterparts in the field, the CN-strong cluster giant IC4651/23 exhibits no ultra-violet deficiency with respect to the Hyades sequence (solid line) or the field star locus of Fitzgerald (1971) (dashed line).

The field star colors have not been corrected for reddening, since this is small for solar neighborhood giants (see e.g., Janes 1975).
The nature of the CN-weak giants displaying evidence for high-temperature hydrogen burning in the vicinity of the Hα line is examined in this section. It is established that the distribution of CN-weak giants is consistent with a model of the CN reaction in these stars, as proposed by Feast et al. (1975) and Feast and Whitelock (1975). The CN-weak giants are not associated with any known cluster or association, and it is suggested that they may represent a population of low-metallicity giants that are not part of a stellar association. The CN-weak giants are found to be approximately 0.1 magnitude brighter than the CN-strong giants, and they are more numerous in the lower temperature range. The CN-weak giants exhibit a lower degree of hydrogen burning than the CN-strong giants, as indicated by their lower emission line strengths.
VI. THE NATURE OF THE CN-STRONG PHENOMENON

Giants displaying enhanced cyanogen, and with ages greater than that of the Hyades cluster, are known to occur in a range of environments. They are commonplace in globular clusters (see e.g., the reviews by Kraft, 1979; and Freeman and Norris, 1981), with some systems such as 47 Tuc apparently consisting of two identifiable CN-populations (Norris and Freeman, 1979). In the disk of our galaxy, field giants displaying very strong cyanogen bands have been described by Roman (1952), Schmitt (1971), McClure (1970), Janes and McClure (1971), and Janes (1975). The super-metal-rich giants are perhaps a more exclusive subset of these CN-strong giants in that they also show enhanced heavy element spectral features. Boyle and McClure's (1975) $\delta CN$ distribution for Schmitt's (1971) sample of spectroscopic CN-strong stars peaks at $\delta CN \sim 0.07$ i.e., at the Hyades abundance, and so the open cluster giants listed in Table 3 may rightly be regarded as CN-strong, although their parent clusters cannot (while not forgetting that the extent of possible field star contamination of this sample needs to be determined). A number of strong-CN stars were found in a survey of the Hyades moving group by Boyle and McClure, and Smith (1981) finds that a large percentage of the HR 1614 moving group stars identified by Eggen (1978) have strong cyanogen.

There are at least two possible ways in which the CN-strong stars may have originated;

a) They may have formed from gas already enriched in nitrogen and/or carbon (and possibly other elements).

b) Alternatively, these stars may be displaying at their surfaces the products of interior ON or CN-cycle hydrogen
burning, which have been brought to the surface through the action of a convective envelope.

Globular clusters, by virtue of their high stellar densities, may have been a favourable site for star formation from enriched gas, provided that they were massive enough to retain stellar ejecta which had been enhanced in nitrogen. The possibility that globular clusters could have confined such ejecta within their regions of active star formation may explain why they have such large populations of CN-strong stars. At present however no conclusive statements can be made in this direction, since there is conflicting evidence to support both mechanisms (a) and (b) (see e.g., Freeman and Norris 1981, and references therein). On the other hand, it is doubtful whether open clusters could have accomplished self-enrichment because of their smaller masses. The calculations of Wheeler, Mazurek, and Sivaramakrishnan (1980) and Smith (1982) indicate that a single supernova would have enough energy to disrupt a molecular cloud of mass $\sim 10^4 M_\odot$. This may account for why the open clusters are so homogeneous, since the protoclouds from which they formed may have been dispersed before being significantly enriched. It seems plausible to invoke the action of mechanism (b) to explain the open cluster CN-strong giants.

The stars which are of concern here all develop degenerate helium cores upon evolving off the main sequence, and there are three subsequent stages of their evolution where extensive interior mixing may occur.

1) **The first ascent of the red giant branch**

The calculations of Iben (1967) show that during this phase a convective envelope reaches down to the region of CN-cycle processing and dredges up secondary nitrogen. The occurrence of
this process among Pop I field stars has been given credence by the observations of Lambert and Ries (1977), but the work of Da Costa and Demarque (1981) shows that the large nitrogen enhancements seen in many of the giants in the globular cluster 47 Tuc cannot be accounted for in this way.

2) The core helium flash

So far standard models of this event have failed to produce mixing between the helium burning region and the outer envelope (see e.g. Despain 1980). This is in accord with observations such as those of Janes (1974), who finds no significant difference in \[ ^5 \text{CN} \] between the clump and giant branch stars in M67.

3) The helium shell flashes during asymptotic giant branch evolution

The calculations of Sweigart (1974), Gingold (1974) and Iben (1982) for low mass giants undergoing these flashes do not produce extensive mixing. However, the existence of 1.6 \( M_\odot \) carbon stars in the SMC and some of the LMC globular clusters indicates that dredge-up of the products of helium burning may occur during this phase (see e.g. Bessell, Wood, and Lloyd Evans 1981).

The \( V, B-V \) photometry of Eggen (1971a), and the \( C(45-48), C(42-45) \) colors presented here, are consistent with IC 4651/23 being a clump star. It has therefore only evolved through phases (1) and (2). Of these, it is only during (1) that standard calculations produce a surface nitrogen enhancement. However if this is the relevant process, it is difficult to explain why the majority of the cluster giants do not show similar cyanogen strengths. It seems that a non-standard variable needs to be included in the theory, as discussed for example by Iben (1979) in relation to the core flash. Such non-standard parameters may include the presence of interior
magnetic fields (Iben, 1979), rotation (see e.g., Sweigart and Mengel 1979), or membership of a binary system (Renzini, Mengel and Sweigart 1977). In relation to this later point, McClure, Fletcher and Nemec (1980) conclude that the field BaII stars are components of binaries.

The existence of blue stragglers in open clusters may be cited as evidence for non-standard evolution. Wheeler (1979) and Saia and Wheeler (1980) have discussed several mechanisms by which these stars could have originated, and conclude that the most feasible is one in which a star has its main sequence lifetime extended either by undergoing mixing, which causes it to evolve quasi-homogeneously, or by virtue of it having a non-thermal pressure support (e.g., magnetic or centrifugal) which permits the star to be in hydrostatic equilibrium at a lower temperature than would be necessary in the presence of thermal gas pressure alone. It is interesting in this regard that 5 of the 8 clusters listed in Table 3 have blue straggler populations, the numbers of such stars being included in the table along with a reference. NGC 7789 in fact, is seen to have quite a sizeable blue straggler population. Given the presence of blue stragglers within open clusters it seems feasible to invoke a non-standard form of evolution as the origin of their CN-enhanced giants. The scarcity of both these CN-stars and the blue stragglers is then compatible, although an evolutionary link between them is not proposed, since for example, NGC 2506 has a blue straggler population but its giants have very similar cyanogen strengths (McClure, Twarog and Forrester, 1981). Regarding IC 4651, a total of four blue stragglers was revealed in the photometry of Eggen (1971a) so that again evidence is obtained for an incidence of stars that have evolved in a non-standard way in a cluster containing a CN-strong giant.
The primordial and mixing explanations for the cyanogen excess of IC 4651 23 will be reassessed in the next chapter in the light of further data.
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__________, 1976, A.J., 81, 182.


Spectra have been obtained of the 4314 Å CH and 4319 Å bands for a giant with a large CN and CN blue excess in the open cluster IC 4621. The anomalous giant 823 is found to have a stronger CH band and CN band than a comparison giant 822, which has an CN excess similar to the cluster mean. No spectrum synthesis analysis indicates that both the CH and CN band differences are consistent with the carbon abundance in 823 being 8.1 dex higher than in 822. No need is found to invoke a nitrogen abundance difference between these two stars. The nature of the cyanogen anomaly in 823 therefore appears to be different to that seen in the giants of globular clusters such as 47 Tuc, where the strong cyanogen bands result from an enhancement in the surface nitrogen abundance.
CHAPTER 7

IC 4651 23: A CN-STRONG GIANT IN AN OLD OPEN CLUSTER

Graeme H. Smith

ABSTRACT

Spectra have been obtained of the $\lambda$4216 CN and $\lambda$4300 G bands for a giant with a large $\delta$CN DDO cyanogen excess in the open cluster IC 4651. The anomalous giant E23 is found to have a stronger G-band and CN-band than a comparison giant E22, which has an $\delta$CN excess similar to the cluster mean. A spectrum synthesis analysis indicates that both the CN and CH band differences are consistent with the carbon abundance in E23 being 0.1 dex higher than in E22. No need is found to invoke a nitrogen abundance difference between the two stars. The nature of the cyanogen anomaly in E23 therefore appears to be different to that seen in the giants of globular clusters such as NGC 6752, where strong cyanogen bands result from an enhancement in the surface nitrogen abundance.
I. INTRODUCTION

Photometric and spectroscopic investigations made during the last decade have shown that fundamental differences appear to exist between the chemical properties of galactic globular clusters and the old disk open clusters. Most globular clusters are found to possess substantial cyanogen band strength variations among their constituent red giants (cf. the reviews by Kraft 1979, Freeman and Norris 1981 and references therein). The old open clusters are much more homogeneous (cf. Hesser, Hartwick and McClure 1976), and anomalously strong cyanogen bands, if present at all, are restricted to only one or two giants. Recently, Smith (1982a) has found that the open cluster IC 4651, which has a metallicity comparable to that of the Hyades, possesses a giant with a DDO cyanogen excess characteristic of the super-metal-rich field giants, and so appears to exhibit a stronger $\lambda 4216$ CN band than the other cluster giants. In the present paper spectra of this star are presented for regions around the $\lambda 4216$ CN and $\lambda 4300$ CH bands. The CH-rich giants in globular clusters are often found to have higher nitrogen and lower carbon abundances than the CN-weak giants in the same cluster (Norris and Cottrell 1979, Da Costa and Cottrell 1980, Norris et al. 1981, Suntzeff 1981). This abundance anticorrelation is reflected by an anticorrelation between the strengths of the CN and CH bands among giants of the same temperature and gravity. The aim of this investigation is to see whether a similar comparison exists between the CN-enhanced giant in IC 4651 and another more typical member of this cluster.
The observational data are presented in the following section. In § III the observed spectral differences between the two program stars are compared with theoretical spectra in order to assess the magnitude of any C and/or N abundance differences present. The results are discussed in § IV.

II. THE OBSERVATIONAL DATA

The CN-enhanced open cluster giant and the comparison star which are of interest in this work are IC 4651 23 and 22 respectively (Eggen 1971a; these program stars will be designated E23 and E22). Dereddened photometric data for these stars, and the sources from which they are derived (taking $E(B-V) = 0.15$; Eggen 1971a, Smith 1982a) are given in Table 1. The similarity of the B-V, R-I and C(42-45) colors indicates that these stars have almost identical temperatures, and it will be shown below that their gravities are also similar. Any differences in the CN and CH band strengths between them are therefore taken to indicate a real abundance difference. As judged by their C(41-42) colors and $\delta$CN cyanogen excesses, E23 is expected to display in its spectrum a stronger $\lambda 4216$ band than E22, which has a $\delta$CN value similar to that of the cluster mean (Smith 1982a). The cluster membership of the program stars has been verified by Smith (1982a).
TABLE I

Photometric Data for IC 4651 22 and 23

<table>
<thead>
<tr>
<th>Star</th>
<th>(B-V)$_0$</th>
<th>(R-I)$_{K,0}$</th>
<th>C(45-48)$_0$</th>
<th>C(42-45)$_O$</th>
<th>C(41-42)$_O$</th>
<th>δCN$_O$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E22</td>
<td>0.99</td>
<td>0.31</td>
<td>1.168</td>
<td>0.863</td>
<td>0.237</td>
<td>0.067</td>
</tr>
<tr>
<td>E23</td>
<td>0.975</td>
<td>0.29</td>
<td>1.186</td>
<td>0.863</td>
<td>0.336</td>
<td>0.134</td>
</tr>
</tbody>
</table>

(1) Eggen (1971a); (2) Eggen (1971b); (3) Smith (1982a).

Spectra were obtained of E23 and E22 by using the Anglo-Australian Telescope (3.9 meter) with the RGO spectrograph/Image Photon Counting System (IPCS) combination. Spectra in the region of the G-band were acquired in April 1981, and of the λ4216 CN band in August 1981. The 1200 1 mm$^{-1}$ R grating, oriented blaze to collimator, was used in 2nd order during both runs with the 82cm camera to give a dispersion of 5 Å mm$^{-1}$. A slit width of 250µ was used in April, and 120 µ in August. A long slit was used to permit simultaneous recording of star and sky spectra, the sky background being later subtracted.

The spectra for the two program stars are shown overlapped in Figures 1a and 2a, where the thicker line represents that for E22. During data reduction the spectra were convolved with a gaussian of 2 pixels FWHM. The instrumental profiles corresponding to the resultant spectra have resolutions of 0.6 and 0.4 Å (FWHM) for Fig. 1a and 2a respectively. Figure 1a shows the region of the G-band, where both spectra are normalised at λ4316, while the
FIG. 1 - (a) A comparison between the observed spectra for E22 (thick line) and E23 (thin line) for the region of the G-band. The strong CN star E23 is shown to also exhibit the stronger G-band. The spectra are normalised at $\lambda 4316$, a region where the recorded counts are $\sim 1.15 \times 10^3$ per pixel.

(b) Synthetic spectra chosen to represent the observations. The model atmospheres are characterised by $T_{\text{eff}}/\log g/[A/H] = 4830/2.70/0.2$. Carbon and nitrogen abundances adopted are $[C/A] = 0.1$, $[N/A] = -0.3$ for E22 (thick line), and $[C/A] = 0.2$, $[N/A] = -0.3$ for E23 (thin line).
FIG. 2 -  (a) Observed spectra in the region of the blue
$(\Delta v = -1)$ CN system. The spectra are normalised at $\lambda 4217$, a region where the recorded counts are $\approx 530$ per pixel.

(b) Synthetic spectra calculated for the same parameters as given in the caption for Fig. 1 (see discussion in § III). In both panels star E23 is represented by the thin line, and E22 by the thick. A synthetic spectrum computed for $[C/A] = 0.2$, $[N/A] = -0.2$ (i.e. $[N/A]$ enhanced by 0.1 dex over that used for the E23 model represented in the figure) reveals that the regions most sensitive to nitrogen abundance are around $\lambda 4215$, $\lambda 4197$ and to some extent $\lambda 4193$. A comparison between the observed and theoretical spectra at these wavelengths provides little reason for invoking a significant nitrogen abundance difference between E23 and E22 ($[N/A]_{23} - [N/A]_{22} \leq 0.1$ dex).
region of the $\lambda_{4216}$ $\Delta v = -1$ CN band is shown in Fig. 2a, the normalisation being affected at $\lambda_{4217}$. As expected from the DDO photometry, E23 exhibits the stronger cyanogen bands. However this star also has an enhanced G-band, suggesting that E23 has a higher carbon abundance than E22. There is no evidence from the present data for the existence of a CH,CN anticorrelation, as is the case between the globular cluster CN-weak and CN-rich giants. It now remains to determine whether the carbon abundance difference between E23 and E22, as measured from the differences in the G-band spectra, can also explain the difference in $\lambda_{4216}$ CN band strengths, without recourse to invoking a nitrogen abundance difference between the two stars. To address this question synthetic spectra have been computed for comparison with the observed spectra.

III. SPECTRUM SYNTHESIS ANALYSIS

a) The Atmospheric Parameters

The effective temperatures of the program stars can be determined from the photometry in Table 1. Figure 3 shows loci of constant $T_{\text{eff}}$ and log g in the C(45-48) vs C(42-45) plane, these data having been obtained from the theoretical colors of Bell and Gustafsson (1978) extrapolated to a metal abundance of $[\text{A/H}] = 0.2$ appropriate to the Hyades (Branch, Lambert and Tomkin 1980). The Hyades-like abundance of this cluster was demonstrated by Eggen (1971a) and Smith (1982a). The colors of E22 and E23 are shown in this diagram, and the values of $T_{\text{eff}}$ obtained are recorded in Table 2. Errors of 0.01 in the C(45-48) and C(42-45) colors will lead to errors in $T_{\text{eff}}$ of 9K and 23K respectively. A temperature of 4830 K is adopted for both stars.
FIG. 3 - The C(45-48) vs. C(42-45) diagram calibrated in terms of $T_{\text{eff}}$ and log $g$ using the theoretical color grid of Bell and Gustafsson (1978), extrapolated to [A/H] = 0.2. The observed colors of stars E23 and E22 are depicted by filled and open circles respectively.
Surface gravities were derived from the equation

$$\log g = 4 \log T_{\text{eff}} + 0.4 M_{\text{bol}} + \log \frac{M}{M_\odot} - 12.52$$

The magnitudes $M_{\text{bol}}$ were calculated by using $(m-M)_0 = 9.5$ and $E(B-V) = 0.15$ (Eggen 1971a, Smith 1982a). The bolometric correction B.C. was obtained from the B.C./$T_{\text{eff}}$/log $g$/ [A/H] grid of Bell and Gustafsson (1978), where again an extrapolation to [A/H] = 0.2 was applied. Since B.C. has a slight sensitivity to gravity, these two quantities were obtained iteratively from equation (1) and Bell and Gustafsson's B.C. grid. A stellar mass of 1.5 $M_\odot$ was adopted (Patenaude 1978). The calculated values of log $g$ are given in Table 2. A value of log $g = 2.7$ is adopted for both stars in the synthetic spectra calculations. Good agreement exists between the gravities derived from equation (1) and Figure 3 for star E22 but not E23. The value obtained from equation (1) is preferred because of the reduced sensitivity to observational errors; for example, errors of 100 K, 0.1 and 0.5 $M_\odot$ in $T_{\text{eff}}$, $M_{\text{bol}}$ and $M$ respectively lead to an error in log $g$ of 0.15. Alternatively, when

### Table 2

Atmospheric Parameters for IC 4651 22 and 23

<table>
<thead>
<tr>
<th>Star</th>
<th>$M_V$</th>
<th>$T_{\text{eff}}$(DDO)</th>
<th>$T_{\text{eff}}$(B-V)</th>
<th>$T_{\text{eff}}$(R-I)</th>
<th>log $g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E22</td>
<td>0.99</td>
<td>4816</td>
<td>4782</td>
<td>4916</td>
<td>2.68</td>
</tr>
<tr>
<td>E23</td>
<td>0.73</td>
<td>4845</td>
<td>4823</td>
<td>5021</td>
<td>2.59</td>
</tr>
</tbody>
</table>
using Figure 3, an error of 0.01 in $(45-48)$ will produce an error of 0.3 in $\log g$. In addition, Gustafsson and Bell (1979) find that the variation of the synthetic $(45-48)$ color with gravity is too small for their giant models, by comparison with observations.

Upon adopting $\log g = 2.7$ and $[A/H] = 0.2$ for both E23 and E22, the theoretical colors of Bell and Gustafsson (1978) and Bell (1980) can be used to derive temperatures from B-V and (R-I)$_K$. These are given in Table 2. The mean differences between them and the DDO determinations are $T_{\text{eff}}(\text{DDO}) - T_{\text{eff}}(\text{B-V}) = 28K$, and $T_{\text{eff}}(\text{DDO}) - T_{\text{eff}}(\text{R-I}) = -138K$. The agreement between the DDO and B-V temperatures supports the temperatures adopted here.

b) The Synthetic Spectra

Theoretical spectra in the region of the CH and CN bands have been computed by using the program developed by Cottrell, and described in Cottrell and Norris (1978). Model atmospheres for a metal abundance of $[A/H] = 0.2$ were obtained by extrapolating within the grid of Bell et al. (1976). In the absence of a spectroscopic determination, a Doppler broadening velocity of 2 km s$^{-1}$ was adopted, this being consistent with the majority of the models of Bell et al. (1976). Synthetic spectra adopted to match the difference observed between the spectra of E22 and E23 are shown in Figure 1b for the region of the G-band, and Figure 2b for the region of the $(0,1)$ and $(1,2)$ bandheads of CN at $\lambda 4216$ and $\lambda 4197$. The fluxes have been convolved with gaussian profiles of 0.6 Å and 0.4 Å FWHM for Figures 1b and 2b respectively. The adopted carbon and nitrogen abundances are $[C/A] = 0.1$, $[N/A] = -0.3$ for E22, and $[C/A] = 0.2$, $[N/A] = -0.3$ for E23; the oxygen abundance was chosen to be
[O/A] = 0 in both cases. It was not possible to match simultaneously the G-band region at λ4310 and the CH line at λ4323, these two features indicating carbon abundances which differ by 0.2 dex. No inferences will therefore be made in relation to the absolute sizes of the C and N abundances quoted. The emphasis of this work is only to model the spectral differences between E22 and E23. Figure 1a shows that these differences are consistent with E23 having a carbon abundance higher than that of E22 by Δ[C/A] = 0.1 dex, with an estimated error in Δ[C/A] of ~0.05 dex, as judged from the mismatch between the theoretical and observed spectra. Figure 2a shows that a [C/A] difference of this size also reproduces the observed difference in the CN bands; there does not appear to be a need with the present data to invoke a nitrogen abundance difference between the two stars. Theoretical spectra computed for a difference of 0.2 dex in [C/A] did not give a good representation of the data.

Since a rather large difference exists between the temperatures indicated by the DDO and B-V colors on one hand, and R-I on the other, synthetic spectra for E23 and E22 were also calculated for T_{eff} = 5000K. Within the context of a differential analysis, these models lead to the same conclusions as the 4830 K ones.

It can be demonstrated that reasonable differences in log g, or T_{eff} between E23 and E22 cannot account for their spectral differences. A synthetic spectrum of the G-band was calculated for an atmosphere with T_{eff}/log g/[A/H] = 4830/1.7/0.2, and is compared in Figure 4 to that for a model with log g = 2.7; both atmospheres having [C/A] = 0.1, [N/A] = -0.3. Comparison of Figs. 1a and 4 indicates that even invoking a large gravity
FIG. 4 - Synthetic spectra calculated in the region of the G-band for log g = 2.7 (thick line) and 1.7 (thin line); with $T_{\text{eff}} = 4830$ K, [$A/H] = 0.2$, [$C/A] = 0.1$ and [$N/A] = -0.3$ for both cases. It is apparent from this diagram that no reasonable differences in gravity between E23 and E22 can account for the observed differences in their G-band strengths.
difference in log g of 1 between E22 and E23 still does not account for the observed G-band difference. This insensitivity of the G-band strength to changes in gravity has been described by Schadee (1968) and Cottrell and Norris (1978).

It is interesting to note that the existence of a 0.1 dex [C/A] enhancement in E23 will affect its C(42-45) color. Using the calculations of Dickens, Bell and Gustafsson (1979) as a guide (although with the caution that their DDO colors were computed for a metal abundance of [A/H] = -0.5), their Figure 14 indicates that a carbon abundance increase in [C/A] of 0.1 will redden C(42-45) by ~0.02, and so result in the temperature of E23 being underestimated by 50K. A difference in $T_{\text{eff}}^{\text{DDO}}$ of 80K may therefore exist between E23 and E22. The B-V and R-I colors also indicate E23 to be hotter than E22; by 40K in $T_{\text{eff}}^{\text{B-V}}$ and 100K in $T_{\text{eff}}^{\text{R-I}}$, although the R-I difference may be exaggerated by CN line blanketing causing the color of E23 to be too blue (Gustafsson and Bell 1979). The existence of such a temperature difference between E23 and E22 has little effect on the present analysis, since synthetic spectra calculated at 4830 and 4900 K exhibit a negligible difference in the G-band region, and so do not alter the conclusion that a carbon excess exists in E23. In the region of the λ4216 CN band, a difference of 70 K in the temperature of E23 relative to E22 would mask a nitrogen difference in [N/A] of 0.1, and so the possibility of a mild [N/A] excess in E23 relative to E22 cannot be ruled out.

It is concluded from the synthetic spectrum analysis that the most natural way of explaining the spectral differences between IC 4651 23 and 22 is in terms of a small difference in composition. Figures 1 and 2 indicate a difference in carbon abundance of $\Delta\text{[C/A]} = [\text{C/A}]_{23} - [\text{C/A}]_{22} \sim 0.1$. Spectra computed at a constant
carbon abundance indicate that the observations are also consistent with E23 being depleted in oxygen by 0.2 dex relative to E22. At present this alternative cannot be excluded.

Using the work of Deming (1978) it is possible to check whether the C abundance difference indicated by the spectra, is consistent with the differences in the photometric cyanogen excess $\delta_{CN}$ observed by Smith (1982a; see Table 1). Deming's theoretical $\delta_{CN}$ indices were calculated for a 4500/2.25/0.0 model atmosphere, and so are relevant here. Figure 9 of his paper indicates that an increase of 0.1 dex in $[C/H]$ would increase $\delta_{CN}$ by 0.06, which is in good agreement with the difference of 0.067 observed between E23 and E22.

IV. DISCUSSION

One of the aims of the present work is to determine whether the CN-strong phenomenon as manifested by the open cluster giant IC 4651 23 is a replica of that seen in the CN-rich giants of globular clusters such as NGC 6752 (Da Costa and Cottrell 1980, Norris et al. 1981). This does not appear to be the case. The stronger CN bands in E23 appear to result from its having a higher carbon (or lower oxygen) abundance than E22, whereas the CN-rich giants in NGC 6752 are generally found to have an increased nitrogen and depleted carbon abundance relative to their CN-weak counterparts. Giants with strong CH and CN bands have been found in small numbers in a few globular clusters (see e.g., McClure and Norris 1977, and references therein), although the large carbon enhancements ($[C/A] \sim 0.4-0.5$) found by Bell and Dickens (1974) for the $\omega$Cen giants RGO 55 and 70 appear to be more extreme than that evinced by E23. In
comparison with the abundance variations exhibited among globular cluster giants, those found between IC 4651 22 and 23 are quite mild.

Abundance variations between these open cluster giants may have been present in the gas from which they formed (the primordial alternative) or could be the result of deep mixing during their evolution. Within the context of a primordial theory, it can be asked why there were not more stars like E23 formed if the proto-cluster cloud was inhomogeneous when it collapsed. The inhomogeneity would need to be very localised at the time of star formation within the cloud, and suggests the possibility of element pollution by a massive star. Theoretical calculations by Mazurek (1980); Wheeler, Mazurek, and Sivaramakrishnan (1980); and Smith (1982b) indicate that through HII region and supernova remnant formation, even a single massive star would have a very destructive effect on an open cluster proto-cloud. Heavy element injection by a star external to the cloud may seem more feasible. A detailed abundance analysis of E23 is needed before one can assess whether its abundance anomalies are consistent with such an origin.

The colors of E23 are consistent with it being a horizontal branch star, so that in terms of a mixing theory its anomalous surface abundance may have originated during dredge-up on the giant branch or at the helium core flash as discussed by Smith (1982a). The present observations are inconsistent with dredge-up of CN-processed material during the ascent of the giant branch, since this would produce a carbon depletion rather than an enhancement. Deming (1978) has also shown that the addition of CN-processed material to the surface could not produce the large value of $\delta$CN observed for E23. The dredge-up of ON-enhanced material could produce a surface oxygen depletion, but this should be accompanied
by a nitrogen enhancement. With an initially solar O/N ratio, a depletion of \( \Delta [O/A] = [O/A]_{\text{new}} - [O/A]_{\text{old}} = -0.2 \) would result in a nitrogen abundance increase of \( \Delta [N/A] = [N/A]_{\text{new}} - [N/A]_{\text{old}} \approx 0.6 \). The possibility of such a high nitrogen abundance for IC 4651 23 is ruled out by the present observations. In addition, neither standard stellar evolution models for low mass stars \((1-1.5 \, M_\odot; \text{Iben} \, 1967)\), or the meridional circulation theory of Sweigart and Mengel (1979) predict dredge up of ON-processed material. It appears that the observations are incompatible with dredge-up during the first ascent of the giant branch. As suggested by Smith (1982a), it may be necessary to invoke the mixing up of carbon enriched material during the helium core flash, along the lines postulated by Smith and Demarque (1980). It would be valuable to determine whether the Sr and Ba lines are enhanced in the spectrum of this star, and thereby infer whether any s-processing has occurred during the hypothetical mixing episode.
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CHAPTER 8

THE CHEMICAL INHOMOGENEITY OF THE SCULPTOR DWARF SPHEROIDAL GALAXY

Graeme H. Smith and Michael A. Dopita

ABSTRACT

Panoramic photometry of red giants in the Sculptor dwarf spheroidal galaxy has been obtained by employing a narrow-band filter system designed to measure the absorption at the $\lambda3883$ CN band, and the CaII H+K lines. Sculptor is found to be inhomogeneous with respect to both cyanogen and calcium. Furthermore, the Ca and CN enhancements are correlated, suggesting similarities between the enrichment process in Sculptor and the globular clusters ωCen and M22.
I. INTRODUCTION

Much of the recent interest in the dwarf spheroidal galaxies has been concerned with their chemical inhomogeneity. The color-magnitude diagrams of Draco (Stetson 1979, Zinn 1980b), Ursa Minor (Schommer, Olszewski and Kunkel 1977; Zinn 1981; Schommer, Olszewski and Cudworth 1981), Fornax (Demers, Kunkel, and Hardy 1979), and Sculptor (Norris and Bessell 1978) all appear to display giant branches wider than can be explained by the observational uncertainties alone. This suggests the presence of internal variations in the low-ionisation-potential elements such as Fe, Si and Mg (Renzini 1977). The existence of such variations in Draco was demonstrated by Zinn (1978) who found, from scanner observations of the line blanketed spectral region blueward of 5000Å, an \( [\text{Fe/H}] \) abundance spread of \( \sim 0.3 \) dex. This result was verified from measurements of CaII H+K line strengths by Kinman, Kraft and Suntzeff (1981) who in addition found giants apparently more metal-poor than those in M92. Variations in \( [\text{Fe/H}] \) were identified among four giants in Ursa Minor by Zinn (1981), on the basis of multi-channel scanner observations, while spectra obtained of giants in Sculptor by Norris and Bessell (1978) show that \( [\text{Fe/H}] \) and/or \( [\text{Ca/H}] \) variations also exist within this system. The observations of van den Bergh (1969), Danziger (1973), Harris and Canterna (1977), and Zinn and Persson (1981), all indicate that a range of metal abundance exists among the globular clusters in Fornax.

The \( [\text{Fe/H}] \) and \( [\text{Ca/H}] \) inhomogeneities displayed by the dwarf spheroidals are reminiscent of those in the globular clusters \( \omega \)Cen (Freeman and Rodgers 1975; Butler, Dickens, and Epps 1978; Rodgers et al. 1979; Norris 1980; Mallia and Pagel 1981; Cohen 1981).
and M22 (Hesser and Harris 1979, Norris and Freeman 1982). However among the globular clusters these two appear to be unique in this way. Within most clusters variations in the spectroscopic appearance of carbon and nitrogen features e.g. the λ 3883 and 4216 CN bands and the λ 4300 G-band, are common among red giants of similar temperatures and gravities, as outlined in the reviews by Kraft (1979), McClure (1979), and Freeman and Norris (1981), but these are not generally accompanied by large variations in the Ca or Fe abundance. The data available on C and N variations within dwarf spheroidals are very limited. Kinman, Carbon, Suntzeff and Kraft (1981) find from a sample of nine Draco giants that although this galaxy has the same mean [Fe/H] abundance as M92, its [C/Fe] is on average three times that of M92, with one star having five times the mean M92 ratio. DDO photometry of five Draco giants by Hartwick and McClure (1974) shows none of the extreme CN band strengths characteristic of some ωCen giants (see e.g. Bessell and Norris 1976). A giant with strong G or CN bands was identified in Ursa Minor by Canterna and Schommer (1978), the nature of this star being further defined by Norris and Bessell (1978) and Zinn (1981). Norris and Bessell (1978) from spectra of one giant on the blue, and one on the red side of the Sculptor giant branch, found that the redder star had stronger λ 3883 CN band and CaII H+K line absorption, a property characteristic of ωCen (Bessell and Norris 1976, Norris 1980) and M22 (Norris and Freeman 1982).

In view of the lack of any extensive survey of cyanogen band strengths among the dwarf spheroidals, such a program has been undertaken for the Sculptor galaxy, with a view to providing a cyanogen distribution for comparison with those now available for a number of globular clusters such as ωCen (Norris 1980), NGC 6752
(Norris et al. 1981) and M22 (Norris and Freeman 1982). Considering also the [Fe/H] and [Ca/H] differences detected by Norris and Bessell (1978), a survey has also been made of the CaII H+K line strengths. The combined CN and Ca data will provide a test for the hypothesis of Norris and Bessell that the Sculptor giants possess correlated Ca and CN inhomogeneities in a manner similar to those in ωCen. The present observations consist of panoramic photometry employing a narrow-band filter system designed to measure the strength of the 3883 CN band and the CaII H+K lines (see § II). The data reduction procedure is described in § III, while the results are presented in § IV and discussed in § V.

II. OBSERVATIONS

Observations were obtained in September and November of 1980 by using the 3.9m Anglo-Australian Telescope at f/8, with the Image Photon Counting System (IPCS; Boksenberg 1972) in the direct imaging mode. The photocathode of this device has a blue-enhanced S-20 response. Each image obtained was 440x440 picture elements (pixels) in format, with the scale of each frame being 0.5 pixel^-1 E-W and 0.5 pixel^-1 N-S. Two fields in Sculptor were observed, with centers at (r.a., dec) 1950 = (00:58:13, -33:59:57) and (00:58:05, -33:58:42). These will be designated fields 1 and 2 respectively, and were chosen to include in total about 80 of the stars from the color-magnitude diagram of Kunkel and Demers (1977).

Exposures were obtained through each of four narrow band interference filters. Two of these have bandpasses of 36Å and 31Å FWHM with peak wavelengths (λc) of 3868 Å and 3905 Å, and are centered respectively on the λ3883 cyanogen absorption system, and a
pseudo-continuum region between the CN system and the CaII H+K lines. The filters are used to form a color equivalent to the spectroscopic $S(3839)$ cyanogen index of Norris et al. (1981). Observations of the cyanogen distribution among the subgiants in NGC 362, obtained using this filter system are described by Smith (1982). Of the two other filters, one has $\lambda_c = 3955 \AA$ (FWHM = 43 $\AA$) and the other $\lambda_c = 4018 \AA$ (FWHM = 38 $\AA$). These are used respectively to measure the absorption in the CaII H and K lines, plus a redward pseudo-continuum region.

On each run observations of the dawn or dusk sky were obtained for the purpose of flat-fielding. These frames were smoothed with a 6 x 6 pixel half-width two-dimensional gaussian filter, and normalised with the average counts per pixel, before dividing into the Sculptor images. This procedure corrects for coarse variations in the image tube response across the field, as well as for possible transmission variations across the interference filters. No attempt was made to correct for small scale pixel-to-pixel variations in the image-tube response. All observations of Sculptor were made during dark of moon.

A typical example of the data is shown in Figure 1, which is a section from an exposure of field 2 through the $\lambda 3905$ filter. Two exposures were obtained through the $\lambda 3868$ and $\lambda 3905$ filters for each of fields 1 and 2 during both September and November observing runs. The exposures were typically of 1000 seconds duration, although 1500 or 2000 second exposures were occasionally made with the $\lambda 3868$ filter. Observations of both fields were made with the $\lambda 3955$ and $\lambda 4018$ filters only in September.
FIG. 1 - A 180 x 180 pixel$^2$ grey-scale display of a region in field 2, obtained through the 3905Å filter. Typical sky counts accumulated during a 1000 second exposure through this filter averaged ~ 18.4 per pixel, with a standard deviation of ~ 1.4 across the region occupied by the program stars.
III. DATA REDUCTION

Instrumental magnitudes were derived for the program stars by using the APEX panoramic photometry computer program written by Dr E.B. Newell. A full description of the algorithms used in this program is presented by Newell (1979).

The data reduction, which is highly automated and run on the Mount Stromlo VAX 11/780 computer, takes place in several steps.

1) From the main 440x440 pixel$^2$ frames, smaller 31x31 pixel$^2$ arrays are extracted around each program star. It is on these sub-arrays that reduction proceeds.

2) The profiles of a sample of stars with well defined images are fitted by an analytic expression of the form

$$\psi(x) = a \left[ (1-Q) \exp (-2\pi \beta) + Q/(\beta + 1) \right]$$

where

$$\beta = \left[ 2x/F \right]^2,$$

$a$ is the height of the profile, and $F$ is the full-width of the profile at half height. This is a Lorentzian - Gaussian profile, with the size of the Lorentzian wings determined by the parameter $Q$. Average values of $F$ and $Q$ were computed for each 440x440 frame. Typical values of $F$, which is the parameter that reflects the seeing, and controls all size-dependent aspects of the APEX software, were from 2.5 to 4 pixels.

3) The centers of the program stars within their individual 31x31 pixel$^2$ arrays are next determined. Firstly the sky intensity is determined from an annular zone around each star. Sky-subtracted intensity distributions are then determined along two mutually perpendicular strips centered on the approximate position of the star. The precise center of the star is determined from
the peaks in the cross-correlation function obtained by cross-
correlating these distributions with the standard profile $\psi(x)/a$.
The centering routines were found to be successful for $> 80\%$ of the
program stars in each frame. The centers determined in this way
could be visually inspected on a RAMTEK grey-scale display monitor
linked to the VAX, and manually altered if deemed necessary. In
cases where the centering algorithms were unsuccessful, the centers
were judged by eye.

4) Stellar magnitudes are calculated by summing up intensities
within concentric circles. A sequence of ten such circles with
radii incremented by $f/4$ are laid down, centered on the star, while
an annulus of larger radius is used as a sky zone. A distribution
of intensities is derived from all pixels whose centers lie within
the sky zone, and the mode of this distribution $I_s$ is used as the
sky intensity. Newell (1979) has shown that this mode reliably
takes account of stellar contamination in the sky zone providing
that crowding is not too severe (see also Smith 1982). Such
crowding is not a problem with the present data, since in general
the extracted $31 \times 31$ pixel $^2$ arrays contained either no or only one
other star in addition to the program star. The magnitude of the
star within the $n$th circle, $m_n$ (where $n=1$ to $10$) was calculated from
the relation

$$m_n(\lambda_c) = 25.0 - 2.5 \log_{10} \left[ \frac{\sum_{k=1}^{P} I_k - PI_s}{P} \right]$$

where $P$ is the total number of pixels included within the $n$th
circle, $I_k$ is the intensity recorded in the $k$th pixel.

Ten magnitudes are therefore calculated for each star,
requiring a decision as to which one of these to use. This was made
by inspecting the repeatability of the magnitudes obtained from two exposures of the same field, as a function of aperture size. An example of such data is shown in Fig. 2, where the mean absolute value of the magnitude difference between two exposures, $|\Delta m_{\lambda_n}|$, averaged over all stars in the field, and allowing for systematic differences, is plotted versus circle number. Each curve is defined by the filter through which the two exposures were made, the field observed, and the month in which the observations were made. These curves were found to reach a minimum near circle 4 (radius = $r$), which was therefore chosen as the aperture from which all magnitudes were taken. Since the size of this circle scales with the stellar profile half-widths, which are determined for each exposure, all measurements sample the same region of the stellar images.

IV. RESULTS

a) The Cyanogen Indices.

Once magnitudes were obtained from each 440x440 pixel$^2$ frame, they were combined in the following way. The magnitudes measured from the two exposures per filter of each field were averaged together, and a cyanogen index

$$s_{cn} = m(3868) - m(3905)$$

was calculated, giving four sets of such colors, i.e. for the two fields observed in both November and September. The colors from these two months were then averaged, producing a set of $s_{cn}$ for fields 1 and 2. A sample of 14 stars exist in common between the two fields, which were chosen to provide some overlap, from which the mean difference $s_{cn}$ (field 1 - field 2) was calculated. This was treated as the systematic difference between the color systems.
The mean of the absolute values of the stellar magnitude differences (after correcting for a systematic difference) between two exposures of the same field plotted versus ring number. Each curve is designated by the filter through which the two exposures were made, the field observed, and the month in which the observations were made. The purpose of the plot is to show that the repeatability between exposures is optimised for magnitudes measured within aperture four.
\[ \Delta m_n (\lambda_c) \]

Circle number (n)
defined by the two fields, and used to transform the field 2 values onto the field 1 system. The uncertainty in this difference is 0.03 mag.

The results are given in Table 1. Column 1 gives the Kunkel and Demers (1977) star number, columns 2 and 3 give the V and B-V photometry obtained from Kunkel and Demers, column 4 gives the $s_{cn}$ color (on the field 1 system) for each star, while column 6 indicates whether the star is placed in field 1, field 2 or both. Where a star was situated in both fields, its field 1 and transformed field 2 colors were averaged.

The uncertainty in the data can be assessed in a number of ways. Figure 3 shows a plot of (Sept. - Nov.) $s_{cn}$ colors as a function of V magnitude for both fields, corrections having first been made for systematic differences between the two months. Brighter than V=19.5 the photometry generally repeats to better than 0.2 mag, but fainter than this limit much larger errors are incurred. Averaging the quantity $r = s_{cn}(\text{Sept}) - s_{cn}(\text{Nov})$ over all stars in each field, gives $r_m = 0.18$ for field 1, and $r_m = 0.16$ for field 2. Since the final $s_{cn}$ values are averages over the November and September runs, the theory of small sample statistics (Keeping 1962) indicates that the standard error in these mean colors ($\sim 0.63 r_m$) is 0.12 for field 1, and 0.10 for field 2. An independent estimate of the errors can be obtained by assuming that the red horizontal branch stars have the same $s_{cn}$ values. This assumption is supported by the work of Smith (1982), who finds no evidence for an intrinsic variation in $s_{cn}$ among the RHB stars in NGC 362, for which $B-V < 0.7$; these stars being too hot to show significant CN bands. The observational error is then estimated to be the standard deviation in the distribution of the RHB star $s_{cn}$.
Table 1

Data for 72 Sculptor Giants

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<th>Star</th>
<th>V</th>
<th>B-V</th>
<th>S$_{cn}$</th>
<th>S$_{ca}$</th>
<th>Field</th>
<th>Star</th>
<th>V</th>
<th>B-V</th>
<th>S$_{cn}$</th>
<th>S$_{ca}$</th>
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$^a$ Denotes horizontal branch star
FIG. 3 - The differences between September and November $s_{cn}$ colors for fields 1 and 2 are plotted as a function of $V$ magnitude. This diagram illustrates the uncertainty in the cyanogen colors.
A standard deviation of 0.6 was calculated to be appropriate for those stars with only a single of a field's values, with a standard error of 0.45. In both cases, the average over the 11 stars is shown.

![Graph](image-url)

- **ΔCN (Sept - Nov)**
  - Field 1
  - Field 2

![Axis Labels](image-url)
colors given in Table 1, which is 0.10. Finally, if the difference in the field 1 and field 2 $s_{cn}$ values for the 14 stars in common is considered, a standard deviation of 0.06 is calculated to be appropriate for those stars with only a field 1 or a field 2 color, while a standard error in the mean of 0.04 is more appropriate to those stars found in both fields, these estimates being an average over the 14 stars.

b) The Calcium Indices.

A calcium color was formed as

$$s_{ca} = m(3955) - m(4018).$$

This is similar in concept to the spectroscopic $m_{HK}$ index of Suntzeff (1980), although the bandpasses and central wavelengths are different. The values of $s_{ca}$ are given in column 5 of Table 1, where a constant has been added to the field 2 values to transform them onto the field 1 system. The error in this constant, which is derived from 13 common stars, is $+0.05$ (s.e.).

Figure 4 gives an idea of the uncertainty in the data. The absolute values of the difference between the two $m(3955)$, and the two $m(4018)$ magnitudes for field 1 are shown, where again the deterioration in the quality of the photometry at faint magnitudes is apparent. Since no data are available from November, the uncertainty in the $s_{ca}$ values given in Table 1 is estimated from the difference in the field 1 and field 2 colors for those stars in common. This indicates an error of $+0.12$ for those stars located in only one field, and $+0.08$ for those in both. The standard deviation of the red horizontal branch star $s_{ca}$ values is 0.11.
FIG. 4 - The uncertainty in the $s_{\text{ca}}$ calcium colors is indicated by this diagram, which shows the absolute values of the differences between the two measurements of the $m(3955)$ magnitudes, and the two $m(4018)$ measurements obtained from the September observations of field 1, plotted against V.
Field 1

- m (4018)
- m (3955)
V. DISCUSSION

The V, B-V color-magnitude diagram of the Sculptor galaxy is plotted in Figure 5 from the data of Kunkel and Demers (1977). The stars represented in Table 1 are shown in Figure 5 as open circles. Also included on the diagram is a hand-drawn fit to the mean giant branch\(^1\), which is defined for V > 18.0 by

\[(B-V)_{m} = -0.154V + 3.901.\]

A plot of \(s_{cn}\) versus V is shown in Figure 6. A baseline to the data, with the equation

\[s_{cn,o} = -0.142V + 2.833\]

is also shown. Relative to this line the cyanogen excess

\[\delta s_{cn} = s_{cn}(V) - s_{cn,o}(V)\]

is measured, in an identical manner to the \(\delta S(3839)\) parameter of Norris et al. (1981) and Norris and Freeman (1982). A generalised histogram (see Searle and Zinn 1978) of \(\delta s_{cn}\) values is shown in Figure 7. The convolving gaussian kernel has a dispersion of 0.05 (i.e. \(\sim 0.5\sigma\)), and so does not artificially broaden the distribution to any significant extent. Figures 6 and 7 indicate that Sculptor contains cyanogen enhanced giants. Restricting attention to stars with V < 19.6 (in view of Figure 3) it is apparent that stars 120, 305, 314 and 312 have strong cyanogen bands. The \(\delta s_{cn}\) values for

---

1. At this point star 194 is excluded from further analysis. Relative to the mean giant branch it is bluer by \(\sim 0.1\) mag in B-V than any other non-horizontal branch star in Table 1. It is possibly a field star or an asymptotic giant branch star. In view of the problem of defining the asymptotic giant branch in the Draco dwarf spheroidal (Stetson 1979, 1980; Zinn 1980b) and the possibility that very metal-poor stars may exist in the dwarf spheroidals, no other giants in Table 1 have been excluded from analysis as being either suspected field or AGB stars.
FIG. 5 - The color-magnitude diagram for Sculptor is shown, with every star in Table 4 of Kunkel and Demers (1977) being represented. The stars observed in the present work are depicted by open circles. Also drawn is a fiducial giant branch locus.
FIG. 6 - A plot of $s_{\text{cn}}$ versus $V$ for the non-horizontal branch stars observed. A fiducial baseline is also included, relative to which the cyanogen excess parameter $\delta s_{\text{cn}}$ is measured, as indicated in the diagram.
FIG. 7 - The generalised histogram of the cyanogen excess $\delta s_{cn}$ for the non-horizontal branch stars.
these stars are 0.50, 0.39, 0.53, and 0.59 respectively, which represent an ~3σ increase above the mean $\delta s_{\text{cn}}$ defined by the remaining stars in this magnitude range ($\delta s_{\text{cn}}[\text{mean}] = 0.14 \pm 0.10$).

Norris and Smith (1981) have reviewed the cyanogen distributions for ten globular clusters. It is apparent from comparing Figure 7 with their Figures 1 and 2, that Sculptor contains a smaller proportion of CN-enriched stars than most globular clusters, the exception being M55 (Smith and Norris 1982a). This is the first important result of the present work. Only 4 out of 36 Sculptor stars (i.e. 11%) with $V < 19.6$ show greatly enhanced CN, but in contrast, as many as 50% of the giants in clusters such as NGC 6752 (Norris et al. 1981) and 47 Tuc (Norris and Freeman 1979) exhibit strengthened CN bands. In clusters such as M5 (Smith and Norris 1982b), and notably M13 (Suntzeff 1981), the percentage of CN-rich (first ascent) red giants is much greater.

As a result of the small number of CN-enriched stars in Sculptor, the cyanogen distribution by itself is not distinctive enough to be classified as either ωCen-like or bimodal. In order to further compare the Sculptor inhomogeneities with those in the globular clusters, the calcium data must be considered. A plot of $s_{\text{ca}}$ vs. $V$ for Sculptor is shown in Figure 8. A reference baseline, chosen to be

$$s_{\text{ca},0} = -0.205V + 3.899$$

is also drawn in. The generalised histogram of $\delta s_{\text{ca}}$ calcium excess indices, measured relative to this line, is shown in Figure 9, a gaussian kernel of 0.06 dispersion being employed. The mean $\delta s_{\text{ca}}$ for the entire sample of stars is 0.276, with a standard deviation of $\sigma_{\text{ca}} = 0.165$. Taking the observed $s_{\text{ca}}$ values to have an uncertainty of 0.12 (std. dev.), the intrinsic standard
FIG. 8 - The plot of $s_{ca}$ versus $V$ for the non-horizontal branch stars with $s_{ca}$ values given in Table 1. The fiducial baseline is drawn in, and the definition of the $\delta_s_{ca}$ calcium excess parameter illustrated.
FIG. 9 - The generalised histogram of $\delta s_{ca}$ for the non-horizontal branch stars.
deviation \( \sigma_i \) is assumed to be given by the relation

\[
\sigma_{ca}^2 = \sigma_i^2 + 0.12^2
\]

which produces \( \sigma_i = 0.11 \). This suggests that intrinsic \( s_{ca} \) differences, comparable to the observational errors, exist among the Sculptor giants.

A very direct test of whether the present data reflect real calcium abundance variations is to see whether the calcium excess correlates with a B-V color excess

\[
\delta_{BV} = (B-V) - (B-V)_m
\]

measured relative to the mean giant branch sequence, as shown in Figure 5. The spectra of Norris and Bessell (1978) indicate that the metal abundance in Sculptor ranges from M92-like to M3-like i.e. from [Fe/H] = -2.3 to -1.7 (Zinn 1980a). Over such an abundance range at constant V magnitude, the \( m_{HK} \) calcium index of Suntzeff (1980) increases monotonically with [Fe/H], which in turn determines the giant branch color. The plot of \( \delta s_{ca} \) versus \( \delta_{BV} \) is shown in Figure 10, which includes only stars with 18.0 < V < 19.5, because of the large errors incurred in \( s_{ca} \) at fainter magnitudes (see Figure 4), and because the giant branch is poorly defined for V < 18.0. A correlation is readily apparent, with a correlation coefficient of 0.57, which means that the null hypothesis of no correlation is rejected at the 0.005 level of significance. The second important result of this work is therefore that like the globular clusters \( \omega \) Cen and M22, and the Draco, Ursa Minor and Fornax dwarf spheroidal galaxies, Sculptor is chemically inhomogeneous in [Ca/H], and so also presumably in [Fe/H].
FIG. 10 - This plot illustrates the correlation between $\delta_{ca}$ and $\delta_{BV}$, for stars with $18.0 < V < 19.5$. 
At this point it is necessary to make a comment on the possibility of field star contamination in the Sculptor fields. Using data from Allen (1973), and the solar neighbourhood spectral type distribution of Jones et al. (1981), it is estimated that in the magnitude and color ranges $18 < V < 19.5$, $0.65 < B-V < 1.2$, a total of $\approx 2$ field stars (assumed to be dwarfs) can be expected in the combined fields 1 and 2. The galactic disk model of Jones et al. (1981) predicts that $\approx 1$ field dwarf would be expected. While it would be valuable to obtain membership data such as radial velocities, or measurements of the $\lambda 5211$ MgH band strengths as used by Zinn (1978), it is not practical to do so individually for a sample of 70 very faint stars. The above calculations however indicate that the conclusions of this work should not be affected by the lack of such information.

The further extent of the similarity of Sculptor to $\omega$Cen and M22 is revealed by Figure 11, which shows a correlation between $\delta s_{cn}$ and $\delta s_{ca}$, only stars with $V < 19.5$ being represented. The correlation coefficient is 0.46, and the hypothesis that these two parameters are uncorrelated can be rejected at the 0.005 level of significance. A similar connection between cyanogen and calcium variations has been found among the giants in $\omega$Cen (Norris 1980) and M22 (Norris and Freeman 1982). These data provide strong support for the conjecture of Norris and Bessell (1978) that Sculptor exhibits the "$\omega$Cen anomaly". It is possible however that star 314, with $\delta s_{cn} = 0.53$ and $\delta s_{ca} = 0.18$ does not fit into this categorisation, since its calcium excess appears to be too small for its cyanogen excess.

The most plausible explanation for the observed inhomogeneities is that they existed at the time of star formation within
FIG. 11 - This plot illustrates the correlation between $\delta s_{\text{ca}}$ and $\delta s_{\text{cn}}$, for stars with $V < 19.5$. 
Sculptor. This indicates two possibilities, as discussed by Zinn (1981).

1) The stars responsible for the earliest heavy element production in the halo may have been widely separated in the remote regions where the dwarf spheroidals formed. If in addition the outer proto-halo gas was relatively quiescent, the metal-enriched material ejected by these stars may have mixed together only poorly, resulting in a very inhomogeneous halo. These inhomogeneities may have been preserved throughout the fragmentation and collapse of the large clouds from which the dwarf spheroidals formed. In this picture the inhomogeneities were established prior to any star formation in Sculptor.

2) Alternatively, a number of massive stars which formed early during the collapse of Sculptor may have expelled enriched material back into their gaseous environment while star formation was still in progress. The supernova explosions which form an integral part of this process eventually produced a cessation of star formation, and a sweeping of gas from Sculptor. Such a picture of galactic self-enrichment has been modelled by Larson (1974), who finds that it is capable of producing metal abundance gradients within galaxies. In addition, Saito (1979) has suggested that virial expansion following sudden gas removal may account for the low central concentrations of the dwarf spheroidals. Observationally it may be possible to distinguish between these two possibilities by searching for color gradients within Sculptor, similar to those found within 47 Tuc by Chun and Freeman (1979).

Spectroscopic observations are also needed to identify the cause of the cyanogen enhancements in some of the Sculptor giants, i.e. are they a consequence of an enhancement in the atmospheric
abundance of carbon, or of nitrogen? By analogy with the giants in M22, the observations of Norris and Freeman (1982) suggest that carbon enhancements may be present among the metal-enriched Sculptor stars, a conjecture which is perhaps given modest credence by the discovery of large \([\text{C/Fe}]\) enhancements among the giants in Draco by Kinman, Carbon, Suntzeff and Kraft (1981), and particularly by the discovery of two relatively blue carbon stars in Sculptor itself by Frogel et al. (1982). As discussed by Frogel et al., these two stars are similar in color and luminosity to the C stars in \(\omega\) Cen, thereby furthering the analogy between the stellar populations in this cluster and Sculptor.

The origin of the cyanogen variations seen in the majority of globular clusters is the subject of debate (see e.g. the reviews by Kraft 1979, and Freeman and Norris 1981), since the surface nitrogen and carbon abundances of red giants may be altered by interior mixing. The strongest argument against the mixing theory, not only in Sculptor, but \(\omega\) Cen and M22 as well, is the cyanogen, calcium correlation (see Norris 1980; Norris and Freeman 1982). To reconcile the mixing theory to these observations, it may be suggested that the CaII H and K line strengths are enhanced by a restructuring of the outer atmosphere by molecular line blanketing and backwarming, rather than by an increased calcium abundance. Synthetic spectrum calculations made by Norris (1980) however, lead him to conclude that this effect is not substantial enough to explain the observed spread in H+K line widths among the \(\omega\) Cen giants. In addition, evidence that the H and K lines are reflecting a real abundance spread in \(\omega\) Cen comes from the work of Cohen (1981), who finds that the weak metal lines also vary in strength. Unfortunately high resolution spectra are unattainable for the
Sculptor giants, however it would be valuable to obtain low resolution spectra to investigate whether other strong features such as the Mg b and Na D lines also vary.

In summary, the following facts have resulted from the present work.

1) The Sculptor dwarf spheroidal possesses cyanogen-enhanced giants, although not to the same extent as the globular clusters ωCen, M22 and NGC 6752 for example.

2) The Sculptor giants of similar luminosity display variations in the CaII H+K line strengths. In this respect, the Sculptor and Draco systems are similar.

3) The cyanogen and calcium anomalies are correlated, as is the case with ωCen and M22.
Harris, H.C., and Canterna, R., 1977, A.J., 82, 798.


Smith, G.H., 1982, in preparation. (Chapter 4)


Stetson, P.B., 1979, A.J., 84, 1149.


In this thesis data have been presented on the cyanogen distributions among giants within globular clusters, open clusters and the Sculptor dwarf spheroidal galaxy. The main results of this work will now be summarised, as well as some of their implications.

1. The cyanogen band strengths of the red giants within most globular clusters are distributed bimodally. This is known to be true of 47 Tuc (Norris and Freeman 1979), NGC 6752 (Norris et al. 1981), M4 (Norris 1981), M5, NGC 3201, NGC 362, probably M71 (this thesis), and M3 (Suntzeff 1981). The great frequency with which the bimodality turns up within globular clusters leads to the suggestion that an identical process has produced the CN inhomogeneities in most of them. This leads to the hope that once this process has been found for one cluster, then it has been found for most of them. The most notable exceptions to this generalisation are the clusters ωCen (Norris 1980) and M22 (Norris and Freeman 1982b), which show single peaked cyanogen distributions which tail off gradually toward high CN excesses. In addition, the CN variations in these clusters are accompanied by calcium abundance variations, which strongly suggest the occurrence of primordial enrichment.

One aspect of the bimodal distribution that does vary between clusters is the ratio, \( n \), of CN-rich to CN-poor stars. This is listed in Table 1 for the bimodal clusters. The uncertainty in this ratio, \( \sigma \), is calculated by assuming that the uncertainty in
The ratio of CN-rich to CN-poor stars

<table>
<thead>
<tr>
<th>Cluster</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>47 Tuc</td>
<td>1.7, 1.3, 0.5</td>
</tr>
<tr>
<td>NGC 362</td>
<td>3.0</td>
</tr>
<tr>
<td>NGC 3201</td>
<td>1.0</td>
</tr>
<tr>
<td>M3</td>
<td>0.9</td>
</tr>
<tr>
<td>M5</td>
<td>2.6</td>
</tr>
<tr>
<td>M4</td>
<td>1.5</td>
</tr>
<tr>
<td>NGC 6752</td>
<td>1.5</td>
</tr>
<tr>
<td>M71</td>
<td>0.4</td>
</tr>
</tbody>
</table>

1 This gives the ratios for the radial zones r<3', 6'<r<15', and r>15' respectively.
2 Only giants with $M_v < 0$ are considered.

The measured number of CN-rich and CN-poor stars in each cluster is governed by Poisson statistics. The value of n is given for three different radial zones in 47 Tuc, in view of the evidence for a radial CN gradient in this cluster. From Table 1, it appears that 47 Tuc, NGC 3201, M3, M4 and NGC 6752 all have values of n close to 1.2 i.e. only a slight excess of CN-rich stars. M5 and NGC 362 appear to have about twice this value of n, although the difference is only 1o, while M71 has a significantly lower ratio.

In Chapter 2 it was found that bimodal distributions exist within clusters having a large range in both total mass and central
mass concentration. A prime example of this is the 47 Tuc, M71 comparison. In fact, Figure 2 of Norris and Smith (1981), in which the C(41-42), V diagrams of these clusters are plotted side by side, shows that their giant populations are virtually indistinguishable in this plane. The infrared photometry of Frogel, Persson and Cohen (1981) shows that in the metallicity sensitive V, (V-K) color-magnitude diagram, the 47 Tuc and M71 giants again define identical sequences. In addition to the M71, 47 Tuc comparison, the clusters M5 and NGC 362 do not appear to be atypical in their mass or central concentration by comparison with systems such as M3 or NGC 6752 which have a lower proportion of CN-rich stars. The existence and form of the bimodal CN distributions do not appear to be related to the morphology of the globular clusters in which they are found.

3. The only cluster which under close scrutiny has failed to reveal marked cyanogen band strength variations is M55. Part of this result may be due to the fact that because of its low abundance ([Fe/H]<-1.8, Zinn 1980a, b) the cyanogen bands will be intrinsically weak. However, because the metallicity of M55 is similar to the baselevel abundance in ωCen and M22, it is clear that M55 has not been subjected to the same, presumably primordial, enrichment processes that have occurred within these other two clusters.

The M71 and M55 results therefore indicate that while the bimodal cyanogen distribution can be set up within low mass clusters, the ωCen-like distribution, accompanied as it is with calcium abundance variations, cannot. There are at least two possible explanations for this phenomenon, and the isolation of the correct one will not be easy.
a) The bimodal CN distribution may have a mixing origin. The attribute of red giants which causes them to mix in such an extreme manner is then assumed to be present in most (if not all) globular clusters. Correlated cyanogen, calcium inhomogeneities are then taken to be the result of supernova induced primordial enrichment, a process which might lead to the disruption of low mass clusters rather than to their enrichment.

b) The bimodal CN distribution may have a primordial origin. However, whereas calcium is presumably ejected by energetic supernova explosions, nitrogen may be expelled relatively quiescently in the stellar winds of intermediate mass (5-10 \( M_\odot \)) stars. Hence nitrogen enrichment, unaccompanied by calcium enrichment, may have been possible within low mass clusters such as M71. Enriched star formation would then have to take place before a significant fraction of the intermediate mass stars go supernovae. This is the scenario proposed by Cottrell and Da Costa (1981).

The interpretation of the M71, M55 comparison is however made difficult by the possibility that the present masses of these clusters may not be in the same ratio to the masses of their initial proto-cluster gas clouds.

4. The development of a panoramic photometry technique for measuring the \( \lambda 3883 \) CN band strength for a large sample of stars was reported in Chapter 4. This has been used to probe the cyanogen variations among a sample of subgiants in NGC 362. It was found that CN inhomogeneities exist among stars almost 2 magnitudes fainter than the turn-on luminosity at which the meridional circulation theory of Sweigart and Mengel (1979) predicts that such inhomogeneities should first be seen.
5. Anticorrelations of either CN and CH, or CN and CO band strengths appear to be a characteristic of the giants in clusters possessing bimodal cyanogen distributions. The data presented in this thesis indicate the existence of such anticorrelations in NGC 3201, M5 and M71. The data concerning the CN, CO anticorrelation in M71 is only based on a small sample of giants however. In addition, it remains to be discovered whether the small 2.3 µ CO colors of the CN-rich giants are due to a CO underabundance or to CN blocking in the comparison filter. High resolution infrared spectra of the CO bands in the M71 giants are required to settle this question. In 47 Tuc, where a CN, CO-color anticorrelation has been clearly discovered by Frogel, Persson and Cohen (1981), a carbon and nitrogen abundance anticorrelation has been found among the asymptotic giant (Norris and Cottrell 1979) and red horizontal branch (Norris and Freeman 1982a) stars, but has yet to be demonstrated among the red giants. A C,N abundance anticorrelation is also known to exist among the giants in M3 (Suntzeff 1981) and NGC 6752 (Da Costa and Cottrell 1980, Norris et al. 1981), while Norris (1981) finds a CN, CH band anticorrelation between two M4 giants.

6. In Chapter 5 the implications of the C,N anticorrelation for theories concerning the origin of the cyanogen inhomogeneities were explored. Most of the emphasis was directed towards the constraints this observation places on the primordial theory. Comprehensive expositions on the difficulties in reconciling a mixing theory with the globular cluster CN observations have been presented by Sweigart and Mengel (1979) and Da Costa and Demarque (1982).

The observation of a C,N anticorrelation would seem to intuitively favour a mixing explanation. However, as mentioned in
Chapters 1 and 5 the sheer size of the nitrogen overabundance alone in the CN-rich stars of clusters such as NGC 6752, indicates that either:

A) ON-processed material must be present in the atmospheres of these stars (but not to such a large extent that the C,N anticorrelation is erased), or

B) if the dredge-up of only CN-processed material is assumed, then a non-solar initial C:N ratio is needed.

Within the context of the primordial theory it seems natural to identify the CN-enhanced stars in 47 Tuc and NGC 6752 as those which formed out of nitrogen-enriched gas, and the CN-poor stars as those which formed from the pristine material that initially constituted the proto-cluster cloud (Norris and Freeman 1979, Cottrell and Da Costa 1981). However, in Chapter 5 it was found that several problems are associated with this hypothesis.

A) In 47 Tuc, it appears necessary to invoke that the 5-10 $M_\odot$ nitrogen-producing stars were formed according to a mass function of different slope to that determined by Da Costa (1977) for the present main sequence stars. In view of the uncertainties that exist in the estimated quantities of $^{14}\text{N}$ ejected by intermediate mass stars, plus the lack of any strong reason for believing that all of the stars which formed within a particular cluster must follow the same mass function, this requirement does not impose any major constraint on the primordial theory.

B) The carbon depletion observed in the CN-enhanced giants does however pose a difficulty to the primordial theory. This is because the pristine proto-cloud material must be diluted with large amounts of (presumably) carbon depleted ejecta from massive stars. This imposes severe constraints on the slope $x$ of the mass function.
of the first generation of stars, which must be flat enough to produce large numbers of massive stars. It was found that no reasonable values of $x$ could account simultaneously for both the carbon and nitrogen abundance differences between the CN-weak and CN-rich stars in NGC 6752 and 47 Tuc.

The difficulty which the C, N anticorrelation presents to the primordial theory may stem from equating the composition of the CN-weak stars to that of the original proto-cluster gas cloud. If in fact the CN-weak stars have been enriched in carbon but not nitrogen, and the CN-rich stars have been enriched in nitrogen and not carbon, the need to explain a carbon "depletion" in the CN-rich stars would vanish. This hypothesis does however suffer from the rather unpalatable implication that almost all of the stars within NGC 6752 and 47 Tuc have formed from primordially enriched gas.

A substantial amount of observational work remains to be undertaken with regard to the C,N anticorrelation. Important questions which remain to be answered are:

1) What are the [N/A] and [C/A] abundances of the CN-weak and CN-strong stars in clusters such as NGC 3201, M5 and NGC 362?

2) Is the C,N anticorrelation evinced by every star within a cluster possessing a bimodal CN distribution, or do some stars show correlated CN, CH bands?

The constraints which an anticorrelation places on the mixing and primordial theories will be better understood once these questions are answered.

7. In Chapters 6 and 7 observations of the giants in the open cluster IC 4651 were presented. The DDO photometry presented in the first of these chapters shows that this old disk cluster has a metal
abundance only slightly less than that of the Hyades. Of particular interest was the discovery that the giant E23 possesses a significantly higher cyanogen excess $\delta$CN than the other cluster giants. This star has a cyanogen excess comparable to that of the super-metal-rich giants, a fact that distinguishes it from cyanogen-enhanced giants in other open giants.

In Chapter 7, spectra of the G band, as well as the $\lambda$4216 CN band, were presented for this star, as well as for a comparison cluster giant of similar temperature and gravity. It was found that both spectral features were stronger for the cyanogen enhanced giant. The results of a spectrum synthesis analysis revealed that both bands were consistent with E23 being enhanced by 0.1 dex in $[\text{C}/\text{A}]$ relative to the comparison star, with the possibility of an accompanying enhancement of $\sim$ 0.1 dex in $[\text{N}/\text{A}]$. Compared to the cyanogen and G band anomalies found among giants within globular clusters like NGC 6752 those seen in IC 4651 23 are therefore distinguished by two properties.

A) The strong CN band is mainly a result of a surface carbon overabundance, whereas the CN-rich giants in NGC 6752 (and probably the other globular clusters possessing bimodal CN distributions) show a carbon depletion, their strong CN bands being due to a large nitrogen overabundance.

B) The $[\text{C}/\text{A}]$ and $[\text{N}/\text{A}]$ differences between E23 and the comparison star are very mild compared to those existing between globular cluster giants.

It appears that the anomalies shown by IC 4651 23 are quite distinct from those seen among the giants within globular clusters displaying cyanogen bimodalities. Stars with enhanced carbon do however exist in $\omega$Cen and M22. In particular, Norris and Freeman
(1982b) have shown that the G band strength correlates with the CaII H+K line strength among the M22 giants. This suggests that carbon enhancements could be established primordially. In the context of low mass open cluster formation, element pollution from external supernovae is likely to be necessary to avoid disruption of the proto-cluster. Such an external source of enrichment could in fact be a natural consequence of the sequential star formation models (e.g. Elmegreen and Lada 1977) being proposed for the formation of young star clusters on the surfaces of massive molecular clouds within the present galactic disk. Of course it remains to be seen whether a similar mode of star formation was prevalent in the old disk. An equally feasible alternative to the primordial explanation of the small carbon enhancement in E23 is the possibility of the dredge-up of C-enriched interior material during the helium core flash, although it still remains to be shown theoretically that such a process can take place.

There is scope for much more observational work on the old open cluster giants. Surveys, using for example DDO photometry, are needed of a larger sample of clusters in order to search for more cyanogen-enhanced giants. In addition, the cluster memberships of those already known need to be verified. A comprehensive spectroscopic investigation is then needed to identify those elements which are enhanced (or depleted) within these stars.

8) The results of a survey of the cyanogen and calcium inhomogeneities within the Sculptor dwarf spheroidal galaxy were presented in Chapter 8. The panoramic photometry technique described in Chapter 4 was also used to obtain the Sculptor data. Narrow band interference filters were employed to measure the absorption strengths of the λ3883 CN band and the CaII H+K lines. It was
found that the Sculptor giants display correlated cyanogen, calcium inhomogeneities, in a manner reminiscent of ωCen. It appears that primordial enrichment was capable of occurring within the low density dwarf spheroidals. Cyanogen variations therefore appear to be commonplace within Population II stellar systems, be they globular clusters or dwarf spheroidals, but are rare within Population I systems.

It is important to follow up this photometric investigation of Sculptor with a spectroscopic study. Two important questions about Sculptor could then be answered:

1) Does the G band strength correlate with cyanogen and calcium, as found by Norris and Freeman (1982b) for M22?

2) Are the CaII H+K variations accompanied by variations in the strength of other metallic line features, such as the Mgб and NaD lines?
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