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The Nature of Star Formation in the Trapezium Cluster

A thesis submitted for the degree of
Doctor of Philosophy
of the
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- The work presented in this thesis is entirely that of the candidate alone except
- (i) where acknowledged in the text, and
 - (ii) for the observations and initial data reduction of the near-infrared photometry. This work was shared between the candidate, Dr. P. J. McGregor, and Prof. A. R. Hyland.


Angela E. Samuel

To Brett and Daisy

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*Worlds on worlds are rolling ever
From creation to decay,
Like the bubbles on a river
Sparkling, bursting, borne away.
But they are still immortal
Who, through birth's orient portal
And death's dark chasm hurrying to and fro,
Clothe their unceasing flight
In the brief dust and light
Gathered around their chariots as they go;
New shapes they still may weave,
New gods, new laws receive,
Bright or dim are they as the robes they last
On Death's bare ribs had cast.*

Percy Bysshe Shelley, 1822: from *Hellas*

Abstract

The Trapezium Cluster stellar population is studied in detail using near-infrared and optical means in order to probe the clustered mode of low and high mass star formation. We determine fundamental stellar parameters such as the spectral types, ages, masses, extinctions and dust excesses for a significant number of cluster stars. Various techniques are applied to deredden the stars in the color-magnitude diagram and hence compare intrinsic positions with theoretical evolutionary tracks. Through these means, we estimate properties of the low mass stellar population to greater accuracy than has previously been achieved.

Near-infrared photometry of Trapezium Cluster stars provides an initial evaluation of the nature of the cluster population. This evaluation is improved upon using optical spectroscopy to measure spectral types of a large number of Trapezium Cluster stars for the first time. We find our sample of Trapezium Cluster stars to have a mean spectral type of mid-K, in agreement with findings for the low mass stars in the vicinity of, and external to, the central cluster. The stars are dereddened on the color-magnitude diagram using our acquired spectral types. Their intrinsic positions provide the most accurate determination for the cluster age obtained to date, $\sim 10^6$ yr, confirming the pre-main sequence nature of the population. This age estimate is extended to the infrared cluster population of more than 550 stars revealed by infrared-array images. The K luminosity function for the infrared cluster is used in combination with the cluster age to derive the stellar mass distribution. The slope of the mass function obtained here is found to be comparable with the slopes of field initial mass functions. A mean stellar mass of $\sim 0.9 M_{\odot}$ is estimated for the low mass stars. Our determinations for the masses, ages, and spectral types of Trapezium Cluster stars shows that they are a similar stellar population to the more extended Orion Nebula Cluster population, except in density of stars. The mass density of the Trapezium system of low mass and high mass (Θ^1 Ori) stars is found to be $\sim 4690 M_{\odot} \text{ pc}^{-3}$, approximately 1.5 times greater than previous estimates based on optical studies. The stellar mass derived for the low mass cluster is also used to calculate the star formation efficiency in the region to first order, $\sim 72\%$. This is similar to, but higher than, the star formation efficiencies determined in other regions of embedded cluster formation.

The mean extinction estimated for the low mass cluster stars in our sample place the stars at approximately the same depth into the molecular cloud as the Trapezium OB stars, at the near-face of the cloud. Our sample is biased towards optical members of the cluster, suggesting that a significant number of the low mass stars may be embedded more deeply in the molecular cloud than the OB stars. However, using the K luminosity function for the infrared cluster we determine that the low mass cluster is most probably not spread through the whole cloud, but is pre-

dominantly located close to the near-face of the cloud. Dust excess determinations show that the Trapezium Cluster stars sampled here contain a typical proportion of classical (dust-excess) T Tauri stars compared with naked (no dust-excess) T Tauri stars for a young stellar population. Approximately one-third of our sample have insignificant dust excesses.

Calcium II IR triplet emission is observed in members of our Trapezium Cluster sample. We judge that the strengths of the triplet features imply a circumstellar disk origin for the emission. The frequency of calcium triplet emitting stars is estimated for our sample. We compare this estimate with the proportion of triplet emitters in a sample of Chamaeleon pre-main sequence stars. We find that 20–30 % of classical T Tauri stars in the two populations exhibit triplet emission; the frequency of triplet emission in the Trapezium Cluster sample is found to be comparable with that in Chamaeleon.

We perform an approximate dynamical analysis of the Trapezium Cluster star-forming region using our estimates for stellar mass and age. The low mass cluster is found to be at an early stage in its dynamical evolution, and has not had time to completely relax as a system and lose its initial characteristics. It is too young, therefore, to exhibit mass segregation, and the observed isothermality of the stars is proposed here to arise from the distribution of the clumps from which the stars have formed. The high mass stars considered separately are determined to be old enough to have relaxed as a system. We find that, if the Θ^1 Ori stars are located centrally with respect to the low mass cluster, then they are most likely to have formed in their present locations rather than have arrived there from larger radii through dynamical friction processes. In addition, the binding energies of the two high mass binary systems are found to be almost forty times the energy of the low mass cluster. It is suggested that the binary energies must have been acquired through their formation processes instead of through dynamical interactions with the low mass cluster. Thus, present characteristics of the stellar population of the Trapezium Cluster directly relate to the conditions under which the cluster formed, and are not due to dynamical processes among the stars themselves. The total stellar mass determined for the low mass cluster is estimated to be sufficient to bind the cluster at this time. This remains true even with future removal of gas from the region. However, continued dynamical interactions may lead to the eventual dissipation of the low mass cluster.

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Chapter 1

Introduction

1.1 Thesis Perspective

Stars from $\sim 0.1 M_{\odot}$ to at least $100 M_{\odot}$ form in molecular cloud complexes of dust and gas. Until recently, studies suggested that low and high mass star formation occurred in spatially distinct locations (for example, Shu, Adams & Lizano 1987; Genzel 1987). Dark clouds such as Taurus, Lupus, and ρ Ophiuchus are regions in which only low mass ($< 3 M_{\odot}$) stars are forming. Many regions of intermediate-high mass ($> 3 M_{\odot}$) star formation have also been identified, including Orion, S106, M17 and GL437. No significant populations of low mass stars had been observed in association with most of these regions. However, the results obtained using infrared (IR) array technology over the last five years have revealed that young high mass stars are often, if not always, accompanied by populations of young lower mass stars. Indeed, the bulk of galactic low mass star formation may occur in regions forming high mass stars (Lada & Lada 1991). How large numbers of stars of different masses form in close proximity is currently poorly understood, but has important implications for the origin of the initial mass function and the formation of star clusters. This thesis aims to define fundamental parameters of stars forming in cluster environments in order to constrain theories of this mode of galactic star formation. We focus on the closest and therefore most accessible of these regions, the Trapezium Cluster (~ 440 pc) in the Orion Nebula.

Infrared studies (Allen, Bailey, & Hyland 1984; McCaughrean 1988; Hyland, Allen, & Bailey 1993) have confirmed that the Trapezium Cluster is an extremely dense population of low mass stars surrounding the central high mass Trapezium OB system. In the work presented here, it is treated as a prototype of the clustered mode of star formation where both high and low mass stars are forming in close proximity. Recent investigations of the Trapezium Cluster conducted at optical wavelengths (Herbig & Terndrup 1986) have not included the entire infrared population as re-

vealed by McCaughrean (1988), and have been affected by the uncertainties involved in discriminating between interstellar and circumstellar contributions to reddening. In addition, nebula subtraction has always posed a significant problem to investigators of stars in this extremely nebular environment. We use both optical and infrared means to overcome these obstacles and identify characteristics of the low mass Trapezium Cluster stellar population. We aim to obtain detailed knowledge of the mass and age distributions of stars in the cluster, which provide the foundation for an understanding of this star formation environment.

The initial mass function, first studied by Salpeter (1955), is derived observationally from the distribution of stars in a region with respect to mass. The slope of the mass function is such that the number of stars formed in a particular environment is commonly found to increase towards lower masses. The Salpeter slope of 1.35 has been revised by Scalo (1986) to the steeper value of 1.7 for low mass stars. Whether there is a low mass truncation in the initial mass function of young stellar populations is the subject of ongoing debate (Scalo 1986; Larson 1991; Gatley et al. 1991; Rayner et al. 1991; among others). The stellar initial mass function is directly related to the mass function of the original star-forming molecular cloud cores (Zinnecker, McCaughrean & Wilking 1992, and references therein). Hence, determination of stellar masses helps constrain models of possible mechanisms by which these cores are created and subsequently give birth to stars. Comparison with mass distributions in regions of solely low mass star formation give additional insights into the way stars form in extremely dense environments with low *and* high mass stars. Knowledge of the stellar mass function is necessary to ascertain the star formation efficiency of the cluster environment. This parameter has not as yet been satisfactorily determined for the Trapezium Cluster. A satisfactory determination of the mass spectrum in the Trapezium Cluster will also provide a relatively accurate value for the mass density in the region.

One of the important outstanding questions in star formation is whether there is a temporal distinction between low and high mass star formation. Even if separate mechanisms are responsible for the formation of low and high mass stars, it remains uncertain whether low and high mass stars form continuously or if high mass star formation in a region leads to the termination of local low mass star formation. The evaluation of ages for cluster members defines their evolutionary status with respect to present understanding of pre-main sequence (PMS) stellar evolution, and provides a basis for examining the relative timescales of low and high mass star formation.

Combining mass and age estimates for the Trapezium Cluster permits an assessment of the dynamical status of the high and low mass populations. Determination of dynamical timescales for these systems provides insights into the interaction history and the future dynamical evolution of the stars. Also in question for the Trapezium

Cluster in particular, and embedded cluster populations in general, is the extent to which the cluster is bound. Related to this are the factors giving rise to this bound/unbound situation. The efficiency with which gas is converted into stars and the rate at which gas mass is lost are important factors in deciding whether the stellar group formed is bound (Mathieu 1983; Elmegreen 1983; Lada, Margulis & Dearborn 1984; Verschueren 1990). We hope to probe these unresolved issues in the current investigation.

Another fundamental aspect of the Trapezium Cluster star formation environment which has not yet been properly evaluated is the relative physical dimensions of the various stellar populations and the overall morphology of the region. Genzel & Stutzki (1989) summarize evidence for and against a scenario where the low mass population extends through the entire molecular cloud. High mass stars are known to be forming interior to the cloud close to the Trapezium OB stars in the KL nebula (Becklin & Neugebauer 1967; Rieke, Low & Kleinmann 1973; among others). This poses the question of whether any low mass stars are associated with this secondary site of high mass star formation, and what relationship any such low mass population has with the Trapezium Cluster low mass stars. Are they in fact the same population ? These concerns can be examined via an extensive survey of the low mass stars near the Trapezium OB stars to determine associated extinctions. However, in order to do this, it is crucial to distinguish between interstellar extinction and circumstellar dust associated with individual stars. In the analyses presented in this dissertation, we investigate various means of making this assessment. Extinction estimates not only allow the extent of the low mass Trapezium Cluster to be gauged, but also provide information regarding the modelling of low mass star formation in regions with more than one site of massive star formation. The frequency and extent of circumstellar disks associated with low mass Trapezium Cluster stars has possible implications for the influence of stellar interactions on circumstellar material in this populous environment. The proportions of classical T Tauri stars (with dust excesses) to naked T Tauri stars (no significant dust excesses) in the Trapezium Cluster will be compared with the proportions found in other star-forming regions. Hence, the effect of the cluster-mode of star formation on the circumstellar environment of the stars can be ascertained.

1.2 Overview of Galactic Star Formation

Star formation as an ongoing galactic process gained early support with findings such as the youth of high mass stars in OB associations (Ambartsumian 1947). Lower mass T Tauri stars, identified as a class by Joy (1942, 1945, 1949), were categorized as young objects by Herbig (1962) and the surveys of young clusters by Walker (1956,

1957, 1959, 1961, 1969). These surveys placed cluster members in PMS locations compared with theoretical evolutionary tracks (Heney, LeLevier & Levee 1955; Iben & Talbot 1966) in the color-magnitude diagram. Herbig (1962) proposed that low mass stars form continuously in molecular clouds, until the process is terminated by the formation of massive stars and the associated dispersal of star-forming gas and dust. The ideas presented by Herbig were extended by observations of sequential OB sub-groups, such as in the Orion region (Blaauw 1964). Elmegreen & Lada (1977) suggested that the formation of massive stars not only ends further low mass star formation but also compresses the molecular cloud material, initiating further high mass star formation through the cloud. Silk (1977) and Larson (1985) proposed that high mass star formation inhibits further low mass star formation by heating the local environment and increasing the Jeans mass. This sequential-mass star formation process is questioned by Stahler (1985), who sees no correlation between stellar mass and age in the PMS populations of NGC 2264 and NGC 6530.

Infrared detections have provided the most significant advances in the observational study of star formation. This is mainly because extinction and obscuration from dusty natal molecular cloud environments is much reduced at these wavelengths compared with the optical. The advent of near-IR detectors in the late 1960s led to the identification of new classes of young embedded objects. Compact H II regions were detected and O stars were observed buried in their interiors (Mezger et al. 1967). Embedded high mass protostars were also discovered, such as the Becklin-Neugebauer (BN) IR source (Becklin & Neugebauer 1967). In the 1970s to early 1980s, the discovery at near-IR wavelengths of young populations of low mass stars in dark clouds focussed star formation studies on the low mass end of the spectrum. Relevant literature published during this time includes Strom, Strom & Yost (1971), Strom et al. (1972), Henize & Mendoza (1973); Grasdalen, Strom & Strom (1973); Strom, Strom & Grasdalen (1974), Strom, Grasdalen and Strom (1974), Vrba et al. (1975), Strom, Vrba and Strom (1976), Elias (1978a, b), Cohen & Kuhl (1979), Hyland, Jones & Mitchell (1982), Appenzeller, Jankovics & Krautter (1983), Adams, Strom & Strom (1983).

The great potential of studying star-forming regions at infrared wavelengths was demonstrated by the extensive data obtained with the Infrared Astronomical Satellite (IRAS) in 1983. Young, low mass populations were found in great numbers in dark clouds such as Taurus, Lupus, Chamaeleon, and ρ Ophiuchus (for example, Wilking & Lada 1983; Jones et al. 1985; Young, Lada & Wilking 1986; Whittet et al. 1987; Wilking, Lada & Young 1989; Strom et al. 1989). High mass star-forming regions, however, tend to be more distant and hence confused in the large IRAS beam. As well, there are fewer massive sources, demonstrated by the shape of the initial mass function.

One of the few regions where low mass stars have long been known to be forming close to young, massive stars is the Trapezium region in the Orion complex (Baade & Minkowski 1937). However, the presence of strong nebula emission has inhibited investigations of the low mass stars in this star-forming region. Significant new observations have only been made in the last decade. Lonsdale et al. (1982), identified a population of faint, low mass infrared objects close to the embedded high mass BN object some 2' NW of the Trapezium. These were studied in detail by Hyland et al. (1984) at near-infrared wavelengths, in order to determine whether they represent another Trapezium-type region of clustered low- and high-mass star formation. The question remains open even with the latest observations of this region, using infrared-array technology. McCaughrean (1988) presented IR-array images of the Trapezium environment, revealing the true extent of the low mass cluster for the first time. These images confirm the results of previous optical studies (Herbig & Terndrup 1986, and references therein) that the stellar density in the region is extremely high. IR-array imaging is currently exposing many similar embedded low mass clusters in association with high mass star formation, in regions such as S106, M17, S255/257, and GL437 (Gatley et al. 1991; McCaughrean et al. 1991; Carpenter, Snell & Schloerb 1991; Rayner, Hodapp & Zinnecker 1991; Lada et al. 1991; Greene & Young 1992; among others). As mentioned earlier, it is possible that *most* galactic low mass stars are created through this mode of star formation. The fact that the Trapezium Cluster is the closest of these star-forming environments makes it the obvious place to begin studying this phenomenon.

1.3 The Orion Star-Forming Region

The Orion molecular complex has consistently been a major focus for star formation studies due to its proximity at ~ 440 pc. The molecular cloud has a mass of $\geq 2 \times 10^5 M_{\odot}$ (Kutner et al. 1977; Thaddeus 1982) and is embedded in a large H I cloud of comparable mass (Chromey, Elmegreen & Elmegreen 1989). The brightest stellar components of the complex at optical wavelengths are the four subgroups of the I Orion OB association (Blaauw 1964; Warren & Hesser 1978). These range from Ia, with an age of $\sim 12 \times 10^6$ yr, through to the young Id subgroup, $\leq 4 \times 10^6$ yr in age and located at the northern end of the Orion A molecular cloud. The Id subgroup is located in the Orion Nebula (M42) (Kutner et al. 1977; Maddalena et al. 1986). It includes the central Θ^1 Ori stars also known as the Trapezium OB system and the low mass Trapezium Cluster stellar population, located within $\sim 5'$ in radius (~ 0.6 pc) of the Trapezium OB stars (Hyland et al. 1993). The following dissertation concentrates on the Trapezium Cluster, in the core of the Orion Nebula.

It is well established (Genzel & Stutzki 1989 and references therein) that the

Orion Nebula H II region lies at the near surface of the molecular cloud which, in the vicinity of the H II region, is called OMC-1 (Zuckerman & Palmer 1974 and references therein). The visual extinction through OMC-1 is estimated to be between 100 and 200 mag (Thaddeus et al. 1971; Hyland et al. 1984). From its location, the nebula has been described as a “blister” at the surface of OMC-1 (Zuckerman 1973; Baldwin et al. 1991). An ionization front exists at the interface between the ionized gas and the molecular cloud and is progressing into the cloud. Simultaneously, the density gradient between the region behind the Trapezium OB stars and the less dense material in front of them and towards us causes a “champagne”-like flow of ionized gas in our direction (Tenorio-Tagle 1979).

The molecular ridge of OMC-1 is the site of a large population of H α emission stars (Parsamian & Chavira 1982; Herbig & Bell 1988 and references therein). The mass density of this low mass population decreases with increasing distance from the Trapezium OB stars. The Orion Nebula Cluster is defined quite arbitrarily as the low mass stars within the central 2.5×4.5 pc area ($\sim 20' \times 35'$) projected on the sky, excluding the extremely dense core (Genzel & Stutzki 1989 and references therein). Approximately 1000 stars are included in the Orion Nebula Cluster (Jones & Walker 1988). The observed stellar density peaks within a 0.6 pc diameter core ($\sim 10'$ diameter) around the Trapezium OB stars. This population is separately defined as the Trapezium Cluster, with an estimate for the mass density of $\sim 1800 M_{\odot} \text{pc}^{-3}$ (Herbig & Terndrup 1986). The brightness of the nebulosity has severely hindered optical analyses of this region of extremely high mass density. However, infrared images of the region (Allen et al. 1984; McCaughrean 1988) dramatically demonstrated the power of infrared observations of these sites. The infrared array images of McCaughrean revealed a population of more than 450 faint stars.

Located interior to OMC-1 and $\sim 2'$ northwest of Θ^1 Ori C is the BN object (Becklin & Neugebauer 1967). At least two other embedded high mass stars have been discovered near BN, IRc2 and IRc9 (Rieke, Low, & Kleinmann 1973; Wynn-Williams & Becklin 1974; Downes et al. 1981). The source IRc2 has created the Kleinmann-Low (KL) nebula (Kleinmann & Low 1967), an H II region spatially separate from the Orion Nebula and $\sim 10''$ south of BN, with a diameter of $\sim 30''$. The ultraviolet luminosity derived for BN corresponds to that of a main sequence B0.5 star (e.g., Scoville et al. 1983), while IRc2 is even more luminous. BN is estimated to have a mass of $\sim 15 M_{\odot}$, and IRc2 of $\sim 25 M_{\odot}$ (Phillips & Beckman 1980), and their ages are between 10^3 – 10^4 yr (Phillips & Beckman 1980; Mundy et al. 1986). These ages, and the strength of Br α emission observed from BN, imply that the high mass stars are at least nearing the main sequence. The entire BN-KL star formation region lies at greater depths into the molecular cloud than the Trapezium region, with visual extinction estimates varying from 15 to 50 mag

(Gillett et al. 1975; Joyce, Simon & Simon 1978; Scoville et al. 1983; Beckwith 1982; Hyland et al. 1984). It is uncertain to what depth into the molecular cloud the faint low mass sources discovered near the BN-KL region by Lonsdale et al. (1982) lie. They may be members of the Trapezium Cluster or may constitute a separate embedded low mass population associated with the BN-KL star formation region.

Determining the properties of the stars themselves is clearly vital to understanding the complex nature of star formation in the Trapezium region. The first stars studied in detail were naturally the visible high mass Trapezium OB stars. Proper-motion work by Parenago (1954) set the expansion age of the Trapezium stars at $\leq 10^4$ yr. The age of the Orion Nebula was derived by Kahn & Menon (1961) and Vandervoort (1963) as $1-2 \times 10^4$ yr, from calculations of the Stromgren sphere growth rate. Note that the nebula age is smaller than the age of the OB stars themselves, given a turn-on time for these stars. Assuming that the OB stars are approximately zero-age-main-sequence stars (Warren & Hesser 1978), a lower age estimate for the Θ^1 Ori stars is estimated from the PMS lifetime for massive stars (Iben 1965) of $\sim 6 \times 10^4$ yr. The spectral types determined for the Trapezium OB stars are O7 for Θ^1 Ori C, B0 for Θ^1 Ori D, and B2 for both Θ^1 Ori B, and Θ^1 Ori A (Struve & Titus 1944, Conti & Alschuler 1971). The visual extinction to the Trapezium OB stars has been estimated to be between 1 and 2.5 mag (Peimbert 1982; Herbig & Terndrup 1986; Garay et al. 1987). Peimbert (1982) proposes that the Θ^2 Ori OB stars, also located in the Trapezium region, are less extincted than the Θ^1 Ori stars by 0.75 mag at V. This implies that they are foreground stars relative to the Θ^1 Ori OB-group. Cardelli & Clayton (1988) confirm the extinction estimates for the Θ^1 Ori and Θ^2 Ori stars and hence their relative morphology.

As mentioned, the brightness of the emission nebulosity in the central regions surrounding the high mass Trapezium stars has inhibited optical observations of the low mass Trapezium Cluster. Thus, initial work on the fainter stars concentrated on the more extended Orion Nebula Cluster (Johnson 1957; Walker 1969; Penston, Hunter & O'Neill 1975). The first detailed investigation of cluster stars was made by Cohen & Kuhn (1979). They studied H α emission stars from several star-forming regions, including ~ 53 from the Orion Nebula Cluster. Cohen & Kuhn estimated an age spread from between 3×10^4 yr and $\sim 6 \times 10^6$ yr for their Orion Nebula Cluster sample, confirming the PMS nature of the stars. This evidence supports a model of continuous low mass star formation in the Orion Nebula Cluster. The work of Cohen & Kuhn is based on H α emission stars. These objects are most probably classical T Tauri stars (Brand & Wouterloot 1992). The mean spectral type determined for the Cohen & Kuhn sample is K4, with a range from K1-M0. The masses derived are in the range $0.35-3 M_{\odot}$, with an average of $1 M_{\odot}$. The extinction to the cluster is

uncertain due to the difficulties involved in separating the relative contributions of circumstellar dust and interstellar reddening. It has generally been assumed to be $A_V \sim 0.2$ mag (Walker 1969; Cohen & Kuhi 1979; Breger et al. 1981). A comparison with the reddening estimated towards the Θ^1 Ori stars suggests that the Trapezium OB stars are more embedded than the Orion Nebula Cluster.

Both the extremely high mass density of the low mass Trapezium cluster and its proximity to high mass star formation make it an appropriate prototype of stellar clusters in which early phases of low- and high-mass star formation are in progress. Detailed studies of the Trapezium Cluster are of relatively recent origin. The optical observations of 68 Trapezium Cluster stars undertaken by Herbig & Terndrup (1986) resulted in the first significant data-set pertaining to these stars. They simplified the problems caused by the nebular environment by dereddening the stars assuming a mean extinction of $A_V \sim 2.4$ mag. This simplification translates to uncertainties in their resulting mass and age estimates. The stellar masses derived are from < 0.7 to $3 M_\odot$, with ages for most stars of less than 10^6 yr. The stars are clearly PMS in nature, despite the uncertainties. The youth of the Trapezium Cluster population is also suggested by the discovery of x-ray emission from several cluster stars (Ku, Righini-Cohen & Simon 1982). Herbig & Terndrup (1986) use their optical observations to calculate a mass density for the low mass Trapezium Cluster of at least $1800 M_\odot \text{ pc}^{-3}$. The near-infrared array image obtained by McCaughrean (1988) of the Trapezium Cluster has revealed many of the optically obscured stars and hence allows a more accurate determination of this parameter. Hyland et al. (1993) have also undertaken near-infrared observations of the Trapezium Cluster; the results of their scans are in good agreement with McCaughrean's array data. In total more than 500 stars are identified as part of the Trapezium Cluster.

A satisfactory determination of stellar parameters for the Trapezium Cluster, such as mass and age distributions, has yet to be obtained. These estimates, in combination with the corresponding values for the other stellar groups in the region, are necessary to probe the nature of the initial mass function, and to resolve the question of coeval versus continuous star formation. The contributions to stellar extinction from interstellar extinction and circumstellar dust should be evaluated. Estimates of interstellar extinction to individual stars are needed to reveal the relative depths into the molecular cloud material of the low mass population compared with the Trapezium OB stars, the Orion Nebula Cluster, and the BN-KL region. Knowledge of these depths are of direct significance to questions such as how the cluster environment has influenced stellar evolution, whether there is a physical relationship between the various stellar groups or whether they are separate entities and what processes produce stars of such diverse masses in close proximity. At present, it is not even clear that the various clusters identified historically are sepa-

rate entities. Mass segregation in some form appears to exist (Jones & Walker 1988; Abt, Wang, & Cardona 1991), with the massive Trapezium OB stars occupying the central position with respect to the low mass Trapezium Cluster and Orion Nebula Cluster stars in the plane of the sky. It is less obvious whether this is merely a function of our perspective or a real effect, and whether mass segregation also extends to the low mass population. Quantitative estimates of circumstellar dust associated with individual stars provide evidence for the possible evolutionary status of the stars. Together with extinction values, they demonstrate the effects of the nebular environment and neighbouring stars on the presence of circumstellar material. Importantly, spectral types are known for very few Trapezium Cluster stars. Accurate classifications will provide stellar temperatures which are needed to place the stars on the color-magnitude diagram. As well, differences in spectral type between inner Trapezium Cluster stars and outer Orion Nebula Cluster stars or interior BN-KL objects reflect differences in the masses of stars that are forming. The dynamical state of the cluster and its future evolution have been the subject of considerable debate since the Orion Nebula star-forming region was first studied. This issue is also examined in detail in the current investigation. It is envisaged that the results obtained here will be extendable to the low mass/high mass cluster regions now being discovered with infrared arrays, and hence becoming of increasing significance.

1.4 Thesis Summary

In Chapter 2, the results obtained from near-infrared photometry of a sample of Trapezium Cluster stars are presented in the color-color plane. The stars are dereddened and their intrinsic colors are plotted on the color-magnitude diagram with theoretical evolutionary tracks overlain. Hence, the age and mass distributions are estimated. The prevalence of circumstellar dust in association with the cluster stars, indicated by the contribution of infrared excess to stellar reddening, is also gauged.

Chapter 3 presents the optical spectroscopy program undertaken in parallel with the infrared photometry. The spectral types of a sample of Trapezium Cluster stars are measured and used to place the stars more accurately on the color-magnitude diagram than has been done previously. A comparison is made with the results of Chapter 2. The ages of the low mass stars are compared with those estimated for the Trapezium OB stars, the BN-KL sources, and the Orion Nebula Cluster in order to decide whether the stars in the region all formed coevally, or have been forming continuously in the region irrespective of mass. The extinction and dust-excess associated with each star is evaluated also. Thus, the morphology of the low mass stars is related to the various stellar groups in their environment. We discuss

the implications with respect to the initial mass function of the region, and probe the dynamical status of the cluster.

Calcium triplet emission is observed in a few of the Trapezium Cluster stars for which optical spectra are available. In order to determine the frequency of such emission and its significance to the low mass star formation process, we have also obtained optical spectra of low mass PMS stars from the Chamaeleon dark cloud. These are discussed in Chapter 4.

Chapter 5 summarizes the work undertaken here and places it in the context of our understanding of star formation.

Chapter 2

Infrared Photometry of Trapezium Cluster Stars

2.1 Introduction

The Orion Nebula has long been recognized as a region of active high mass star formation due to the presence of the Trapezium OB stars, the Becklin-Neugebauer object (BN), the Kleinmann-Low (KL) nebula, and their associated bipolar CO outflows and OH, SiO and H₂O masers (Becklin & Neugebauer 1967; Genzel & Downes 1983; Genzel & Stutzki 1989). At approximately 440 pc distance (Walker 1969), the Orion Nebula is one of the closest regions of high mass star formation. Low mass stars are known to have formed in a more extended region around the nebula, based on the existence of numerous T Tauri stars (Cohen & Kuhl 1979; Parsamian and Chavira 1982; Herbig & Bell 1988) and Herbig-Haro objects (Münch & Taylor 1974; Cantó et al. 1980; Axon & Taylor 1984). This stellar association, covering approximately $0.3^\circ \times 0.6^\circ$ ($2.5 \text{ pc} \times 4.5 \text{ pc}$), has been referred to as the Orion Nebula Cluster in the literature (Johnson 1965; Penston, Hunter, & O'Neill 1975; Herbig & Terndrup 1986; Genzel & Stutzki 1989).

A further dense population of stars exists at the core of the Orion Nebula Cluster within the bright optical nebulosity and in apparent association with the Trapezium OB stars (Trumpler 1931; Baade & Minkowski 1937; Lonsdale et al. 1982; Hyland et al. 1984). Herbig & Terndrup (1986) refer to this as the Trapezium Cluster. It has a radial extent of $\sim 5'$ (0.6 pc) centered on the brightest Trapezium star, $\Theta^1 \text{ Ori C}$. The stellar mass density in this region is estimated to be at least $1800 \text{ M}_\odot \text{ pc}^{-3}$ (Hyland et al. 1984; Herbig & Terndrup 1986). This is one of the highest known mass densities for galactic open clusters.

The Trapezium OB stars are estimated to be approximately zero-age-main-sequence objects (for example, Warren & Hesser 1978). Thus, a lower limit to their

ages, obtained from the PMS lifetimes for high mass stars, is $\sim 6 \times 10^4$ yr (Iben 1965). Cohen & Kuhl (1979) studied T Tauri stars in the Orion Molecular Cloud region, including around 50 from the Orion Nebula Cluster. The mean age found for their Orion Nebula Cluster stars, using both optical and infrared data, is $\sim 10^6$ yr. Their estimated stellar masses range between ~ 0.35 – $3 M_{\odot}$, with a mean of $\sim 1 M_{\odot}$. Hyland et al. (1984) derive a *K*-band distribution function for sources within a $4' \times 1'$ ($0.5 \text{ pc} \times 0.1 \text{ pc}$) area centred on BN. This distribution function is similar to that for the Cohen & Kuhl Orion Nebula Cluster sample, implying that the two populations are broadly comparable in both mass and age. Herbig & Terndrup (1986) have studied 68 visible Trapezium Cluster stars using narrow-band CCD photometry in an attempt to mimic the broad *V* and *I* passbands while avoiding strong nebular lines. They adopt a mean cluster extinction and find that their sample consists of pre-main-sequence (PMS) stars generally no older than $\sim 10^6$ yr. These results are in good agreement with those for the Orion Nebula Cluster and the Trapezium OB stars. They estimate masses from < 0.5 to $3 M_{\odot}$ for the visible cluster stars, clearly identifying these stars as the low mass component of the Trapezium Cluster. Their results confirm the suggestion of Hyland et al. (1984) that the faint stars in this region have comparable masses to the more extended Orion Nebula Cluster stellar population.

Recent infrared observations of many optically obscured stars in the Trapezium Cluster have provided a more accurate picture of its extremely high mass density (McCaughrean 1988; Hyland, Allen, & Bailey 1993, hereafter HAB). HAB observe a total of more than 550 cluster stars within a $\sim 5'$ radial region. Zinnecker, McCaughrean & Wilking (1992) report that McCaughrean et al. have assumed that the revealed cluster stars formed coevally, with an age of 1 – 2×10^6 yr, in order to obtain an approximate form for the initial mass function. Their approach takes account of the varying amounts of extinction towards cluster stars, but assumes that the associated stellar infrared excesses are insignificant. If this is not the case, then the derived stellar masses will be in error by an amount dependent on the nature of the dust excess, as discussed by these authors. Both assumptions require testing before the nature of the low mass Trapezium Cluster stars can be ascertained. In this chapter, we extend the infrared study of the Trapezium Cluster and its environs by attempting to determine physical parameters for a significant sample of the newly discovered embedded cluster stars. Infrared imaging of other massive H II regions is currently revealing the presence of similar dense young stellar clusters in their cores (Gatley et al. 1991; McCaughrean et al. 1991; Carpenter, Snell & Schloerb 1991; Rayner, Hodapp & Zinnecker 1991; Lada et al. 1991; Greene & Young 1992; among others). It is possible that the Trapezium Cluster star-forming region is prototypical of this mode of high and low mass star formation in a dense cluster, emphasizing

the importance of understanding star formation in this environment.

The structure of the chapter is as follows. In §2.2, we describe near-infrared aperture photometry of stars in the Trapezium Cluster itself as well as in a region surrounding the cluster. We also discuss *I*-band photometry obtained in order to analyse the infrared data. The data are used to investigate stellar masses, ages, extinctions, and infrared excesses in §2.3. We discuss the results obtained in this study in §2.4 in the context of the star formation history of the region.

2.2 Observations

2.2.1 Near-Infrared Photometry

The Trapezium Cluster Sample

JHK photometry of 126 stars in the Trapezium Cluster within 5' of Θ^1 Ori C has been obtained using a single-channel infrared photometer attached to the ANU 2.3m telescope at Siding Spring Observatory during the periods 1989 November to 1990 February and 1990 November to 1991 February. Table 2.1 lists these stars together with their positions from Jones & Walker (1988, hereafter JW) and HAB, their measured infrared magnitudes, and their associated errors. The observed data were obtained on the MSO system (Hyland, Jones & Mitchell 1982) and converted from the MSO to the AAO system using standard transformation equations (Bessell & Brett 1988) to aid comparisons with previous work. The Trapezium cluster stars observed were selected from the HAB sample which is derived from infrared raster scan images. The spatial distribution of the full HAB sample is shown in Figure 2.1 with the stars in our sample indicated. Our sample includes ~ 15 of the reddest Trapezium Cluster stars, and probes to within $\sim 25''$ (~ 0.05 pc) of Θ^1 Ori C. Approximately half of our sample are not visible on the JW *I*-band images.

The standard chopped photometry technique used involves alternate measurements of [object + sky] and [sky] signals. In the brightest regions of the Orion Nebula, sky measurements are dominated by thermal bremsstrahlung from the nebula, even in the near-infrared. This is the major source of photometric error for stars in the central region with $K \geq 9$ mag and significantly increases the difficulty in measuring stars fainter than $K \sim 11$ mag. Accurate measurement of these fainter Trapezium Cluster stars necessitated careful consideration for each source of the chop angle, chop displacement, and aperture size. The adopted values were chosen in order to equalize the signal strength referred to sky positions on either side of the object and, where critical, are listed in columns 7–9 of Table 2.1. This criterion leads to accurate results only if the nebula gradient in the chop direction is linear. We associate an uncertainty in *J-H* and *H-K* of ± 0.10 mag with the measurements

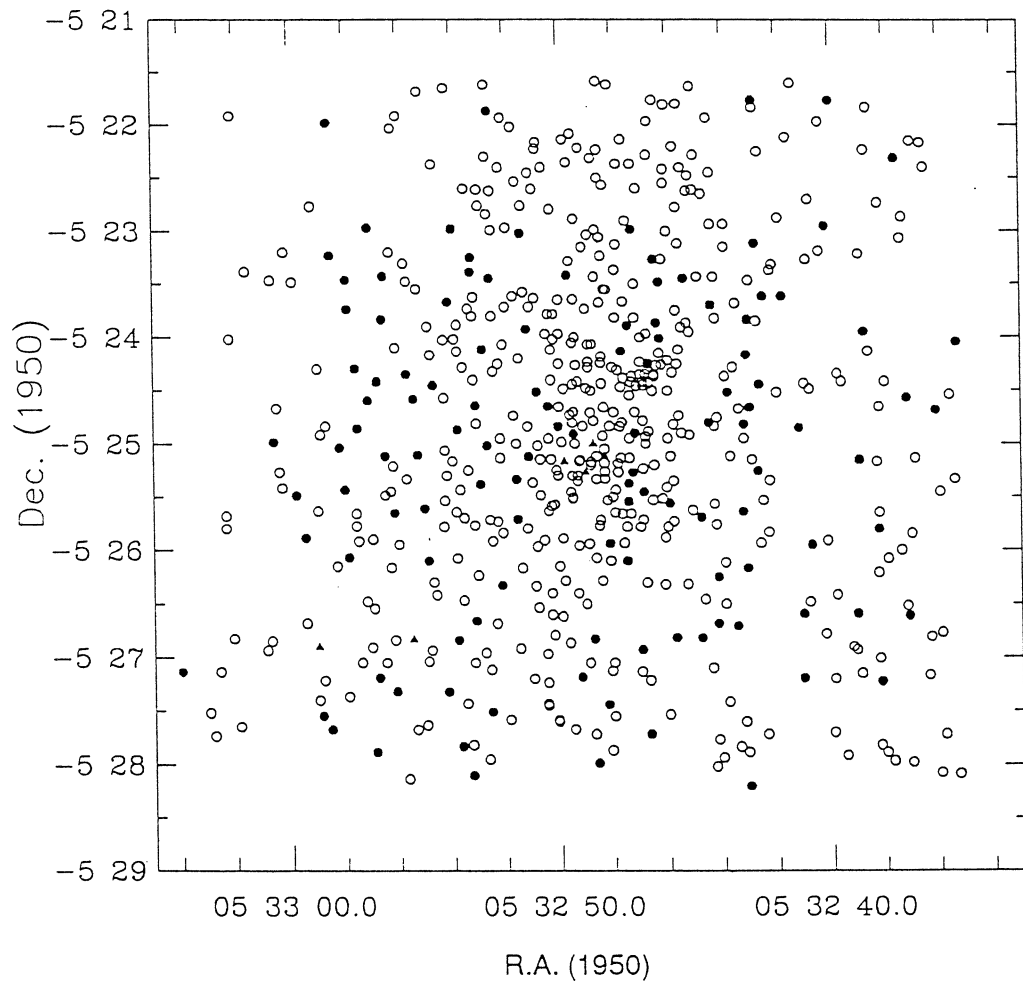


Figure 2.1: Spatial distribution of Hyland, Allen & Bailey (1993) sample with Trapezium Cluster sample observed here indicated by filled circles. The Θ^1 Ori and Θ^2 Ori stars are indicated by filled triangles.

of these program stars.

Source confusion due to the crowded nature of the inner regions of the Trapezium Cluster was also a problem. Our sample of Trapezium Cluster objects excludes most stars in the extremely crowded central region within $\sim 25''$ of Θ^1 Ori C and all stars with neighbors closer than $\sim 5''$. Thus, the combination of nebula brightness and source crowding has prevented us from completely probing the core region of the cluster.

The Outer Annulus Sample

A second sample of 115 stars within an annulus between $6'$ and $8'$ in radius from Θ^1 Ori C was selected from the JW proper motion membership survey in order to compare the Trapezium Cluster stars with their local stellar environment. We refer to this region as the 'outer annulus' in what follows. This region was selected to test whether radial gradients exist in the nature of the stellar population; we examine this below. *JHK* photometry for stars in the outer annulus were obtained with the same instrumental setup described above between 1990 November and 1991 January. These data are listed in Table 2.2.

The *I* band-selected outer annulus sample can only be properly compared with the near-infrared-selected Trapezium Cluster sample if the outer annulus sample is shown to be complete to some near-infrared level. We have attempted to do this by using the single channel infrared photometer on the ANU 2.3m telescope in 1990 December to scan a mosaic of $2'$ square regions covering a significant fraction of the outer annulus region in the *K* band. The total area scanned is shown in Figure 2.2 where the boundaries of the outer annulus are also indicated. The *K* scans were measured through a $7''$ circular aperture on a $3''$ grid. The alt-azimuth telescope was drifted in declination for the duration of one scan line while the infrared signal was averaged over each pixel interval. The telescope was then stepped in right ascension to the start of the next scan line and the procedure repeated. Comparison with aperture photometry of the outer annulus stars (Table 2.2) showed the scans to be complete to a 3σ detection limit of $K \approx 10.5$ mag. Only four new sources were discovered in this way. We therefore conclude that the JW sample is essentially complete to $K \approx 10.5$ mag in the outer annulus region and can be used with confidence in comparisons with the HAB Trapezium Cluster sample.

2.2.2 *I*-band Photometry

The JW *I* magnitudes are estimated from photographic plates which have limited dynamic range. Therefore, the measured magnitudes are of uncertain accuracy. We have used the increased dynamic range of modern CCDs to derive new *I* magnitudes

Table 2.1: Near-Infrared Photometry of Trapezium Cluster stars

Name ⁽¹⁾			RA (1950) Dec		K	$(J - H)_{AAO}$	$H - K$	Ap(")	Throw(")	PA(°)
(1)			(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
JW226	...	HAB1	5 32 35.3	-5 24 03	9.0	1.93 $\pm$ 0.10	1.27 $\pm$ 0.10	10	15	0
...	...	HAB9	5 32 36.1	-5 24 41	11.7	1.26 $\pm$ 0.10	0.67 $\pm$ 0.10	10	12	0
JW251	...	HAB18	5 32 37.1	-5 26 37	11.3	1.24 $\pm$ 0.10	0.39 $\pm$ 0.10	10	15	0
...	...	HAB19	5 32 37.2	-5 24 34	11.6	1.02 $\pm$ 0.10	0.37 $\pm$ 0.10	10	12	0
JW261	...	HAB24	5 32 37.6	-5 22 19	10.6	1.29 $\pm$ 0.10	0.85 $\pm$ 0.10	10	15	0
JW273	P1746	HAB30	5 32 38.2	-5 27 14	7.5	0.93 $\pm$ 0.05	0.68 $\pm$ 0.05	15	...	...
JW276	...	HAB35	5 32 38.2	-5 25 48	11.1	0.82 $\pm$ 0.10	0.27 $\pm$ 0.10	10	12	45
JW286	...	HAB41	5 32 38.8	-5 23 57	9.1	1.75 $\pm$ 0.10	0.78 $\pm$ 0.10	10	15	0
JW289	...	HAB43	5 32 38.9	-5 25 09	12.0	1.15 $\pm$ 0.10	0.59 $\pm$ 0.10	15	20	0
JW291	P1754	HAB45	5 32 39.0	-5 26 36	10.7	0.88 $\pm$ 0.10	0.17 $\pm$ 0.10	15	20	350
...	...	HAB54	5 32 40.0	-5 21 46	12.3	...	0.61 $\pm$ 0.10	15	...	...
...	...	HAB56	5 32 40.2	-5 22 57	10.6	...	1.59 $\pm$ 0.10	15	...	...
JW314	...	HAB62	5 32 40.7	-5 25 57	11.9	1.02 $\pm$ 0.10	0.52 $\pm$ 0.10	10	15	...
JW322	...	HAB66	5 32 41.1	-5 26 36	10.9	0.93 $\pm$ 0.10	0.83 $\pm$ 0.10	10	15	...
JW323	...	HAB67	5 32 41.1	-5 27 12	11.0	1.20 $\pm$ 0.05	0.44 $\pm$ 0.05	10	15	...
...	...	HAB68	5 32 41.2	-5 24 51	10.5	1.46 $\pm$ 0.10	0.63 $\pm$ 0.10	10	10	0
...	...	HAB71	5 32 41.8	-5 23 37	10.3	1.49 $\pm$ 0.10	1.10 $\pm$ 0.10	10	...	...
...	...	HAB79	5 32 42.5	-5 23 37	10.6	1.74 $\pm$ 0.10	1.24 $\pm$ 0.10	10	10	...
JW340	...	HAB83	5 32 42.6	-5 24 27	10.9	1.13 $\pm$ 0.10	0.40 $\pm$ 0.10	5	10	10
JW341	...	HAB86	5 32 42.7	-5 25 15	8.5	1.11 $\pm$ 0.05	0.66 $\pm$ 0.06	15	...	...
JW343	...	HAB88	5 32 42.8	-5 23 07	10.2	1.23 $\pm$ 0.10	0.57 $\pm$ 0.10	10	15	...
JW344	...	HAB87	5 32 42.8	-5 21 46	10.5	1.19 $\pm$ 0.10	0.62 $\pm$ 0.10	10	12	0

Table 2.1 (continued): Near-Infrared Photometry of Trapezium Cluster stars

Name ⁽¹⁾			RA (1950) Dec		<i>K</i>	$(J - H)_{AAO}$	$H - K$	Ap(")	Throw(")	PA(°)
(1)			(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
JW345	P1783	HAB93	5 32 43.0	-5 24 39	9.2	1.01 ±0.10	0.40 ±0.10	5	10	10
...	...	HAB92	5 32 43.1	-5 24 10	10.3	...	1.47 ±0.10	10	15	...
JW347	P1782	HAB91	5 32 43.1	-5 23 50	9.7	0.99 ±0.10	0.51 ±0.10	10	10	...
JW348	P1785	HAB96	5 32 43.1	-5 28 12	8.2	1.02 ±0.05	0.65 ±0.10	15	20	0
JW349	...	HAB94	5 32 43.1	-5 26 10	11.3	...	1.32 ±0.10	10	...	...
...	...	HAB97	5 32 43.2	-5 24 49	10.0	...	...	10	...	...
JW352	P1784	HAB100	5 32 43.2	-5 25 38	7.8	0.91 ±0.05	0.23 ±0.05	10	...	...
JW356	...	HAB103	5 32 43.5	-5 26 42	9.2	1.50 ±0.10	0.91 ±0.10	15	...	...
...	...	HAB107	5 32 43.8	-5 24 31	9.7	...	2.06 ±0.10	5	10	350
JW366	...	HAB117	5 32 44.2	-5 26 15	11.3	0.55 ±0.10	0.51 ±0.10	10	...	45
...	...	HAB118	5 32 44.2	-5 26 41	11.8	1.78 ±0.13	1.37 ±0.10	7	7	300
...	...	HAB126	5 32 44.4	-5 23 42	12.6	0.76 ±0.10	1.08 ±0.10	5	10	90
...	...	HAB130	5 32 44.5	-5 24 48	9.6	1.72 ±0.10	1.08 ±0.10	5	7	330
JW378	P1808	HAB133	5 32 44.8	-5 25 42	9.4	...	...	15	20	...
...	...	HAB134	5 32 44.8	-5 26 49	11.0	...	4.71 ±0.17	10	10	30
...	...	HAB146	5 32 45.4	-5 23 27	9.9	4.52 ±0.26	2.14 ±0.10	7	10	60
JW401	...	HAB160	5 32 45.7	-5 26 49	8.9	1.04 ±0.05	0.52 ±0.05	10	...	...
JW409	P1824	HAB164	5 32 45.9	-5 25 34	9.4	1.16 ±0.10	0.56 ±0.10	5	10	...
...	...	HAB178	5 32 46.3	-5 23 29	11.1	...	...	5	10	90
JW423	P1819	HAB179	5 32 46.3	-5 24 01	8.4	1.16 ±0.05	0.91 ±0.05	5	10	90
...	...	HAB183	5 32 46.4	-5 23 52	7.0	3.71 ±0.05	2.51 ±0.05	5	10	90
...	...	HAB185	5 32 46.5	-5 23 16	9.6	2.20 ±0.10	1.21 ±0.10	10	...	...

Table 2.1 (continued): Near-Infrared Photometry of Trapezium Cluster stars

Name ⁽¹⁾ (1)	RA (1950) (2)	Dec (3)	<i>K</i> (4)	$(J - H)_{AAO}$ (5)	$H - K$ (6)	A_p (") (7)	Throw(") (8)	PA(°) (9)
BN ...	HAB193	5 32 46.7 -5 24 15	5.1	...	...	7	10	315
...	HAB198	5 32 46.7 -5 27 43	10.6	1.00 ±0.10	0.55 ±0.10	10	...	0
JW441 P1843	HAB209	5 32 46.9 -5 25 27	9.2	1.13 ±0.10	0.54 ±0.10	5	...	330
JW443 ...	HAB217	5 32 47.0 -5 26 56	10.8	0.44 ±0.10	0.44 ±0.10	10	...	...
...	HAB223	5 32 47.2 -5 24 54	10.4	...	1.24 ±0.10	5	7	290
JW451 ...	HAB224	5 32 47.3 -5 25 16	10.3	1.48 ±0.10	0.86 ±0.10	5	7	180
...	HAB226	5 32 47.3 -5 22 59	10.2	2.23 ±0.10	1.15 ±0.10	10	...	...
JW455 ...	HAB234	5 32 47.5 -5 25 22	10.0	1.47 ±0.10	0.83 ±0.10	5	7	270
JW456 P1844	HAB236	5 32 47.4 -5 25 33	9.3	0.76 ±0.10	0.39 ±0.10	5	7	330
...	HAB237	5 32 47.5 -5 26 06	9.9	-0.19 ±0.10	1.00 ±0.10	10	12	110
JW457 P1837	HAB239	5 32 47.5 -5 23 53	9.6	0.99 ±0.10	0.31 ±0.10	5	12	350
JW467 P1838	HAB254	5 32 47.9 -5 24 08	8.1	1.52 ±0.05	0.92 ±0.05	5	12	60
JW480 P1871	HAB269	5 32 48.1 -5 25 56	10.0	0.99 ±0.10	0.23 ±0.10	5	7	50
Theta1A P1865	HAB273	5 32 48.3 -5 25 07	5.9	0.09 ±0.05	0.33 ±0.05	10	10	180
JW482 ...	HAB277	5 32 48.2 -5 27 27	9.6	0.84 ±0.10	0.86 ±0.10	10	10	315
...	HAB296	5 32 48.6 -5 27 59	11.4	3.89 ±0.13	0.96 ±0.10	10	15	90
Theta1B P1863	HAB299	5 32 48.7 -5 25 00	6.2	...	...	7	10	180
JW509 ...	HAB306	5 32 48.7 -5 26 50	10.8	1.59 ±0.05	0.87 ±0.05	10	12	60
Theta1C P1891	HAB315	5 32 49.0 -5 25 16	4.4	...	...	7	10	180
...	HAB323	5 32 49.2 -5 27 11	11.3	-0.51 ±0.20	1.27 ±0.21	10	15	10
JW533 P1888	HAB338	5 32 49.5 -5 24 54	9.4	1.39 ±0.10	0.67 ±0.10	5	12	90
JW544 P1884	HAB349	5 32 49.7 -5 23 25	8.1	0.94 ±0.05	0.35 ±0.05	10	10	...

Table 2.1 (continued): Near-Infrared Photometry of Trapezium Cluster stars

Name ⁽¹⁾			RA (1950) Dec		<i>K</i>	$(J - H)_{AAO}$	$H - K$	Ap(")	Throw(")	PA(°)
(1)			(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Theta1D	P1889	HAB350	5 32 49.8	-5 25 10	5.7	0.15 ±0.05	0.14 ±0.05	10	10	180
JW553	P1911	HAB365	5 32 50.0	-5 24 50	8.9	1.14 ±0.05	0.52 ±0.05	5	12	90
JW567	P1910	HAB384	5 32 50.4	-5 24 39	7.8	0.80 ±0.05	0.31 ±0.06	5	12	90
JW589	P1925	HAB397	5 32 50.8	-5 24 31	8.5	1.03 ±0.05	0.27 ±0.05	5	12	90
JW596	P1927	HAB406	5 32 51.2	-5 25 07	7.3	1.54 ±0.05	1.33 ±0.05	10	...	...
JW600	...	HAB408	5 32 51.2	-5 23 55	10.2	1.00 ±0.10	0.44 ±0.10	10	10	...
JW606	...	HAB412	5 32 51.4	-5 23 01	10.0	1.15 ±0.10	0.63 ±0.10	10	15	...
JW607	...	HAB418	5 32 51.6	-5 25 43	10.2	1.64 ±0.10	0.98 ±0.10	5	10	0
JW610	P1928	HAB417	5 32 51.6	-5 25 20	10.6	2.80 ±0.10	1.31 ±0.10	10	12	0
JW622	P1940	HAB431	5 32 52.2	-5 26 20	9.0	1.33 ±0.10	0.75 ±0.10	10	12	330
...	...	HAB438	5 32 52.6	-5 21 52	10.8	2.52 ±0.10	1.42 ±0.10	10	15	90
JW636	...	HAB444	5 32 52.6	-5 27 31	10.2	1.13 ±0.10	0.44 ±0.10	10	15	...
JW637	P1939	HAB440	5 32 52.6	-5 23 27	9.9	1.40 ±0.10	0.21 ±0.10	10	12	10
...	...	HAB448	5 32 52.7	-5 25 01	10.4	...	0.84 ±0.10	10	...	...
JW645	P1959	HAB451	5 32 52.9	-5 24 07	9.8	1.32 ±0.10	0.42 ±0.10	10	10	...
JW648	P1960	HAB452	5 32 53.0	-5 25 23	9.2	1.19 ±0.10	0.61 ±0.10	10	12	25
JW657	...	HAB459	5 32 53.1	-5 24 38	11.4	...	1.18 ±0.10	10	12	90
JW658	...	HAB461	5 32 53.1	-5 26 39	9.3	0.84 ±0.10	0.89 ±0.10	10	15	110
JW662	...	HAB463	5 32 53.3	-5 23 15	10.3	1.18 ±0.10	0.69 ±0.10	10	15	295
...	...	HAB466	5 32 53.3	-5 28 06	12.2	0.89 ±0.10	0.42 ±0.10	10	15	90
JW663	...	HAB467	5 32 53.3	-5 23 23	10.9	1.44 ±0.10	0.30 ±0.10	10	12	300
JW674	...	HAB476	5 32 53.7	-5 27 50	9.9	1.27 ±0.10	0.73 ±0.10	10	...	...

Table 2.1 (continued): Near-Infrared Photometry of Trapezium Cluster stars

Name ⁽¹⁾		RA (1950)	Dec	<i>K</i>	(<i>J</i> − <i>H</i>) _{AAO}	<i>H</i> − <i>K</i>	Ap(")	Throw(")	PA(°)	
(1)		(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
...	...	HAB479	5 32 53.8	−5 24 52	10.8	1.76 ±0.10	0.69 ±0.10	10	...	...
JW678	P1974	HAB483	5 32 53.8	−5 26 50	9.8	0.82 ±0.10	0.15 ±0.10	10	11	40
JW684	...	HAB484	5 32 54.0	−5 22 59	10.3	1.54 ±0.10	1.06 ±0.10	10	...	...
JW687	...	HAB487	5 32 54.1	−5 23 40	9.6	1.71 ±0.10	0.98 ±0.10	10	10	...
JW690	...	HAB489	5 32 54.2	−5 27 19	10.5	0.98 ±0.10	0.33 ±0.10	10	...	...
...	...	HAB496	5 32 54.7	−5 24 27	10.9	1.21 ±0.10	0.59 ±0.10	10	12	0
...	...	HAB501	5 32 54.9	−5 26 06	9.5	1.15 ±0.10	0.57 ±0.10	5	10	330
JW721	P1990	HAB505	5 32 55.0	−5 25 37	10.1	1.12 ±0.10	0.51 ±0.10	10	15	0
JW723	...	HAB508	5 32 55.3	−5 25 06	9.6	2.99 ±0.10	1.08 ±0.10	10	10	0
JW726	...	HAB510	5 32 55.4	−5 24 35	10.3	1.94 ±0.10	0.87 ±0.10	10	...	...
Theta2A	P1993	HAB511	5 32 55.5	−5 26 50	4.9	−0.03 ±0.05	0.06 ±0.05	15	...	...
...	...	HAB512	5 32 55.7	−5 24 21	10.7		1.54 ±0.10	10	...	...
JW737	...	HAB520	5 32 56.1	−5 27 19	10.7		0.84 ±0.10	10	11	320
JW740	...	HAB523	5 32 56.2	−5 25 39	10.4	0.63 ±0.10	0.68 ±0.10	10	15	70
...	...	HAB528	5 32 56.5	−5 25 07	11.2	2.09 ±0.10	1.23 ±0.10	10	12	330
JW748	...	HAB531	5 32 56.6	−5 23 26	10.9	0.93 ±0.10	0.56 ±0.10	10	...	...
...	...	HAB532	5 32 56.6	−5 23 50	11.1	0.53 ±0.10	0.68 ±0.10	10	15	45
...	...	HAB533	5 32 56.8	−5 24 25	10.1	1.84 ±0.10	1.22 ±0.10	5	15	...
JW750	P2012	HAB534	5 32 56.8	−5 27 12	10.1	0.95 ±0.10	0.39 ±0.10	10	11	90
...	...	HAB535	5 32 56.9	−5 27 53	12.1	0.84 ±0.10	0.32 ±0.10	10	15	80
...	...	HAB539	5 32 57.1	−5 22 58	10.7	2.84 ±0.12	1.98 ±0.10	7	15	300
JW761	...	HAB540	5 32 57.1	−5 24 36	11.1	0.76 ±0.10	1.31 ±0.10	10	15	...

Table 2.1 (continued): Near-Infrared Photometry of Trapezium Cluster stars

Name ⁽¹⁾			RA (1950) Dec		K	$(J - H)_{AAO}$	$H - K$	Ap(")	Throw(")	PA(°)
(1)			(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
JW766	...	HAB544	5 32 57.5	-5 24 51	9.0	1.36 ±0.10	0.64 ±0.10	10	...	...
JW770	...	HAB547	5 32 57.6	-5 24 18	10.0	1.12 ±0.10	0.66 ±0.10	10	...	...
JW775	...	HAB548	5 32 57.9	-5 26 04	10.4	1.24 ±0.10	1.03 ±0.10	10	15	...
JW776	...	HAB551	5 32 57.9	-5 23 44	9.9	0.97 ±0.10	0.67 ±0.10	10	15	20
JW777	...	HAB550	5 32 57.9	-5 23 28	9.2	1.66 ±0.10	0.70 ±0.10	10	...	...
...	...	HAB552	5 32 58.0	-5 25 26	10.3	0.75 ±0.10	0.88 ±0.10	10	15	...
JW782	...	HAB553	5 32 58.2	-5 25 02	9.7	1.52 ±0.10	0.90 ±0.10	10	15	...
JW791	...	HAB555	5 32 58.5	-5 23 14	9.3	1.58 ±0.10	0.79 ±0.10	10	15	...
JW792	...	HAB556	5 32 58.5	-5 27 40	9.7	1.29 ±0.10	0.48 ±0.10	10	11	90
JW793	...	HAB557	5 32 58.6	-5 21 59	10.1	1.59 ±0.10	0.64 ±0.10	10	15	0
JW799	P2032	HAB561	5 32 58.9	-5 27 33	8.6	0.76 ±0.05	0.35 ±0.05	10	11	90
Theta2B	P2031	HAB564	5 32 59.0	-5 26 54	6.3	-0.07 ±0.05	0.09 ±0.05	15	...	...
JW807	...	HAB567	5 32 59.5	-5 25 53	11.5	1.06 ±0.10	0.39 ±0.10	10	15	25
JW810	...	HAB569	5 32 59.8	-5 25 29	9.2	1.24 ±0.10	0.77 ±0.10	10	15	0
JW825	...	HAB576	5 33 00.6	-5 24 59	10.1	2.10 ±0.10	0.95 ±0.10	10	15	90
...	P2085	...	5 33 04.0	-5 27 08	7.5	0.11 ±0.05	0.15 ±0.05	15	...	...

1: JW = Jones & Walker (1988); P = Parenago (1954); HAB = Hyland, Allen & Bailey (1993)

Table 2.2: Near-Infrared Photometry of Outer Annulus Stars

Name ⁽¹⁾ (1)	K (2)	$(J - H)_{AAO}$ (3)	$H - K$ (4)
JW71	...	12.3	0.81 $\pm$ 0.10
JW75	P1587	8.9	0.75 $\pm$ 0.05
JW77	P1595	11.0	0.86 $\pm$ 0.10
JW81	P1600	10.5	0.87 $\pm$ 0.05
JW83	...	11.0	1.10 $\pm$ 0.10
JW86	...	11.6	1.56 $\pm$ 0.10
JW90	...	12.5	0.76 $\pm$ 0.10
JW92	...	12.6	0.76 $\pm$ 0.10
JW98	...	11.6	0.89 $\pm$ 0.10
JW99	...	10.0	0.91 $\pm$ 0.05
JW104	...	12.0	0.88 $\pm$ 0.10
JW106	...	11.1	0.75 $\pm$ 0.10
JW108	P1623	7.5	0.51 $\pm$ 0.05
JW110	...	13.7	0.62 $\pm$ 0.10
JW113	...	10.4	1.06 $\pm$ 0.05
JW116	P1633	10.2	0.70 $\pm$ 0.05
JW117	...	10.3	1.00 $\pm$ 0.05
JW118	...	12.2	0.67 $\pm$ 0.10
JW123	P1642	9.7	1.11 $\pm$ 0.05
JW124	...	11.5	0.69 $\pm$ 0.10
JW134	...	12.2	1.07 $\pm$ 0.10
JW138	...	12.0	0.79 $\pm$ 0.10
JW141	...	11.9	0.95 $\pm$ 0.10
JW144	...	12.6	0.82 $\pm$ 0.10
JW147	...	12.0	0.69 $\pm$ 0.10
JW148	...	11.1	1.30 $\pm$ 0.10
JW149	...	12.2	1.00 $\pm$ 0.10
JW150	...	9.3	1.28 $\pm$ 0.05
JW155	...	12.0	0.74 $\pm$ 0.10
JW158	...	10.5	0.86 $\pm$ 0.05
JW164	...	11.2	0.94 $\pm$ 0.10
JW177	...	11.1	1.10 $\pm$ 0.10
JW188	...	12.1	0.69 $\pm$ 0.10
JW207	...	11.9	1.00 $\pm$ 0.10
JW209	...	12.1	0.61 $\pm$ 0.10
JW218	...	12.2	0.70 $\pm$ 0.10
JW222	...	10.6	1.06 $\pm$ 0.06
JW231	...	11.6	0.92 $\pm$ 0.10
JW232	P1727	9.1	0.86 $\pm$ 0.05

Table 2.2 (continued): Near-Infrared Photometry of Outer Annulus Stars

Name ⁽¹⁾ (1)	K (2)	$(J - H)_{AAO}$ (3)	$H - K$ (4)	
JW235	...	10.4	1.02 ±0.10	0.70 ±0.05
JW239	P1725	10.1	0.87 ±0.05	0.35 ±0.05
JW253	...	9.5	1.58 ±0.05	0.99 ±0.05
JW277	...	10.5	1.59 ±0.05	1.13 ±0.05
JW294	...	12.4	0.74 ±0.10	0.43 ±0.10
JW307	...	13.1	0.79 ±0.10	0.27 ±0.10
JW329	...	12.4	0.78 ±0.10	0.38 ±0.10
JW330	P1773	9.9	0.72 ±0.05	0.21 ±0.05
JW364	P1799	8.7	0.67 ±0.05	0.31 ±0.05
JW371	...	11.8	0.75 ±0.10	0.41 ±0.10
JW379	...	11.9	0.74 ±0.10	0.46 ±0.10
JW380	...	11.1	0.71 ±0.10	0.34 ±0.10
JW381	P1809	9.7	1.05 ±0.05	0.60 ±0.05
JW383	...	11.4	0.91 ±0.10	0.31 ±0.10
JW386	...	9.6	1.37 ±0.05	0.54 ±0.05
JW388	...	10.4	1.01 ±0.05	0.39 ±0.05
JW416	...	11.7	0.71 ±0.10	0.24 ±0.10
JW421	P1827	8.8	0.94 ±0.05	0.61 ±0.05
JW428	...	11.5	0.86 ±0.10	0.25 ±0.10
JW517	...	12.4	0.63 ±0.10	0.33 ±0.10
JW528	...	10.7	1.30 ±0.05	0.70 ±0.05
JW566	...	8.7	1.81 ±0.05	1.06 ±0.05
JW590	...	11.9	0.66 ±0.10	0.38 ±0.10
JW601	P1921	11.0	0.56 ±0.05	0.16 ±0.05
JW612	...	11.7	0.90 ±0.10	0.56 ±0.10
JW633	...	11.2	1.43 ±0.10	0.77 ±0.10
JW655	...	8.0	1.30 ±0.05	0.57 ±0.05
JW664	...	10.7	1.12 ±0.05	0.37 ±0.05
JW673	P1976	9.9	0.99 ±0.05	0.63 ±0.05
JW715	...	12.1	0.58 ±0.12	0.52 ±0.11
JW727	...	10.7	1.03 ±0.05	0.55 ±0.05
JW729	...	11.6	0.94 ±0.10	0.48 ±0.10
JW747	P2001	9.5	0.61 ±0.05	0.16 ±0.05
JW751	...	10.2	1.08 ±0.05	0.53 ±0.05
JW753	...	10.7	0.92 ±0.05	0.34 ±0.05
JW767	...	9.7	1.25 ±0.05	0.87 ±0.05
JW788	...	11.0	0.92 ±0.10	0.52 ±0.10
JW789	...	12.7	0.76 ±0.10	0.50 ±0.10

Table 2.2 (continued): Near-Infrared Photometry of Outer Annulus Stars

Name ⁽¹⁾ (1)	K (2)	$(J - H)_{AAO}$ (3)	$H - K$ (4)
JW805	...	11.0	1.19 $\pm$ 0.14
JW811	...	9.3	1.20 $\pm$ 0.05
JW812	...	11.0	0.78 $\pm$ 0.10
JW824	...	9.6	1.35 $\pm$ 0.05
JW836	...	10.3	1.04 $\pm$ 0.05
JW843	...	11.3	0.82 $\pm$ 0.10
JW854	...	10.7	1.18 $\pm$ 0.05
JW863	...	10.7	1.00 $\pm$ 0.05
JW878	...	11.4	0.66 $\pm$ 0.10
JW880	...	11.8	0.70 $\pm$ 0.10
JW883	...	10.3	0.98 $\pm$ 0.05
JW886	...	9.9	1.24 $\pm$ 0.05
JW889	P2098	12.0	0.52 $\pm$ 0.10
JW895	P2099	10.0	1.20 $\pm$ 0.05
JW897	...	12.8	1.10 $\pm$ 0.11
JW898	...	11.2	0.81 $\pm$ 0.10
JW907	P2112	10.9	0.70 $\pm$ 0.05
JW910	...	12.1	0.98 $\pm$ 0.10
JW916	...	12.0	0.66 $\pm$ 0.10
JW929	...	13.4	0.58 $\pm$ 0.10
JW930	...	11.7	0.76 $\pm$ 0.10
JW931	...	8.8	1.95 $\pm$ 0.05
JW933	...	11.2	0.81 $\pm$ 0.10
JW939	...	12.9	1.00 $\pm$ 0.10
JW942	...	12.1	1.39 $\pm$ 0.10
JW945	P2149	8.9	0.93 $\pm$ 0.05
JW947	...	12.1	0.60 $\pm$ 0.10
JW950	P2157	11.1	0.44 $\pm$ 0.10
JW951	...	11.8	0.97 $\pm$ 0.10
JW954	P2166	11.1	0.90 $\pm$ 0.10
JW959	P2167	8.6	0.63 $\pm$ 0.05
JW962	P2175	10.1	0.92 $\pm$ 0.05
JW963	P2164	8.8	0.58 $\pm$ 0.05
JW969	...	11.3	1.18 $\pm$ 0.10
JW980	...	10.8	0.84 $\pm$ 0.05
JW981	P2199	10.7	0.81 $\pm$ 0.05
JW990	...	11.5	0.67 $\pm$ 0.10
JW998	P2209	11.0	0.84 $\pm$ 0.10

1: JW = Jones & Walker (1988); P = Parenago (1954)

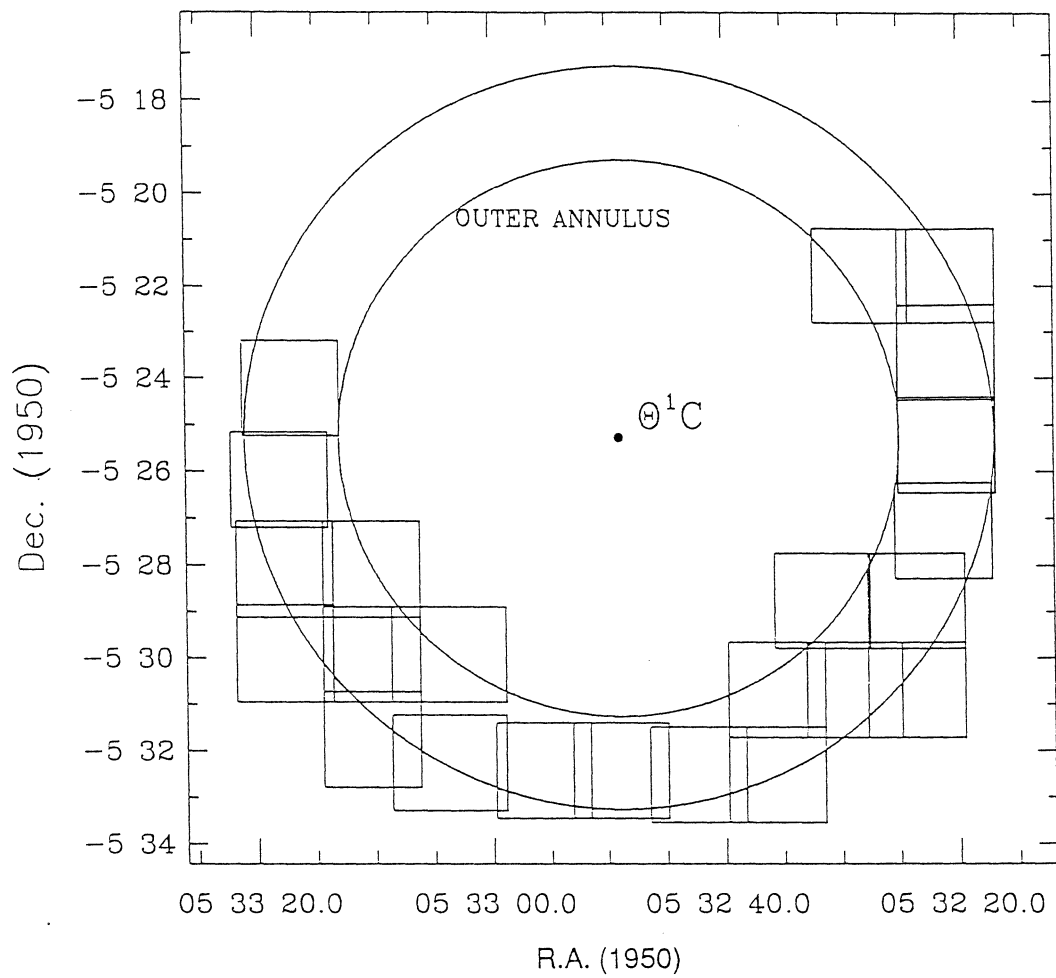


Figure 2.2: Outer annulus region represented by solid circles with coverage of *K*-band scans indicated by solid squares.

for the stars in our two samples. We obtained I -band CCD images of a $9' \times 9'$ square region containing our Trapezium Cluster and outer annulus samples, along with E-region standard frames, in November 1991 using a GEC CCD on the 40" ANU telescope at Siding Spring Observatory. Stellar I magnitudes were measured using the Personal Astronomical WorkStation Photometric (PAWSPHOT) reduction package (Mighell 1989a,b and references therein) which uses a non-linear least squares fitting algorithm and Moffatt curves (Moffatt 1969) to model the stellar point spread function on a tilted sky background. It is designed for use in crowded stellar environments. In total, we have I magnitude estimates for 108 of the 115 outer annulus stars, and for 91 of the 126 Trapezium Cluster stars. We measure stars to $I \sim 17$ mag in both regions using PAWSPHOT, compared with JW whose detection limit is $I \sim 13$ mag in the central region near the Trapezium and $I \sim 16$ mag at greater radii. The fainter limiting magnitude of our detections has allowed the measurement of 15 HAB infrared sources in the Trapezium Cluster region that were not included in the JW survey. The magnitudes and associated errors for stars in each region are given in Tables 2.3 and 2.4, along with the corresponding JW I magnitudes where available. The errors listed in Tables 2.3 and 2.4 reflect the problems presented by the nebulosity for accurate background determination. The correspondence between our I magnitudes and the JW magnitudes (Figures 2.3 and 2.4) is reasonable in the outer annulus, as is expected from the relatively faint nebulosity in this area. The difference in the values obtained for JW811 is considered real here and may reflect intrinsic stellar variability. It is evident from Figure 2.3 that a significant linear relationship exists for stars fainter than $I \sim 12$ mag. This most likely reflects non-linearity in the photographic fluxes of faint stars immersed in the strong nebular background. It highlights the importance of removing background effects as much as possible. Thus, the use of CCDs in the current work to improve this procedure has allowed us to reach to fainter magnitudes with greater reliability. The two stars, JW273 and JW467, are brighter here than when measured by JW, possibly also due to intrinsic variability in the stars. We also compare our measured I magnitudes with those obtained by Herbig & Terndrup (1986) for the 21 stars common to both samples (Figure 2.5 and Table 2.3). As mentioned above, the measurements of Herbig & Terndrup were also made from CCD images of the region. The agreement between the two data-sets is very good overall, except for the measurements for JW596 which may again reflect intrinsic stellar variability.

Table 2.3: *I* Photometry of Trapezium Cluster Stars

Name (1)	I_{PAWS} (2)	I_{JW} (3)	I_{HT} (4)	$(I - J)$ (5)	$(J - K)$ (6)
JW226	15.66 $\pm$ 0.03	15.2	...	3.46 $\pm$ 0.08	3.20 $\pm$ 0.20
HAB9	16.81 $\pm$ 0.06	...	...	3.18 $\pm$ 0.11	1.93 $\pm$ 0.20
HAB19	14.53 $\pm$ 0.02	...	...	1.54 $\pm$ 0.07	1.39 $\pm$ 0.20
JW261	14.25 $\pm$ 0.02	13.9	...	1.51 $\pm$ 0.07	2.14 $\pm$ 0.20
JW273	8.97 $\pm$ 0.39	10.4	...	-0.14 $\pm$ 0.42	1.61 $\pm$ 0.10
JW276	13.93 $\pm$ 0.02	13.8	...	1.74 $\pm$ 0.07	1.09 $\pm$ 0.20
JW286	14.66 $\pm$ 0.03	14.2	...	3.03 $\pm$ 0.08	2.53 $\pm$ 0.20
JW289	16.46 $\pm$ 0.10	15.5	...	2.72 $\pm$ 0.15	1.74 $\pm$ 0.20
JW291	12.75 $\pm$ 0.01	12.9	...	1.00 $\pm$ 0.06	1.05 $\pm$ 0.20
HAB54	17.93 $\pm$ 0.13	...	...	...	...
HAB56	16.56 $\pm$ 0.07	...	...	...	...
JW314	15.87 $\pm$ 0.07	14.2	...	2.43 $\pm$ 0.12	1.54 $\pm$ 0.20
JW322	14.80 $\pm$ 0.01	14.0	...	2.14 $\pm$ 0.06	1.76 $\pm$ 0.20
JW323	13.81 $\pm$ 0.01	13.5	...	1.17 $\pm$ 0.04	1.64 $\pm$ 0.10
HAB68	15.55 $\pm$ 0.06	...	...	2.96 $\pm$ 0.11	2.09 $\pm$ 0.20
JW340	14.39 $\pm$ 0.03	13.6	...	1.96 $\pm$ 0.08	1.53 $\pm$ 0.20
JW341	14.45 $\pm$ 0.03	13.8	...	4.18 $\pm$ 0.06	1.77 $\pm$ 0.11
JW343	13.92 $\pm$ 0.02	13.5	...	1.92 $\pm$ 0.07	1.80 $\pm$ 0.20
JW344	15.59 $\pm$ 0.03	15.0	...	3.28 $\pm$ 0.08	1.81 $\pm$ 0.20
JW345	12.29 $\pm$ 0.02	12.1	12.38	1.68 $\pm$ 0.07	1.41 $\pm$ 0.20
HAB92	16.97 $\pm$ 0.13	...	...	...	...
JW347	12.60 $\pm$ 0.01	12.5	...	1.40 $\pm$ 0.06	1.50 $\pm$ 0.20
JW348	11.06 $\pm$ 0.01	11.4	...	1.19 $\pm$ 0.04	1.67 $\pm$ 0.15
JW349	15.21 $\pm$ 0.05	13.6	...	...	...
JW352	10.38 $\pm$ 0.03	10.3	10.31	1.44 $\pm$ 0.06	1.14 $\pm$ 0.10
JW356	13.71 $\pm$ 0.01	13.6	...	2.10 $\pm$ 0.06	2.41 $\pm$ 0.20
JW366	14.87 $\pm$ 0.04	14.1	...	2.51 $\pm$ 0.09	1.06 $\pm$ 0.20
JW378	12.14 $\pm$ 0.01	12.1	12.18	...	...
HAB146	16.64 $\pm$ 0.11	...	...	0.08 $\pm$ 0.24	6.66 $\pm$ 0.36
JW401	12.40 $\pm$ 0.05	12.5	...	1.94 $\pm$ 0.08	1.56 $\pm$ 0.20

Table 2.3 (continued): *I* Photometry of Trapezium Cluster Stars

Name (1)	I_{PAWS} (2)	I_{JW} (3)	I_{HT} (4)	$(I - J)$ (5)	$(J - K)$ (6)
JW409	12.20 $\pm$ 0.05	12.5	12.88	1.08 $\pm$ 0.10	1.72 $\pm$ 0.20
HAB178	16.56 $\pm$ 0.09	...	...	...	...
JW423	12.37 $\pm$ 0.12	12.1	12.30	1.90 $\pm$ 0.15	2.07 $\pm$ 0.10
HAB183	15.92 $\pm$ 0.05	...	...	2.70 $\pm$ 0.08	6.22 $\pm$ 0.10
HAB198	14.95 $\pm$ 0.02	...	...	2.80 $\pm$ 0.07	1.55 $\pm$ 0.20
JW443	13.93 $\pm$ 0.02	13.4	...	2.25 $\pm$ 0.07	0.88 $\pm$ 0.20
HAB237	14.88 $\pm$ 0.05	...	...	4.17 $\pm$ 0.10	0.81 $\pm$ 0.20
JW457	12.32 $\pm$ 0.02	12.2	12.32	1.42 $\pm$ 0.07	1.30 $\pm$ 0.20
JW467	12.84 $\pm$ 0.01	14.6	13.19	2.30 $\pm$ 0.04	2.44 $\pm$ 0.10
JW480	12.38 $\pm$ 0.05	12.1	12.48	1.16 $\pm$ 0.08	1.22 $\pm$ 0.20
JW482	13.01 $\pm$ 0.03	13.2	...	1.71 $\pm$ 0.08	1.70 $\pm$ 0.20
HAB296	15.45 $\pm$ 0.02	...	...	-0.80 $\pm$ 0.09	4.85 $\pm$ 0.23
JW509	14.69 $\pm$ 0.03	13.0	...	1.43 $\pm$ 0.06	2.46 $\pm$ 0.10
HAB323	14.41 $\pm$ 0.02	...	...	2.35 $\pm$ 0.12	0.76 $\pm$ 0.41
JW533	12.50 $\pm$ 0.05	12.1	12.50	1.04 $\pm$ 0.10	2.06 $\pm$ 0.20
JW544	10.88 $\pm$ 0.00	11.1	10.94	1.49 $\pm$ 0.03	1.29 $\pm$ 0.10
JW553	12.52 $\pm$ 0.06	12.1	12.35	1.96 $\pm$ 0.08	1.66 $\pm$ 0.10
JW567	10.31 $\pm$ 0.01	10.1	10.11	1.40 $\pm$ 0.04	1.11 $\pm$ 0.11
JW589	11.34 $\pm$ 0.19	11.2	11.33	1.54 $\pm$ 0.22	1.30 $\pm$ 0.10
JW596	11.65 $\pm$ 0.08	12.3	13.35	1.48 $\pm$ 0.11	2.87 $\pm$ 0.10
JW600	14.26 $\pm$ 0.07	13.2	...	2.62 $\pm$ 0.12	1.44 $\pm$ 0.20
JW606	13.64 $\pm$ 0.03	13.5	...	1.86 $\pm$ 0.08	1.78 $\pm$ 0.20
JW607	13.96 $\pm$ 0.08	13.1	13.44	1.14 $\pm$ 0.13	2.62 $\pm$ 0.20
JW610	13.71 $\pm$ 0.04	13.3	13.91	-1.00 $\pm$ 0.09	4.11 $\pm$ 0.20
JW622	12.83 $\pm$ 0.02	12.5	12.80	1.75 $\pm$ 0.07	2.08 $\pm$ 0.20
JW636	13.31 $\pm$ 0.01	13.2	...	1.54 $\pm$ 0.06	1.57 $\pm$ 0.20
JW637	12.94 $\pm$ 0.06	12.9	...	1.43 $\pm$ 0.11	1.61 $\pm$ 0.20
JW645	13.26 $\pm$ 0.01	13.2	13.49	1.72 $\pm$ 0.06	1.74 $\pm$ 0.20
JW648	13.17 $\pm$ 0.03	12.7	13.04	2.17 $\pm$ 0.08	1.80 $\pm$ 0.20
JW657	16.12 $\pm$ 0.06	14.8	...	...	...

Table 2.3 (continued): *I* Photometry of Trapezium Cluster Stars

Name (1)	I_{PAWS} (2)	I_{JW} (3)	I_{HT} (4)	$(I - J)$ (5)	$(J - K)$ (6)
JW662	14.65 $\pm$ 0.03	13.5	...	2.48 $\pm$ 0.08	1.87 $\pm$ 0.20
JW663	14.61 $\pm$ 0.03	13.5	...	1.97 $\pm$ 0.08	1.74 $\pm$ 0.20
JW674	13.69 $\pm$ 0.01	13.3	...	1.79 $\pm$ 0.06	2.00 $\pm$ 0.20
HAB479	15.08 $\pm$ 0.04	...	...	1.83 $\pm$ 0.09	2.45 $\pm$ 0.20
JW678	12.00 $\pm$ 0.08	12.0	12.33	1.23 $\pm$ 0.13	0.97 $\pm$ 0.20
JW684	16.12 $\pm$ 0.34	13.8	...	3.22 $\pm$ 0.39	2.60 $\pm$ 0.20
JW687	14.79 $\pm$ 0.06	13.7	...	2.50 $\pm$ 0.11	2.69 $\pm$ 0.20
JW690	13.58 $\pm$ 0.01	13.3	...	1.77 $\pm$ 0.06	1.31 $\pm$ 0.20
HAB496	15.88 $\pm$ 0.04	...	...	3.18 $\pm$ 0.09	1.80 $\pm$ 0.20
JW721	13.36 $\pm$ 0.76	12.9	13.12	1.63 $\pm$ 0.81	1.63 $\pm$ 0.20
JW723	14.73 $\pm$ 0.06	14.9	...	1.06 $\pm$ 0.11	4.07 $\pm$ 0.20
JW726	15.34 $\pm$ 0.02	14.8	...	2.23 $\pm$ 0.07	2.81 $\pm$ 0.20
JW737	14.49 $\pm$ 0.01	13.9	...	...	...
JW740	14.15 $\pm$ 0.02	12.9	...	2.44 $\pm$ 0.07	1.31 $\pm$ 0.20
JW748	14.53 $\pm$ 0.03	14.0	...	2.14 $\pm$ 0.08	1.49 $\pm$ 0.20
JW750	12.79 $\pm$ 0.03	12.8	...	1.35 $\pm$ 0.08	1.34 $\pm$ 0.20
HAB535	15.18 $\pm$ 0.04	...	...	1.92 $\pm$ 0.09	1.16 $\pm$ 0.20
JW761	17.83 $\pm$ 0.08	16.0	...	4.66 $\pm$ 0.13	2.07 $\pm$ 0.20
JW766	14.03 $\pm$ 0.01	13.1	...	3.03 $\pm$ 0.06	2.00 $\pm$ 0.20
JW770	17.49 $\pm$ 0.07	15.7	...	5.71 $\pm$ 0.12	1.78 $\pm$ 0.20
JW775	15.62 $\pm$ 0.04	13.7	...	2.95 $\pm$ 0.09	2.27 $\pm$ 0.20
JW776	12.85 $\pm$ 0.05	13.5	...	1.31 $\pm$ 0.10	1.64 $\pm$ 0.20
JW777	14.00 $\pm$ 0.04	13.3	...	2.44 $\pm$ 0.09	2.36 $\pm$ 0.20
HAB552	15.34 $\pm$ 0.06	...	...	3.41 $\pm$ 0.11	1.63 $\pm$ 0.20
JW782	14.30 $\pm$ 0.04	14.2	...	2.18 $\pm$ 0.09	2.42 $\pm$ 0.20
JW791	14.34 $\pm$ 0.03	13.9	...	2.67 $\pm$ 0.08	2.37 $\pm$ 0.20
JW792	13.53 $\pm$ 0.02	13.5	...	2.06 $\pm$ 0.07	1.77 $\pm$ 0.20
JW793	14.62 $\pm$ 0.02	14.3	...	2.29 $\pm$ 0.07	2.23 $\pm$ 0.20
JW799	10.99 $\pm$ 0.19	10.7	...	1.28 $\pm$ 0.22	1.11 $\pm$ 0.10
JW825	17.01 $\pm$ 0.04	15.4	...	3.86 $\pm$ 0.09	3.05 $\pm$ 0.20
P2085	11.52 $\pm$ 0.19	...	...	3.76 $\pm$ 0.22	0.26 $\pm$ 0.10

Table 2.4: *I* Photometry of Outer Annulus Stars

Name (1)	I_{PAWS} (2)	I_{JW} (3)	$(I - J)$ (4)	$(J - K)$ (5)
JW71	15.61 $\pm$ 0.02	15.4	2.00 $\pm$ 0.07	1.31 $\pm$ 0.20
JW75	11.27 $\pm$ 0.17	11.4	1.43 $\pm$ 0.20	0.94 $\pm$ 0.10
JW77	13.69 $\pm$ 0.03	13.7	1.57 $\pm$ 0.08	1.12 $\pm$ 0.20
JW81	12.98 $\pm$ 0.02	13.1	1.36 $\pm$ 0.05	1.12 $\pm$ 0.10
JW83	14.82 $\pm$ 0.01	14.6	2.24 $\pm$ 0.06	1.58 $\pm$ 0.20
JW86	16.28 $\pm$ 0.03	15.7	2.21 $\pm$ 0.08	2.47 $\pm$ 0.20
JW90	15.64 $\pm$ 0.02	15.5	1.94 $\pm$ 0.07	1.20 $\pm$ 0.20
JW92	16.11 $\pm$ 0.02	15.9	2.30 $\pm$ 0.07	1.21 $\pm$ 0.20
JW98	14.69 $\pm$ 0.01	14.6	1.86 $\pm$ 0.06	1.23 $\pm$ 0.20
JW99	13.15 $\pm$ 0.02	13.4	1.88 $\pm$ 0.05	1.27 $\pm$ 0.10
JW104	15.09 $\pm$ 0.03	14.8	1.66 $\pm$ 0.08	1.43 $\pm$ 0.20
JW106	13.42 $\pm$ 0.02	13.6	1.34 $\pm$ 0.07	0.98 $\pm$ 0.20
JW110	16.52 $\pm$ 0.03	16.1	1.78 $\pm$ 0.08	1.04 $\pm$ 0.20
JW113	13.50 $\pm$ 0.08	13.6	1.39 $\pm$ 0.11	1.71 $\pm$ 0.10
JW116	12.10 $\pm$ 0.03	12.5	1.04 $\pm$ 0.06	0.86 $\pm$ 0.10
JW117	13.13 $\pm$ 0.07	13.4	1.35 $\pm$ 0.10	1.48 $\pm$ 0.10
JW118	14.83 $\pm$ 0.01	14.6	1.74 $\pm$ 0.04	0.89 $\pm$ 0.20
JW123	13.00 $\pm$ 0.03	13.3	1.45 $\pm$ 0.06	1.85 $\pm$ 0.10
JW124	13.94 $\pm$ 0.01	13.9	1.49 $\pm$ 0.06	0.95 $\pm$ 0.20
JW134	16.14 $\pm$ 0.03	15.8	2.39 $\pm$ 0.08	1.55 $\pm$ 0.20
JW138	14.70 $\pm$ 0.01	14.6	1.52 $\pm$ 0.06	1.18 $\pm$ 0.20
JW141	15.39 $\pm$ 0.02	15.2	2.10 $\pm$ 0.07	1.39 $\pm$ 0.20
JW144	15.77 $\pm$ 0.02	15.6	2.03 $\pm$ 0.07	1.14 $\pm$ 0.20
JW147	14.81 $\pm$ 0.01	14.4	1.75 $\pm$ 0.06	1.06 $\pm$ 0.20
JW148	15.36 $\pm$ 0.02	15.1	2.43 $\pm$ 0.07	1.83 $\pm$ 0.20
JW149	15.59 $\pm$ 0.02	15.4	1.89 $\pm$ 0.07	1.50 $\pm$ 0.20
JW150	14.00 $\pm$ 0.02	14.2	2.40 $\pm$ 0.05	2.30 $\pm$ 0.10
JW155	14.99 $\pm$ 0.01	14.8	1.92 $\pm$ 0.06	1.07 $\pm$ 0.20
JW158	13.38 $\pm$ 0.03	13.5	1.72 $\pm$ 0.06	1.16 $\pm$ 0.10
JW164	14.05 $\pm$ 0.02	13.9	1.53 $\pm$ 0.07	1.32 $\pm$ 0.20
JW177	14.55 $\pm$ 0.01	14.3	1.71 $\pm$ 0.06	1.74 $\pm$ 0.20
JW188	14.16 $\pm$ 0.02	14.2	1.21 $\pm$ 0.07	0.85 $\pm$ 0.20
JW207	15.57 $\pm$ 0.02	15.3	2.07 $\pm$ 0.07	1.60 $\pm$ 0.20
JW209	14.12 $\pm$ 0.04	14.1	1.01 $\pm$ 0.09	1.01 $\pm$ 0.20
JW218	14.99 $\pm$ 0.01	14.9	1.63 $\pm$ 0.06	1.16 $\pm$ 0.20

Table 2.4 (continued): *I* Photometry of Outer Annulus Stars

Name (1)	I_{PAWS} (2)	I_{JW} (3)	$(I - J)$ (4)	$(J - K)$ (5)
JW222	14.01 $\pm$ 0.01	13.9	1.79 $\pm$ 0.04	1.62 $\pm$ 0.11
JW232	11.62 $\pm$ 0.27	11.9	1.38 $\pm$ 0.30	1.14 $\pm$ 0.10
JW235	13.42 $\pm$ 0.10	13.4	1.30 $\pm$ 0.15	1.72 $\pm$ 0.15
JW239	12.72 $\pm$ 0.07	13.0	1.40 $\pm$ 0.10	1.22 $\pm$ 0.10
JW253	14.03 $\pm$ 0.06	13.8	1.96 $\pm$ 0.09	2.57 $\pm$ 0.10
JW277	14.42 $\pm$ 0.03	15.3	1.20 $\pm$ 0.06	2.72 $\pm$ 0.10
JW307	15.42 $\pm$ 0.02	15.1	1.26 $\pm$ 0.07	1.06 $\pm$ 0.20
JW329	14.86 $\pm$ 0.02	14.6	1.30 $\pm$ 0.07	1.16 $\pm$ 0.20
JW364	11.26 $\pm$ 0.14	11.3	1.58 $\pm$ 0.17	0.98 $\pm$ 0.10
JW371	14.78 $\pm$ 0.01	14.8	1.82 $\pm$ 0.06	1.16 $\pm$ 0.20
JW379	15.17 $\pm$ 0.02	15.1	2.07 $\pm$ 0.07	1.20 $\pm$ 0.20
JW380	13.80 $\pm$ 0.02	13.9	1.65 $\pm$ 0.07	1.05 $\pm$ 0.20
JW381	13.20 $\pm$ 0.02	14.0	1.85 $\pm$ 0.05	1.65 $\pm$ 0.10
JW383	14.49 $\pm$ 0.04	14.5	1.87 $\pm$ 0.09	1.22 $\pm$ 0.20
JW386	14.00 $\pm$ 0.02	14.1	2.49 $\pm$ 0.05	1.91 $\pm$ 0.10
JW388	13.45 $\pm$ 0.14	13.9	1.65 $\pm$ 0.17	1.40 $\pm$ 0.20
JW416	14.11 $\pm$ 0.02	14.2	1.46 $\pm$ 0.05	0.95 $\pm$ 0.20
JW421	11.68 $\pm$ 0.12	11.9	1.33 $\pm$ 0.15	1.55 $\pm$ 0.10
JW428	13.96 $\pm$ 0.02	14.0	1.35 $\pm$ 0.07	1.11 $\pm$ 0.20
JW517	15.05 $\pm$ 0.01	15.0	1.69 $\pm$ 0.06	0.96 $\pm$ 0.20
JW528	14.86 $\pm$ 0.03	14.9	2.16 $\pm$ 0.06	2.00 $\pm$ 0.10
JW566	14.84 $\pm$ 0.06	14.9	3.27 $\pm$ 0.09	2.87 $\pm$ 0.10
JW590	15.11 $\pm$ 0.02	15.1	2.17 $\pm$ 0.07	1.04 $\pm$ 0.20
JW601	12.43 $\pm$ 0.24	12.7	0.71 $\pm$ 0.27	0.72 $\pm$ 0.10
JW612	14.71 $\pm$ 0.04	14.7	1.55 $\pm$ 0.09	1.46 $\pm$ 0.20
JW633	16.22 $\pm$ 0.02	16.0	2.82 $\pm$ 0.07	2.20 $\pm$ 0.20
JW655	12.32 $\pm$ 0.05	12.9	2.45 $\pm$ 0.08	1.87 $\pm$ 0.10
JW664	13.99 $\pm$ 0.06	14.1	1.80 $\pm$ 0.09	1.49 $\pm$ 0.10
JW673	12.90 $\pm$ 0.10	13.1	1.38 $\pm$ 0.13	1.62 $\pm$ 0.10
JW715	15.22 $\pm$ 0.02	15.4	2.02 $\pm$ 0.08	1.10 $\pm$ 0.23
JW727	13.89 $\pm$ 0.02	14.1	1.61 $\pm$ 0.05	1.58 $\pm$ 0.10
JW729	14.50 $\pm$ 0.01	14.4	1.48 $\pm$ 0.06	1.42 $\pm$ 0.20
JW747	11.18 $\pm$ 0.16	11.4	0.91 $\pm$ 0.19	0.77 $\pm$ 0.10
JW753	13.36 $\pm$ 0.03	13.6	1.40 $\pm$ 0.08	1.26 $\pm$ 0.10
JW788	14.20 $\pm$ 0.02	14.7	1.76 $\pm$ 0.07	1.44 $\pm$ 0.20
JW789	16.12 $\pm$ 0.03	15.8	2.16 $\pm$ 0.08	1.26 $\pm$ 0.20

Table 2.4 (continued): *I* Photometry of Outer Annulus Stars

Name (1)	I_{PAWS} (2)	I_{JW} (3)	$(I - J)$ (4)	$(J - K)$ (5)
JW805	14.99 $\pm$ 0.02	15.0	2.17 $\pm$ 0.09	1.82 $\pm$ 0.24
JW811	11.37 $\pm$ 0.02	13.6	0.06 $\pm$ 0.05	2.01 $\pm$ 0.10
JW812	14.03 $\pm$ 0.01	14.2	1.80 $\pm$ 0.06	1.23 $\pm$ 0.20
JW824	15.54 $\pm$ 0.02	14.6	3.54 $\pm$ 0.05	2.40 $\pm$ 0.10
JW836	13.44 $\pm$ 0.02	13.5	1.57 $\pm$ 0.05	1.57 $\pm$ 0.10
JW843	13.71 $\pm$ 0.02	13.8	1.37 $\pm$ 0.07	1.04 $\pm$ 0.20
JW854	14.67 $\pm$ 0.02	14.5	2.17 $\pm$ 0.05	1.80 $\pm$ 0.10
JW863	14.04 $\pm$ 0.01	13.9	1.71 $\pm$ 0.04	1.63 $\pm$ 0.10
JW878	14.57 $\pm$ 0.02	14.5	2.16 $\pm$ 0.07	1.01 $\pm$ 0.20
JW880	14.09 $\pm$ 0.01	14.1	1.33 $\pm$ 0.06	0.96 $\pm$ 0.20
JW883	13.27 $\pm$ 0.07	13.5	1.70 $\pm$ 0.10	1.27 $\pm$ 0.10
JW886	13.92 $\pm$ 0.01	14.0	2.34 $\pm$ 0.04	1.68 $\pm$ 0.10
JW889	13.31 $\pm$ 0.02	13.4	0.70 $\pm$ 0.07	0.61 $\pm$ 0.20
JW895	12.29 $\pm$ 0.02	13.2	0.28 $\pm$ 0.05	2.01 $\pm$ 0.10
JW898	13.97 $\pm$ 0.01	14.6	1.67 $\pm$ 0.06	1.10 $\pm$ 0.20
JW907	12.87 $\pm$ 0.08	13.1	1.10 $\pm$ 0.11	0.87 $\pm$ 0.10
JW910	15.80 $\pm$ 0.02	15.5	2.12 $\pm$ 0.07	1.58 $\pm$ 0.20
JW916	14.50 $\pm$ 0.02	14.5	1.55 $\pm$ 0.07	0.95 $\pm$ 0.20
JW929	15.85 $\pm$ 0.02	15.6	1.41 $\pm$ 0.07	1.05 $\pm$ 0.20
JW930	13.99 $\pm$ 0.01	13.9	1.28 $\pm$ 0.06	1.01 $\pm$ 0.20
JW931	15.76 $\pm$ 0.02	15.7	4.06 $\pm$ 0.05	2.90 $\pm$ 0.10
JW933	13.64 $\pm$ 0.05	13.7	1.39 $\pm$ 0.10	1.05 $\pm$ 0.20
JW939	16.30 $\pm$ 0.03	15.9	2.02 $\pm$ 0.08	1.38 $\pm$ 0.20
JW942	16.32 $\pm$ 0.03	16.0	2.33 $\pm$ 0.08	1.89 $\pm$ 0.20
JW945	12.45 $\pm$ 0.03	12.9	2.09 $\pm$ 0.06	1.46 $\pm$ 0.10
JW947	14.27 $\pm$ 0.01	14.2	1.26 $\pm$ 0.06	0.91 $\pm$ 0.20
JW950	12.26 $\pm$ 0.08	12.5	0.64 $\pm$ 0.13	0.52 $\pm$ 0.20
JW951	15.72 $\pm$ 0.02	15.6	2.21 $\pm$ 0.07	1.71 $\pm$ 0.20
JW954	14.29 $\pm$ 0.03	14.0	1.68 $\pm$ 0.08	1.51 $\pm$ 0.20
JW959	10.65 $\pm$ 0.36	10.2	1.25 $\pm$ 0.39	0.80 $\pm$ 0.10
JW962	12.71 $\pm$ 0.07	12.9	1.21 $\pm$ 0.10	1.40 $\pm$ 0.10
JW963	10.60 $\pm$ 0.43	10.4	1.14 $\pm$ 0.46	0.66 $\pm$ 0.10
JW969	14.87 $\pm$ 0.01	14.7	1.56 $\pm$ 0.06	2.01 $\pm$ 0.20
JW980	13.64 $\pm$ 0.03	13.8	1.54 $\pm$ 0.06	1.30 $\pm$ 0.10
JW981	12.90 $\pm$ 0.02	13.2	1.14 $\pm$ 0.05	1.06 $\pm$ 0.10
JW990	14.03 $\pm$ 0.02	14.1	1.57 $\pm$ 0.07	0.96 $\pm$ 0.02
JW998	13.26 $\pm$ 0.03	13.4	1.18 $\pm$ 0.08	1.08 $\pm$ 0.20

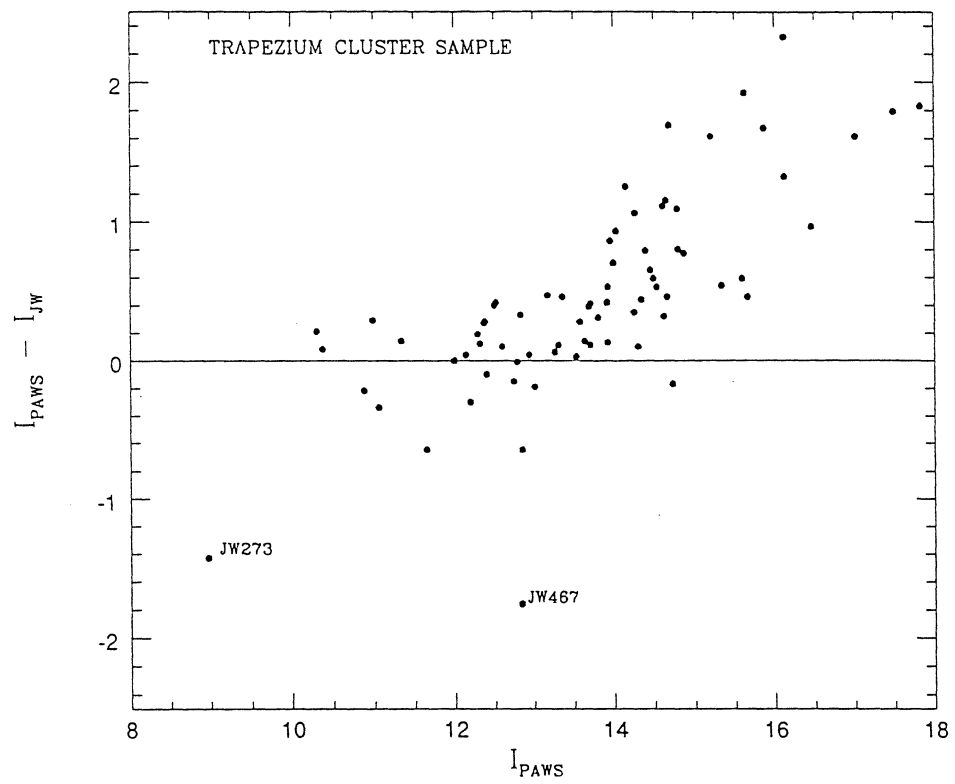


Figure 2.3: Comparison of I magnitudes measured here for the Trapezium Cluster sample using the PAWSPHOT package and those of Jones & Walker (1988).

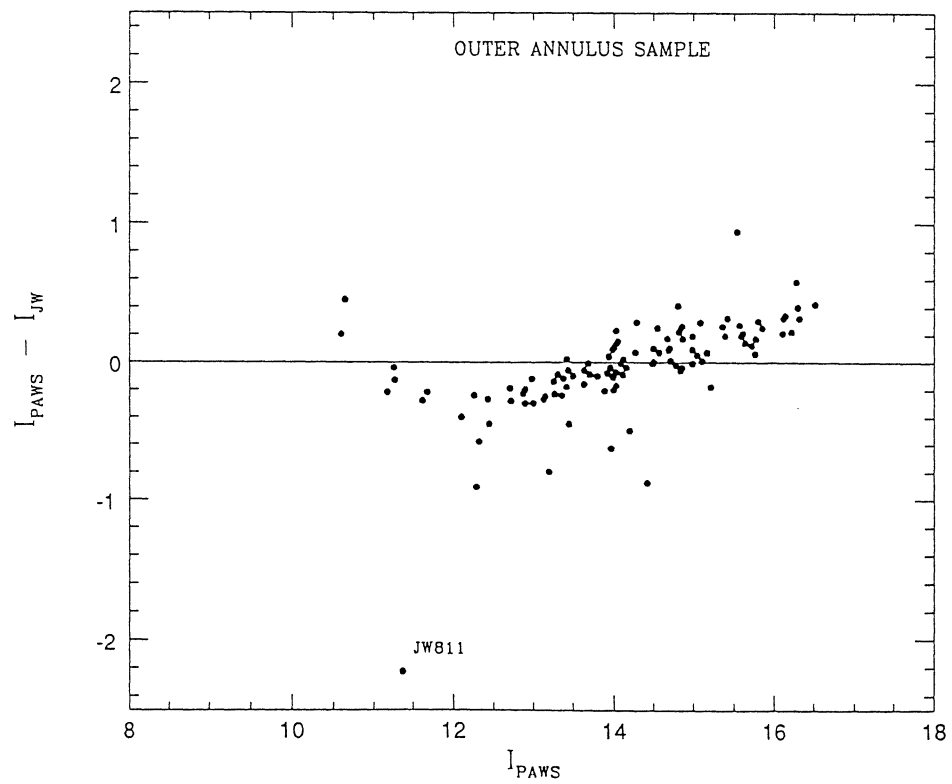


Figure 2.4: As for Figure 2.3, for the outer annulus sample.

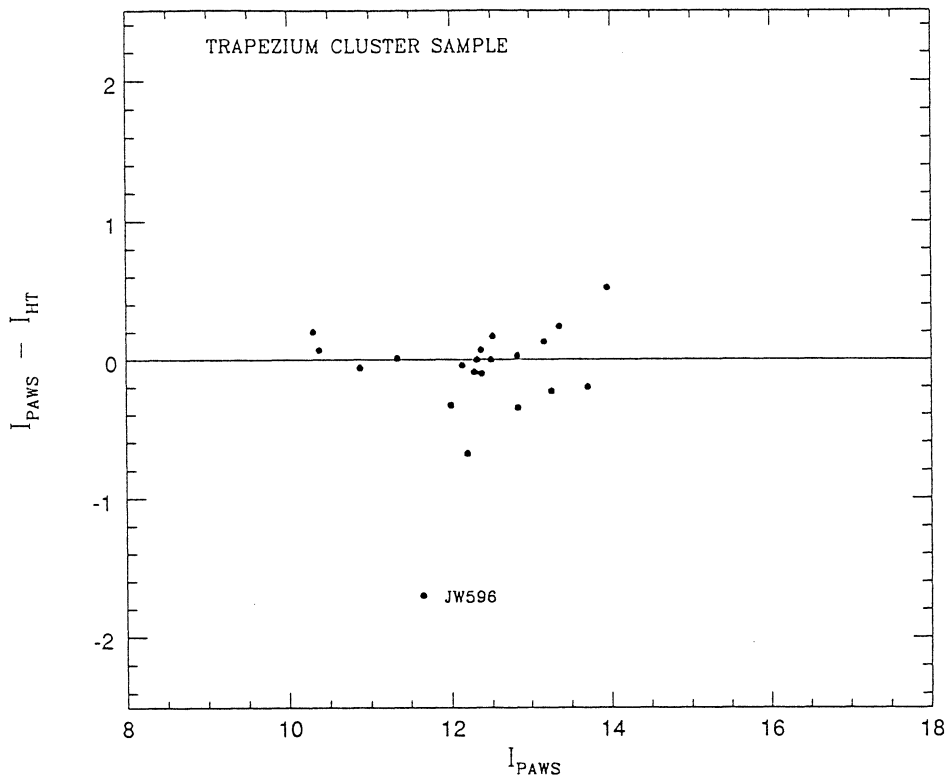


Figure 2.5: Comparison of I magnitudes measured here for the Trapezium Cluster sample using the PAWSPHOT package and those of Herbig & Terndrup (1986).

2.3 Results

2.3.1 The J - H vs H - K Diagrams

The Trapezium Cluster Sample

The J - H , H - K diagram for the 109 Trapezium Cluster stars measured at J , H and K is given in Figure 2.6. It is clear from the diagram that infrared-excess stars exist in the Trapezium Cluster sample from the presence of stars in dust-excess locations away from the loci of reddened main-sequence stars (for example, the group with J - H < 0.75, H - K < 1.3). The positions of these stars are characteristic of classical T Tauri stars. In addition, many Trapezium Cluster stars in Figure 2.6 have locations implying that they are reddened stars with relatively little intrinsic dust excess. Similar groups of stars are seen in the near-infrared two-color diagrams of star-forming regions like the Chamaeleon dark cloud (Hyland et al. 1982). In such regions these reddened stars have been assumed to correspond to background stars, in the case of Chamaeleon providing a good fit to the galactic background-source model derived by Jones et al. (1981). However, the JW proper-motion membership survey has provided direct evidence that background stars are completely obscured in the Trapezium Cluster vicinity by OMC-1, out to at least 12.5' from Θ^1 Ori C. Thus, we assume that all the stars in our two samples belong to the Orion Molecular Cloud. We note that several star-forming regions are found to have significant numbers of member stars without dust excesses (for example, Walter 1986; Walter et al. 1988;

Hartigan 1993). These results underline the importance of distinguishing between ‘naked’ T Tauri stars without disks and classical T Tauri stars with disks.

The stars HAB146, HAB183, HAB296, JW610, HAB438, JW723, and HAB539 are all extinguished by $A_K > 1.7$ mag. HAB183 is the well-known compact infrared source IRC9 (Downes et al. 1981) associated with the Kleinmann-Low (KL) nebula. HAB146 is located within $29''$ of HAB183 in the plane of the sky, and is a likely member of the KL nebula as well. The status of the remaining five highly reddened stars is not clear; their colors may be caused by misidentification of the stars in these cases. The five bright visible stars observed are Θ^1 Ori A (B2), Θ^1 Ori D (O9.5), Θ^2 Ori A (O9), Θ^2 Ori B (B1) and P2085 (B5; Struve & Titus 1944; Strand 1958). While they are very blue in Figure 2.6, as expected, their positions indicate that they are also extinguished by A_K up to ~ 0.4 mag. Our results support the notion that $A_K \sim 0.1$ – 0.3 mag is associated with the Trapezium OB stars (Warren & Hesser 1978; Garay, Moran & Reid 1987). Furthermore, we observe a shift of at least $A_K \sim 0.1$ mag between the intrinsic main sequence locus in Figure 2.6 and the low mass cluster stars. Thus, this diagram demonstrates that the whole Trapezium stellar population is located behind at least $A_K \sim 0.1$ mag of extinction. The two infrared stars HAB237 and HAB323 lie in anomalous positions in the JHK diagram, around $(J-H), (H-K) = (-0.5, 1.1)$. Their colors most probably arise from poor nebula subtraction, although these sources may be knots of nebula material rather than stellar objects.

The Outer Annulus Sample

Figure 2.7 is the $J-H$, $H-K$ diagram for the 115 stars observed from the outer annulus region. Clearly, some outer annulus stars suffer relatively little extinction while others are extinguished by up to $A_K \sim 1.7$ mag. However, no stars with greater extinctions are observed here compared with the seven highly reddened stars detected in our Trapezium Cluster sample. Additionally, no bright OB stars are present in the outer annulus sample. Figures 2.6 and 2.7 illustrate that the two stellar samples observed have colors typical of young stellar populations. A large number of PMS stars with dust excesses are clearly present in both regions. However, there are no outer annulus stars with the dust excesses of the group mentioned above, at $J-H$ colors < 0.75 and $H-K < 1.3$. Thus, proportionately more Trapezium Cluster stars have infrared excesses typical of classical T Tauri stars. In addition, although there are a similar number of reddened stars with relatively little dust excess, some Trapezium Cluster stars are reddened significantly more than the most reddened outer annulus star. More accurate determinations of the nature of the stars are complicated by the extinction due to both circumstellar and interstellar dust. A further ambiguity arises because some stars in both samples can be dereddened to

Figure 2.6: The following page gives the $(J-H)$ vs $(H-K)$ diagram for the Trapezium Cluster sample. Heavy solid curve in lower left represents main-sequence locus with spectral types marked (Bessell & Brett 1988; Bessell 1991). Colors for a typical late-type star with circumstellar dust have been taken from Hyland, Jones & Mitchell (1982); the corresponding locus is indicated as the ‘dust curve’. We have used the model given by Hyland et al. corresponding to a 5400 K star with a maximum shell radius of $10^3 R_*$ ($R_{min}/R_* = 50$). Also given is the extinction vector representing $A_K = 0.5$ mag ($A_V \approx 4.5$ mag), assuming a normal reddening law (Rieke & Lebofsky 1985). The error given in the lower right applies to stars plotted as open circles. Stars brighter than $K \sim 9$ mag have errors which are not more than half the amount shown; these stars are represented by filled circles. For stars with larger than average errors, the positions are plotted with error bars included.

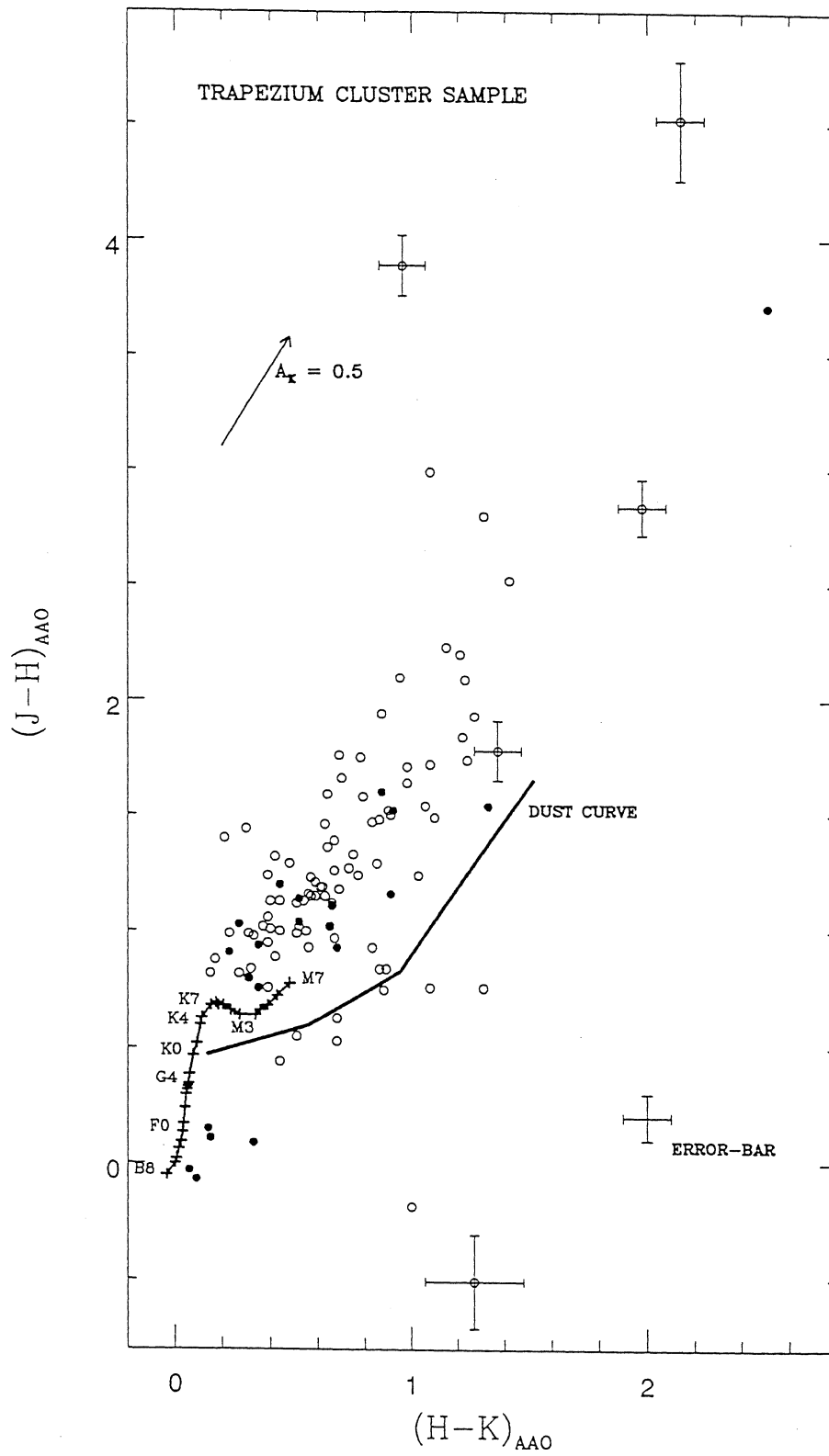


Figure 2.6: *cont.*

intrinsic colors corresponding to either M-type photospheres-plus-dust or early-type photospheres-plus-dust. In light of these difficulties, we have developed a new approach incorporating *I*-band data in our dereddening procedure. The method is described below.

2.3.2 The Dereddening Procedure

It is apparent from §2.3.1 that a tool is required which allows us to separate the effects of circumstellar and interstellar dust as well as eliminating the ambiguity in the intrinsic loci in the *J-H*, *H-K* plane. We proceed by demonstrating in some detail how the *I-J* vs *J-K* diagram can be used for this purpose. In principle, the combination of the *J-H*, *H-K* and *I-J*, *J-K* diagrams allows a unique spectral type interpretation for each star. The stars plotted in Figure 2.8 are a sample of 53 T Tauri stars taken from the catalogue of Rydgren et al. (1984). Their colors are reproduced in Table 2.5. Figure 2.9 is the corresponding *J-H*, *H-K* diagram of these stars.

Initially we consider the position of a reddened star in the *IJK* plane. The locus of the dust curve in this plane is parabolic in nature, having the form:

$$\Delta(I - J) \approx \frac{\Delta(J - K)^2}{4} \quad (2.1)$$

where $\Delta(I - J)$ and $\Delta(J - K)$ are the amounts by which the photospheric colors are reddened by the dust envelope. Taking account of the extinction in this plane, we derive the following equations:

$$(I - J) = (I - J)_o + \frac{E(I - J)}{A_V} A_V + \Delta(I - J); \quad (2.2)$$

$$(J - K) = (J - K)_o + \frac{E(J - K)}{A_V} A_V + \Delta(J - K) \quad (2.3)$$

where $(I - J)$, $(J - K)$ corresponds to the observed position of the star, $(I - J)_o$, $(J - K)_o$ is a position on the main-sequence locus for a particular stellar spectral type, and $\frac{E(I - J)}{A_V} A_V$, $\frac{E(J - K)}{A_V} A_V$ are the amounts of interstellar reddening in each color. The combination of these equations forms a quadratic in A_V :

$$\begin{aligned} \frac{0.17^2}{4} A_V^2 + A_V [0.20 + 0.085(J - K)_o - 0.085(J - K)] - [(I - J) - (I - J)_o \\ - \frac{1}{4}(J - K)^2 + \frac{1}{2}(J - K)(J - K)_o - \frac{1}{4}(J - K)_o^2] = 0 \end{aligned}$$

This is solved for each spectral type to give extinction estimates, A_V , and then used in equation 2.3 to obtain dust excesses, $\Delta(J - K)$. We allow for errors of up to 0.2 mag in the observed *I-J* colors of the stars. In this way, we determine the

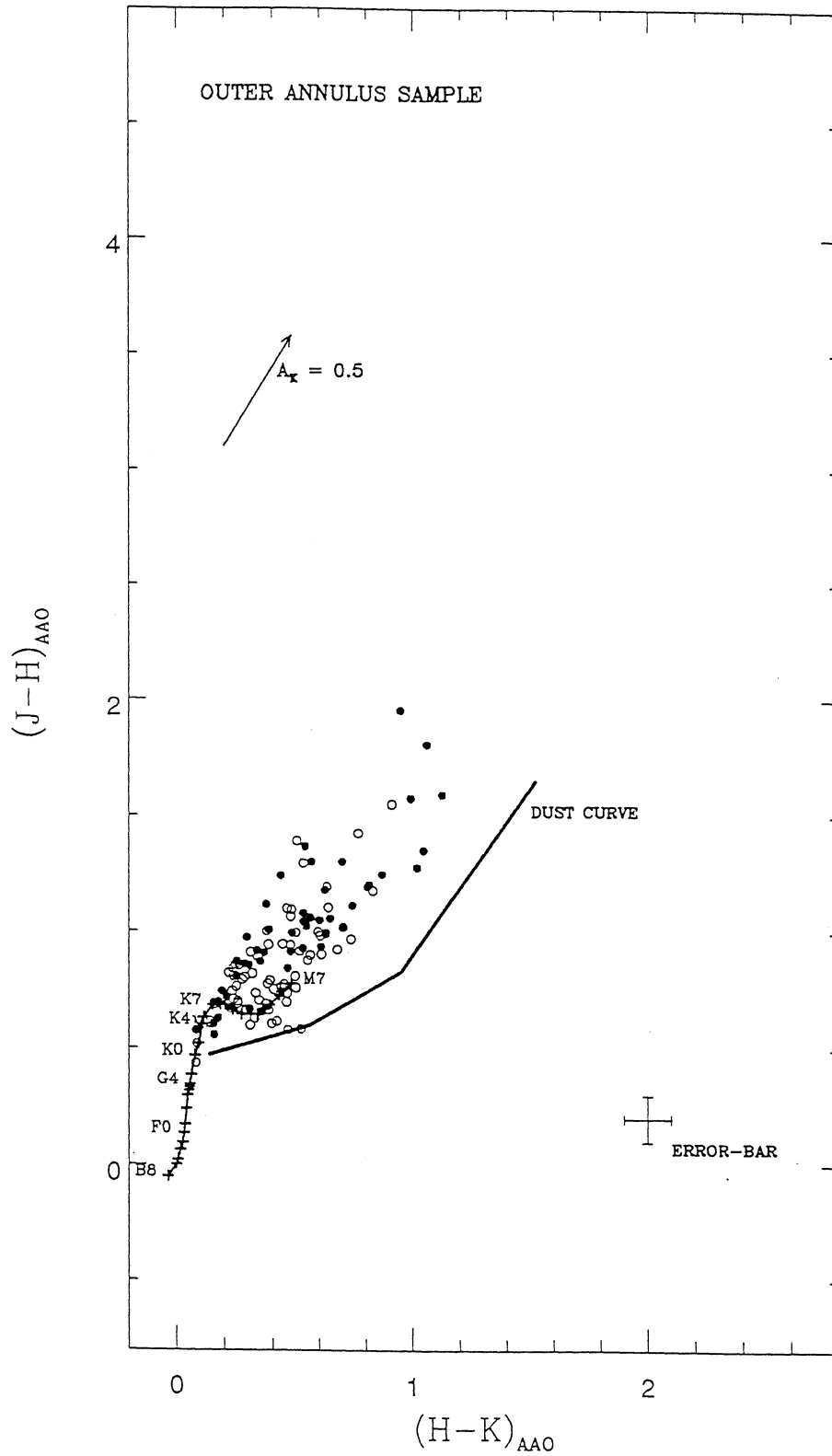


Figure 2.7: $(J-H)$ vs $(H-K)$ diagram for the outer annulus sample observed here. All features are as described for Figure 2.5. Here, stars brighter than $K \sim 10.5$ mag have errors which are, at most, half as large as the error shown.

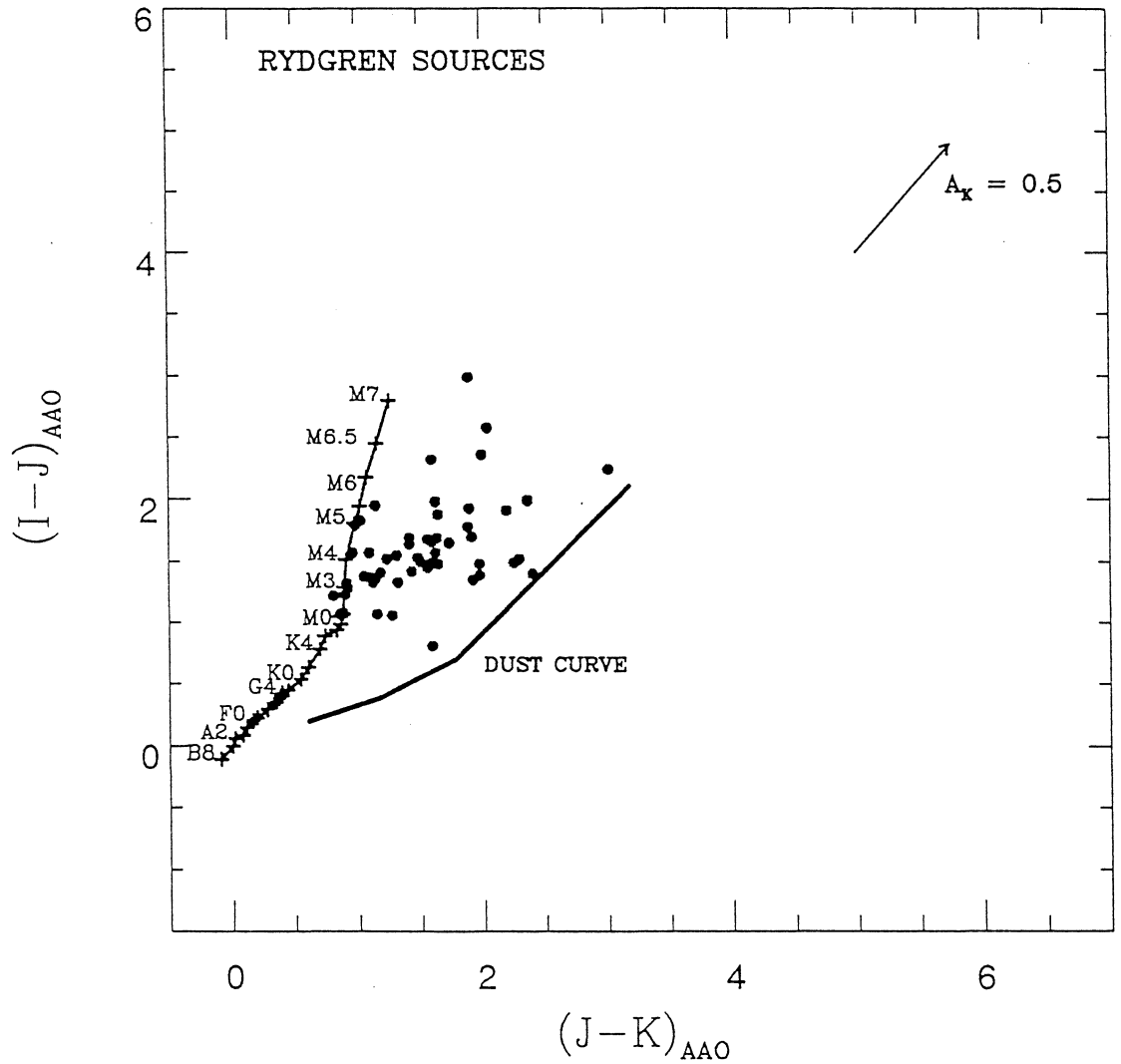


Figure 2.8: $(I-J)$ vs $(J-K)$ diagram for the T Tauri stars of Rydgren et al (1984), represented by filled circles. As for Figures 2.5 and 2.6, the main-sequence locus (Bessell & Brett 1988; Bessell 1991) is given by the solid line to the left of the diagram, with spectral types marked. The position of a (5400 K photosphere+dust) curve (Hyland et al. 1982) in this plane is also indicated, as is the extinction vector corresponding to $A_K = 0.5$ mag ($A_V \approx 4.5$ mag).

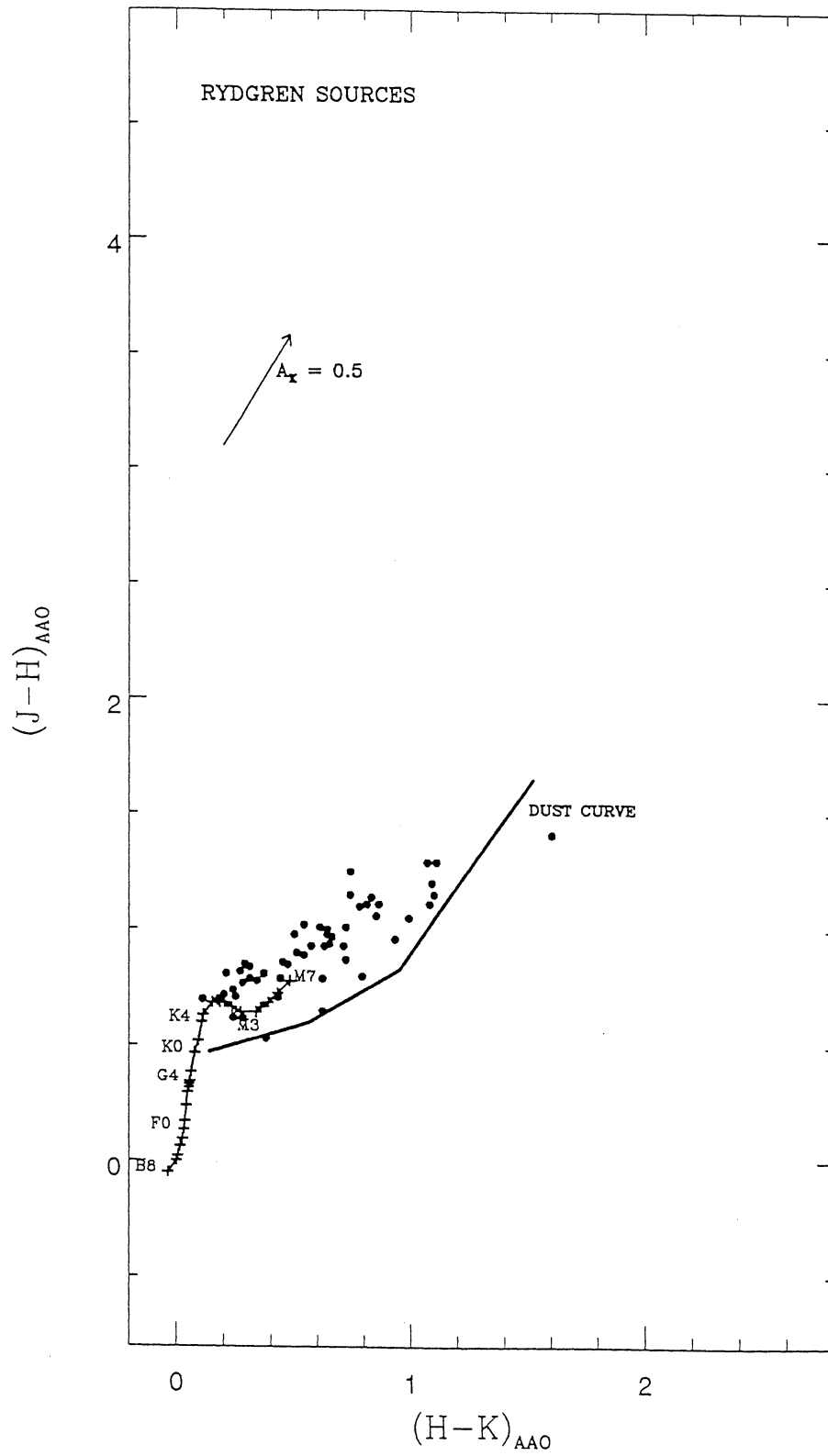


Figure 2.9: $(J-H)$ vs $(H-K)$ diagram for the Rydgren et al. (1984) sample. Features are as described for Figure 2.5.

potential range in spectral type appropriate for the star and deredden the star along the parabolic dust curve and the reddening line to reach these various positions on the main-sequence locus. Thus, the result from the IJK plane is used to provide a number of possible spectral types for the star, with corresponding A_V and $\Delta(J - K)$ measurements.

The results from the IJK plane are then applied in the JHK plane as follows. The reddenings are computed with respect to both $(J-H)$ and $(H-K)$ axes for each potential spectral type, with an 0.2 mag tolerance for photometric error, directly from the A_V values obtained in the IJK plane. We derive the dust excesses appropriate to the JHK plane by again assuming a parabolic form for the dust curve, this time given by:

$$\Delta(J - H) \approx \frac{\Delta(H - K)^2}{2} \quad (2.4)$$

Using the fact that

$$\Delta(J - K) = \Delta(J - H) + \Delta(H - K) \quad (2.5)$$

we express $\Delta(J - K)$ as a quadratic in $\Delta(H - K)$:

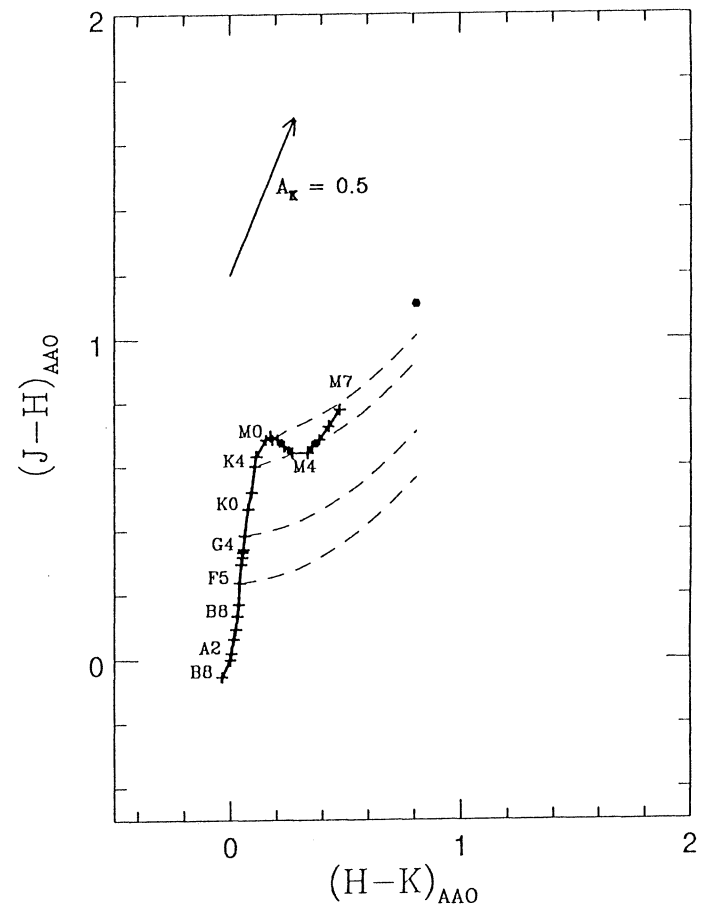
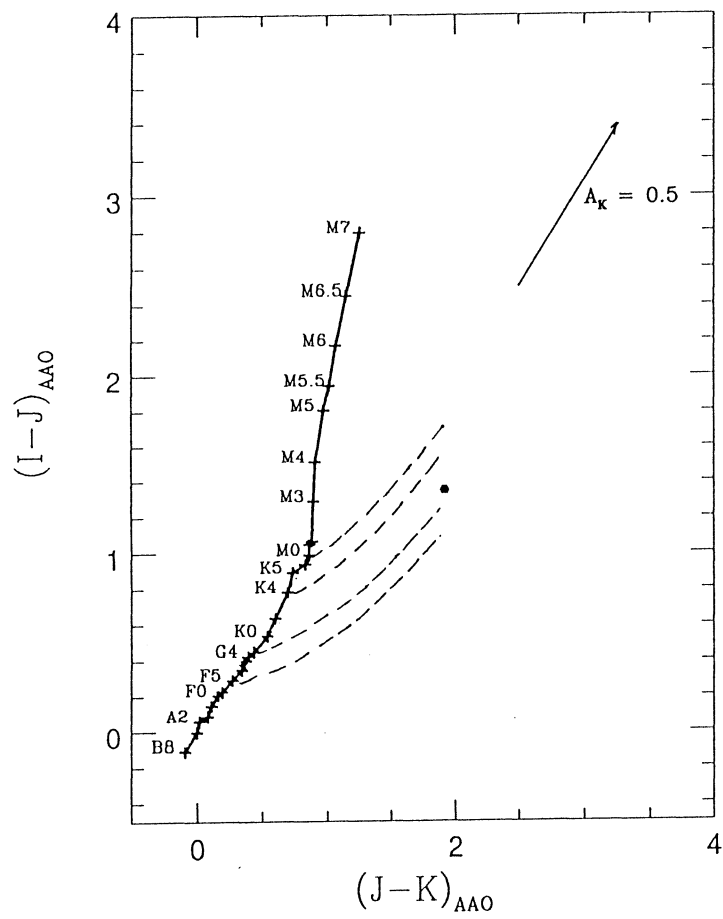
$$\frac{1}{2}\Delta(H - K)^2 + \Delta(H - K) - \Delta(J - K) = 0 \quad (2.6)$$

and solve it for each possible spectral type to obtain a corresponding $\Delta(H - K)$. $\Delta(J - H)$ then follows trivially. The components of A_V and $\Delta(J - K)$ in the $J-H$, $H-K$ plane are then added to the intrinsic main-sequence colors considered. Finally, the difference between the resultant colors for each spectral type and the observed reddened colors of the star is calculated. We take the (spectral type, A_V , dust excess) combination which is closest to the observation as the best fit to the data. Figure 2.10 illustrates the process in detail for one star. Note that more than one combination is possible within the photometric errors assumed.

The results for the Rydgren sample are tabulated in Table 2.6. The spectral types obtained here for 39 of 50 stars show good agreement with the results of Rydgren et al. (1984) within 3 spectral sub-classes, which is deemed satisfactory. Although we have not resolved all the ambiguities in the data, we apply this dereddening procedure as a first approach to the problem in both our Trapezium Cluster and outer annulus samples.

We note that, throughout this study, the normal reddening law given by Rieke & Lebofsky (1985) has been adopted. Some authors have suggested that an anomalous extinction law applies in the nebulous regions of the Orion Nebula. Warren & Hesser (1978), McCall (1981), and Breger, Gehrz & Hackwell (1981) claim from polarization studies that regions of the brightest nebulosity within the Orion Nebula contain

Figure 2.10: On the following page, the dereddening procedure used in this investigation, is illustrated for the T Tauri star CI Tau (Rydgren et al. 1984). The reddened position of the star is plotted in both IJK and JHK planes (filled circles). We use parabolic approximations to the Hyland et al. (1982) dust curves in both planes (described in text). The amount of extinction and dust excess required to deredden the star back to each main-sequence spectral type position in the IJK plane is determined, allowing for a 0.2 mag photometric error. The corresponding dereddening loci are indicated by the dashed lines in the diagram. We apply these computed A_V and dust excess values in the JHK plane. The spectral type positions are used as a starting point with A_V and excess added according to the values found in the IJK plane. The resultant loci are again given by the dashed lines. The difference between the end-points found from our computations and the reddened position of the star is calculated. We take the spectral type, A_V , and excess results which deviate least from the observed colors for the star in question as the final result. In the case illustrated, a spectral type of K7 gives the best fit in both planes. This process is performed on all stars in the sample.

Figure 2.10: *cont.*

larger than normal dust grains. However, Smith (1987) has shown that the effects of large dust grains on the reddening law in the Carina Nebula are only significant at ultraviolet wavelengths and decrease with increasing wavelength. Therefore, any anomalous behaviour in the reddening law is expected to be negligible in the near-infrared region of the spectrum.

2.3.3 Dereddening the Trapezium Cluster and Outer Annulus Samples

The Trapezium Cluster Sample

We use our near-infrared photometry results (Tables 2.1 and 2.2) and I magnitudes (Tables 2.3 and 2.4) to construct the $I-J$ vs $J-K$ diagrams for the two samples under investigation. Figure 2.11 contains the 83 Trapezium Cluster stars with IJK magnitudes measured here. 72 stars appear in locations typical of classical T Tauri stars with varying amounts of circumstellar dust (Rydgren et al. 1984; Figure 2.8). Eleven lie in anomalous positions and thus cannot be dereddened with the technique. Poor nebula subtraction is likely to be responsible for their positions. Table 2.7 list the determined spectral types, A_K values, dust excesses and associated errors derived here for the 59 Trapezium Cluster stars which could be dereddened in both 2-color planes. 39 of these are interpreted without ambiguity. The mean extinction of these 39 stars is $A_K \sim 0.5$ mag, with a maximum of ~ 1.4 mag. We note that the seven stars listed in §2.3.1 as having $A_K > 1.7$ mag are not included. Due to photometric errors in the more reddened of these seven stars, we conclude that $A_K \sim 2.0$ mag is a conservative upper limit for the extinction in the Trapezium Cluster. We find a mean dust excess of $\Delta(J - K) \sim 0.2$ mag, ranging up to a maximum of 0.8 mag. Almost half our sample are determined to have essentially no dust excess. The stars are predominantly late-K and late-M in spectral type, giving a mean spectral type of early M-type.

The Outer Annulus Sample

The 108 outer annulus stars measured at IJK wavelengths are plotted in Figure 2.12. The number of stars to the left of the extinction vector and in close proximity to M-type intrinsic colors strongly suggests that there are many M-type stars with little dust excess in the outer annulus region. 96 stars in this sample could be dereddened in both the JHK and IJK planes using the method described above. The results are given in Table 2.8. 67 stars are unambiguously dereddened. The mean value of extinction here is $A_K \sim 0.2$ mag, and the maximum is ~ 1.3 mag. The average dust excess calculated for this sample is $\Delta(J - K) \sim 0.1$ mag, with a maximum of 0.5 mag. More than half of the outer annulus sample have no

Table 2.5: Rydgren T Tauri Stars - Original Data⁽¹⁾

Name	(<i>I-J</i>)	(<i>J-K</i>)	(<i>J-H</i>)	(<i>H-K</i>)
(1)	(2)	(3)	(4)	(5)
AA Tau	1.45	1.56	1.02	0.54
BP Tau	1.33	1.12	0.78	0.34
CI Tau	1.35	1.92	1.11	0.81
CW Tau	1.99	2.36	1.29	1.07
CX Tau	1.38	1.05	0.77	0.28
CY Tau	1.55	1.31	0.86	0.45
CZ Tau	1.95	1.14	0.71	0.43
DD Tau	2.32	1.59	0.94	0.65
DE Tau	1.42	1.43	0.89	0.54
DF Tau	1.64	1.41	0.79	0.62
DG Tau	1.52	2.29	1.20	1.09
DH Tau	1.52	1.23	0.79	0.44
DI Tau	1.07	1.15	0.84	0.31
DK Tau	1.48	1.97	1.11	0.86
DL Tau	1.69	1.63	0.97	0.66
DM Tau	1.32	0.91	0.53	0.38
DN Tau	1.36	1.14	0.85	0.29
DO Tau	2.58	2.04	1.05	0.99
DP Tau	1.39	1.97	1.14	0.83
DQ Tau	1.68	1.56	0.93	0.63
DR Tau	1.91	2.19	1.11	1.08
DS Tau	1.33	1.32	0.85	0.47
FK Xray1	1.22	0.81	0.70	0.11
FK Xray2	1.28	0.92	0.72	0.20
FK Xray3	1.37	1.10	0.79	0.31
FM Tau	1.88	1.64	0.93	0.71
FP Tau	1.57	0.96	0.71	0.25

Table 2.5 (continued): Rydgren T Tauri Stars - Original Data⁽¹⁾

Name	(I-J)	(J-K)	(J-H)	(H-K)
(1)	(2)	(3)	(4)	(5)
FX Tau	1.57	1.62	0.98	0.64
GG Tau	1.53	1.48	0.98	0.50
GH Tau	1.50	1.50	0.93	0.57
GI Tau	1.66	1.59	0.94	0.65
GK Tau	1.65	1.73	1.01	0.72
GO Tau	1.69	1.41	0.90	0.51
Haro 6-37	2.99	1.89	1.15	0.74
HD283447	1.41	1.18	0.81	0.37
HK Tau	2.36	1.99	1.25	0.74
HL Tau	2.24	3.01	1.41	1.60
HN Tau	1.40	2.40	1.29	1.11
HP Tau	1.78	1.88	1.10	0.78
IQ Tau	1.48	1.64	1.00	0.64
IS Tau	1.98	1.62	1.01	0.61
LkH α 266ab	1.83	1.02	0.81	0.21
RW Aur	0.81	1.59	0.87	0.72
RY Tau	1.49	2.25	1.15	1.10
SU Aur	1.06	1.27	0.65	0.62
T Tau	1.49	1.59	0.80	0.79
UY Aur	1.70	1.91	1.06	0.85
VY Tau	1.23	0.90	0.62	0.28
V410 Tau	1.07	0.86	0.62	0.24
WK Xray1	1.57	1.09	0.82	0.27
WK Xray2	1.08	0.88	0.70	0.18
XZ Tau	1.93	1.89	0.96	0.93
ZZ Tau	1.79	0.98	0.74	0.24

1: Rydgren et al. 1984

Table 2.6: Rydgren T Tauri Stars - Results of De-Reddening

Name (1)	Sp.Type(SMH) (2)	Error (3)	Sp.Type(Ryd.) (4)	Fit (5)
AA Tau	K0-M0	0.06-8	K5-M1	OK
BP Tau	A5-G4,M1-2	0.02-8,0.06-8	K6	NO
CI Tau	K7	0.03	K7	OK
CW Tau	F7-K2,K5,M0-2	0.01-5,0.05,0.01-5	K3	OK
CX Tau	M3	0.08	M2	OK
CY Tau	A2-F5,M3	0.01-7,0.07	M1.5	OK
CZ Tau	M5	0.01	M2	OK
DD Tau	M5	0.02	M0	NO
DE Tau	F7-G6,M1-2	0.01-3,0.00-2	M2	OK
DF Tau	M4	0.05	M1.5	OK
DG Tau	K0-M0	0.04-6	...	
DH Tau	A2,M3	0.01,0.01	M0.5	OK
DI Tau	K7	0.04	M0.5	OK
DK Tau	K0-M0	0.05-7	K5-M0	OK
DL Tau	A5-G4,M2-3	0.01-8,0.07-8	K7	OK
DM Tau	M4	0.02	K5-M2	OK
DN Tau	F7-G6,K5,M1-2	0.01-3,0.04,0.00-2	K6-M1	OK
DO Tau	M5.5	0.02	K7-M1	NO
DP Tau	K7	0.03	M0.5	OK
DQ Tau	B8-F2,M3	0.00-5,0.04	K7-M1	OK
DR Tau	B8-F0,M3	0.01-4,0.02	K5	NO
DS Tau	F7-G6,K5,M1-2	0.01-3,0.04,0.01-2	K3-M0	OK
FK Xray1	M3	0.10	K7-M0	OK
FK Xray2	M3	0.09	K7-M0	OK
FK Xray3	F0,M1-2	0.04,0.08-9	K7-M0	OK
FM Tau	A2,M3-4	0.09,0.06-9	M0	OK
FP Tau	M4	0.05	M3	OK

Table 2.6 (continued): Rydgren T Tauri Stars - Results of De-Reddening

Name (1)	Sp.Type(SMH) (2)	Error (3)	Sp.Type(Ryd.) (4)	Fit (5)
FX Tau	F7-G6,M1-2	0.01-3,0.00-1	M2.5	OK
GO Tau	B8-A2,A7-F0,M3	0.01,0.02-4,0.02	K5-M0	OK
GG Tau	G6-K5,M0-1	0.01-3,0.02-4	K5-M0	OK
GH Tau	F7-G6,M1-2	0.00-3,0.01-2	M2.5	OK
GI Tau	B8-A0,A5-F5,M3	0.05-6,0.00-5,0.06	K6	NO
GK Tau	F5-G4,M1-2	0.01-3,0.03-4	K6	NO
Haro 6-37	M6	0.03	K6	NO
HD 283447	A7-F2,M1-2	0.02-6,0.08-9	K2.5	NO
HK Tau	B8-A2,A7,M3	0.00-2,0.03,0.01	M0.5	OK
HL Tau	B8-A2,A7	0.00-2,0.03	K7?	
HN Tau	K7	0.08	K5	OK
HP Tau	F5-G6,K5,M0-2	0.00-5,0.07,0.01-7	K3	OK
IQ Tau	K0-K5,M0	0.00-2,0.01	M1	OK
IS Tau	M3	0.04	K2	NO
LkH α 266ab	M4	0.02	K7-M3	OK
RW Aur	K7	0.05	G5 Var	
RY Tau	K0-K5,M0	0.01,0.01	G0-K1	OK
SU Aur	A5-F5	0.01-4	G2	OK
T Tau	B8-A2,A7,M3	0.03-4,0.06,0.06	G5-K1	NO
UY Aur	F5-G6,M1-2	0.01-5,0.03-5	G5	OK
VY Tau	M3	0.02	M0	OK
V410 Tau	A2,A7-F0,M2	0.09,0.01-5,0.09	K5	NO
WK Xray1	M3	0.01	K7-M0	OK
WK Xray2	M1-2	0.00-2	K7-M0	OK
XZ Tau	M4	0.01	M2.5	OK
ZZ Tau	M4	0.09	M4	OK

significant excess. Their spectral types peak at the mid-M class.

Comparison of Both Samples

Although not all of our sample can be dereddened using the procedure detailed above, our analysis provides the best estimates currently available for the extinctions, dust excesses and spectral types of individual stars in the Trapezium Cluster region. By using this method, we determine that the mean interstellar extinction, A_K , associated with our Trapezium Cluster sample is greater by 0.3 mag than that in the extended outer annulus sample. Stars with A_K values of > 1.7 mag are found in the Trapezium Cluster stars observed here, while the maximum extinction associated with the outer annulus stars is ~ 1.3 mag. In addition, our results suggest that stars closer to the Trapezium OB stars have slightly greater dust excesses which may indicate that they are younger. The fact that a larger number of stars in the outer annulus region are found to have insignificant dust excesses is illustrated in Figure 2.14. Overall, however, we find that the stellar populations of the Trapezium Cluster and the outer annulus region considered here are both typical of star-forming regions such as Taurus-Auriga (Cohen & Kuhi 1979) and Chamaeleon (Hyland et al. 1982) in that there are a significant proportion ($\sim 50\%$) of dust-excess PMS stars in each sample. The remaining $\sim 50\%$ are reddened with little associated circumstellar dust. We determine that only two stars in our Trapezium Cluster sample suffer $A_K < 0.1$ mag, compared with 25 % of the outer annulus stars. Figure 2.13 illustrates this result, showing a histogram of the number distribution of Trapezium Cluster stars and outer annulus stars with respect to A_K . Both samples observed here are found overall to be around early-to-mid M in spectral type based on the dereddened stellar colors, although both the photometric and dereddening errors mean that the average spectral class could be as early as mid-K. The ambiguity involved in dereddening a proportion of both samples is probably a result of the near-infrared photometric errors (Tables 2.1 and 2.2) together with the errors intrinsic to the dereddening method employed (Tables 2.7 and 2.8). Optical spectroscopy of these stars is required to determine accurate spectral types which will overcome this problem.

2.3.4 The K_o , $(J-K)_o$ Diagram

The Trapezium Cluster Sample

Figure 2.15 shows the K_o vs $(J - K)_o$ diagram of the 59 dereddened Trapezium Cluster stars. The theoretical PMS evolutionary tracks for $0.12 - 3 M_\odot$ stars shown have been transformed from M_{bol} , T_{eff} values obtained from Vandenberg (1991) to K , $J-K$ values at the distance of the Trapezium Cluster. A spline fit was made using

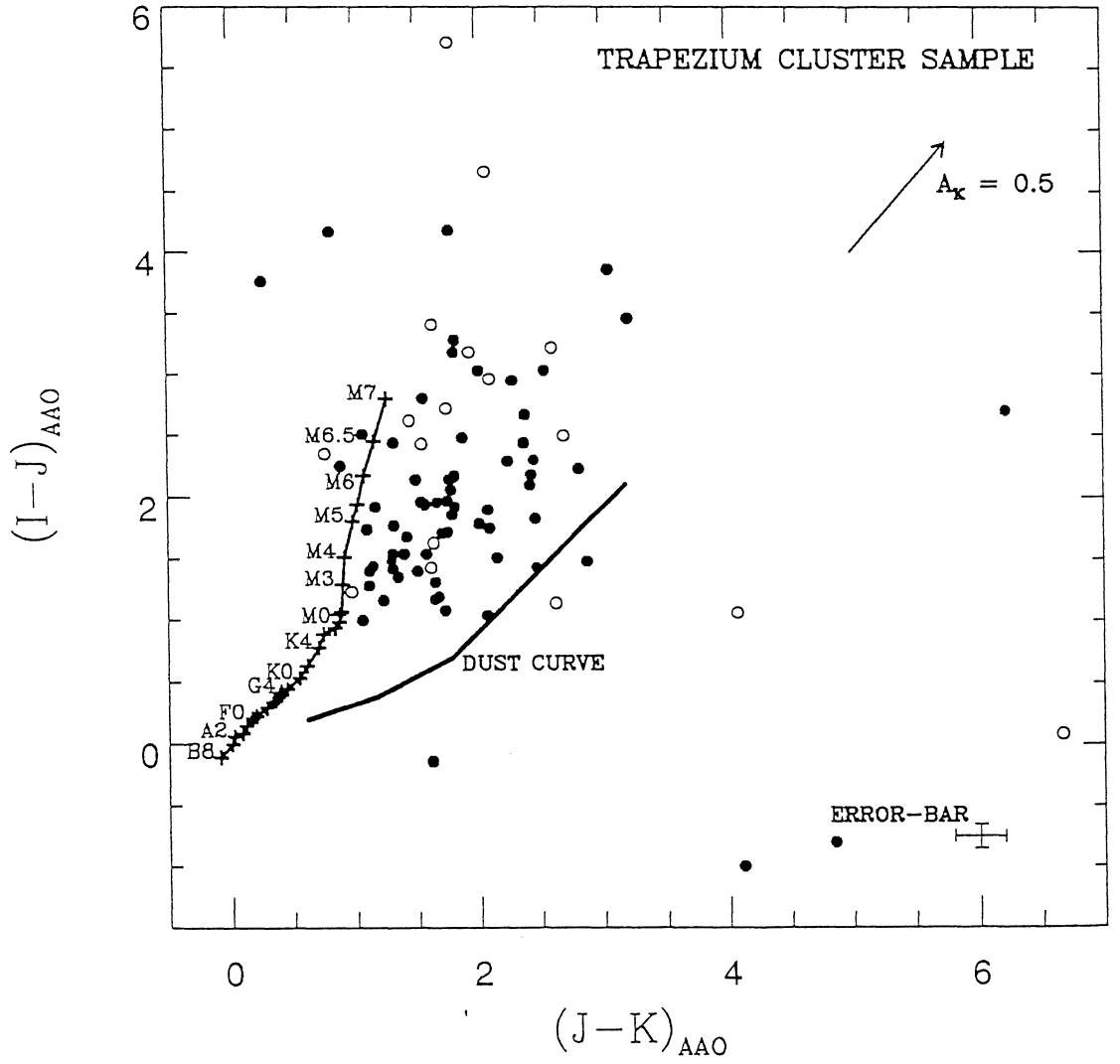


Figure 2.11: $(I-J)$ vs $(J-K)$ diagram for the Trapezium Cluster sample. The error given in the lower right represents errors of < 0.1 mag and applies to stars plotted as closed circles. Stars with larger errors are represented by open circles. All other features are as described for Figure 2.7.

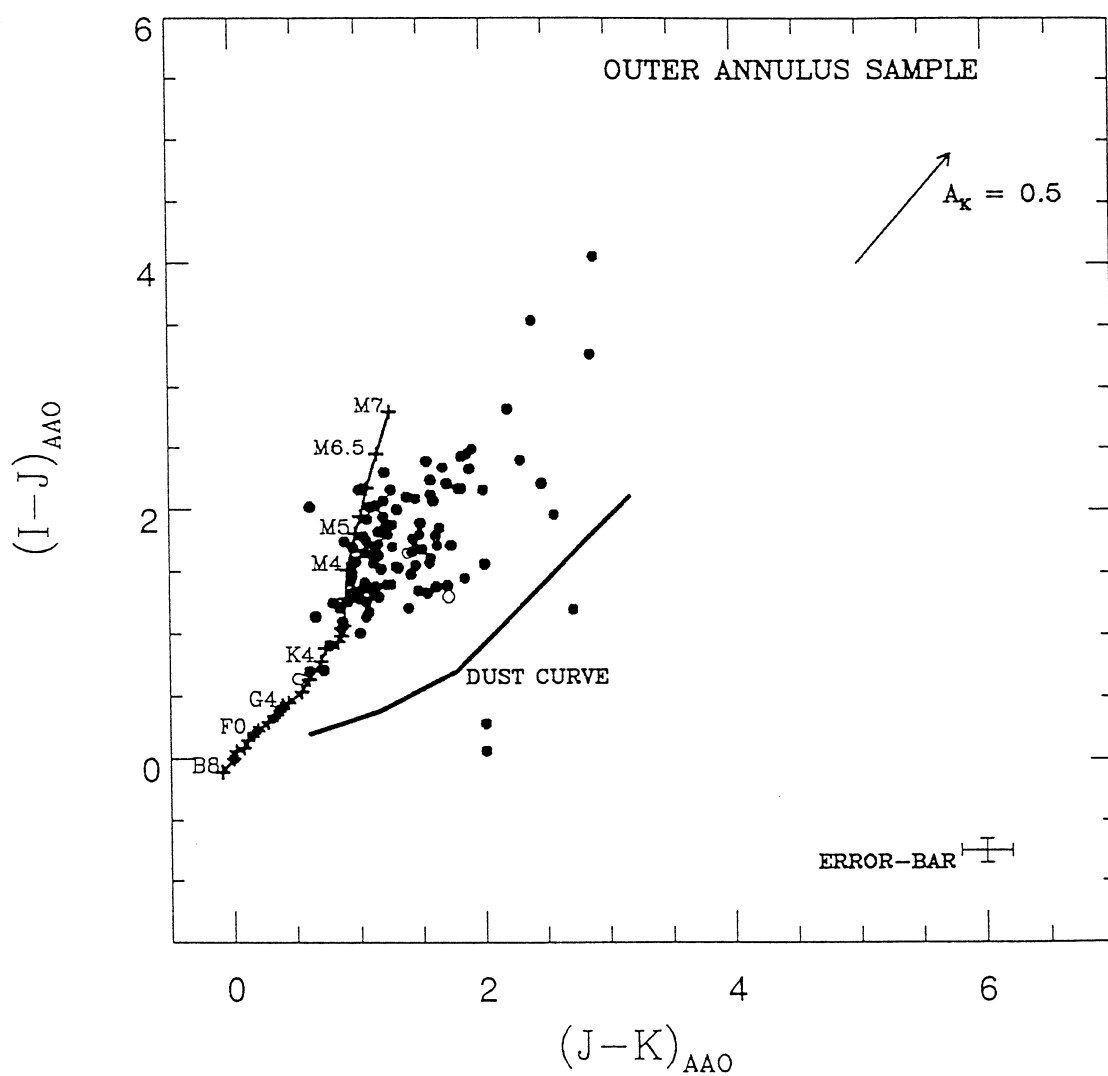


Figure 2.12: $(I-J)$ vs $(J-K)$ diagram for the outer annulus sample, with typical error-bar included. All features are as described for Figure 2.10.

Table 2.7: De-Reddening Parameters for Trapezium Cluster Stars

Name (1)	$(J-K)$ (2)	K (3)	Sp.Type(1) (4)	$A_K(1)$ (5)	Excess(1) (6)	$(J-K)_o(1)$ (7)	$K_o(1)$ (8)	Sp.Type(2) (9)	$A_K(2)$ (10)	Excess(2) (11)	$(J-K)_o(2)$ (12)	$K_o(2)$ (13)
JW226	3.20	8.99	F1	1.84	0.26	0.14 ± 0.06	7.41	M2	1.26	0.42	0.87 ± 0.08	7.32
HAB9	1.93	11.74	M6	0.57	0.01	1.06 ± 0.05	11.19					
HAB19	1.40	11.56	K2.5	0.49	0.03	0.61 ± 0.03	11.09	M0	0.31	0.06	0.86 ± 0.04	11.19
JW261	2.13	10.60	K7	0.36	0.77	0.83 ± 0.13	11.02					
JW276	1.09	11.14	M4	0.13	0.00	0.90 ± 0.08	11.01					
JW286	2.53	9.11	M1.5	1.10	0.00	0.85 ± 0.02	8.01					
JW289	1.74	11.97	M5	0.51	0.00	0.96 ± 0.03	11.46					
JW291	1.04	10.70	K7	0.15	0.00	0.81 ± 0.07	10.54					
JW314	1.53	11.91	M5	0.35	0.03	0.97 ± 0.06	11.59					
JW322	1.76	10.93	M5	0.14	0.57	0.97 ± 0.07	11.36					
HAB68	2.09	10.45	M4	0.81	0.00	0.86 ± 0.06	9.63					
JW340	1.53	10.90	M2	0.50	0.00	0.77 ± 0.05	10.40					
JW343	1.80	10.19	K2.5	0.67	0.14	0.63 ± 0.04	9.66	M0	0.52	0.15	0.86 ± 0.05	9.52
JW344	1.82	10.50	M6.5	0.47	0.00	1.11 ± 0.03	10.04					
JW345	1.40	9.24	G0.5	0.74	0.00	0.28 ± 0.02	8.50	M1.5	0.35	0.01	0.87 ± 0.01	8.88
JW347	1.50	9.74	K4	0.35	0.27	0.71 ± 0.07	9.66					
JW348	1.67	8.22	K7	0.22	0.50	0.83 ± 0.06	8.49					
JW352	1.14	7.84	K5	0.31	0.00	0.67 ± 0.02	7.53	M1.5	0.21	0.00	0.81 ± 0.03	7.62
JW356	2.41	9.24	K7	0.74	0.46	0.83 ± 0.05	8.97					
JW401	1.57	8.88	A2	1.05	0.00	-0.03 ± 0.02	7.83	M3	0.36	0.11	0.90 ± 0.04	8.41

Table 2.7 (continued): De-Reddening Parameters for Trapezium Cluster Stars

Name (1)	(J-K) (2)	K (3)	Sp.Type(1) (4)	A _K (1) (5)	Excess(1) (6)	(J-K) _o (1) (7)	K _o (1) (8)	Sp.Type(2) (9)	A _K (2) (10)	Excess(2) (11)	(J-K) _o (2) (12)	K _o (2) (13)
JW423	2.07	8.40	G0.5	0.83	0.46	0.35 ±0.02	8.03	M1.5	0.43	0.55	0.87 ±0.05	7.42
HAB198	1.55	10.59	M6	0.35	0.00	1.02 ±0.03	10.24					
JW457	1.30	9.59	K2	0.43	0.03	0.62 ±0.07	9.20	M0	0.24	0.07	0.86 ±0.09	9.28
JW467	2.44	8.08	K2	0.89	0.48	0.61 ±0.09	7.67	K7	0.87	0.29	0.83 ±0.04	6.92
JW480	1.23	10.03	K7	0.24	0.02	0.84 ±0.11	9.81					
JW482	1.69	9.64	M4	0.03	0.74	0.90 ±0.00	10.35					
JW544	1.28	8.12	G5.5	0.49	0.02	0.53 ±0.04	7.65	M1	0.26	0.03	0.86 ±0.03	7.83
JW553	1.66	8.90	G0.5	0.90	0.00	0.30 ±0.03	8.00	M1.5	0.51	0.02	0.87 ±0.04	8.37
JW567	1.11	7.77	A5.5	0.73	0.00	0.00 ±0.05	7.04	M2	0.19	0.00	0.83 ±0.09	7.58
JW589	1.29	8.47	K4	0.42	0.00	0.65 ±0.04	8.04	M0	0.31	0.00	0.82 ±0.06	8.16
JW600	1.44	10.23	M6	0.25	0.00	1.06 ±0.11	9.97					
JW606	1.78	10.00	G5.5	0.69	0.19	0.54 ±0.04	9.50	M1	0.46	0.21	0.87 ±0.04	9.33
JW622	2.08	9.03	K7	0.55	0.42	0.83 ±0.09	8.91					
JW636	1.57	10.15	K7	0.46	0.05	0.83 ±0.05	9.74					
JW645	1.74	9.76	K7:	0.55	0.07	0.83 ±0.15	9.27					
JW648	1.80	9.21	A4	1.18	0.00	0.01 ±0.03	8.02	M3	0.49	0.16	0.90 ±0.07	8.56
JW662	1.88	10.33	M4	0.54	0.14	0.92 ±0.02	9.93					
JW663	1.74	10.94	K7	0.69	0.00	0.69 ±0.12	10.24					
JW674	2.01	9.88	K7	0.58	0.28	0.84 ±0.00	9.58					
JW678	0.97	9.77	K5	0.19	0.00	0.69 ±0.01	9.58	M1.5	0.10	0.00	0.83 ±0.07	9.67

Table 2.7 (continued): De-Reddening Parameters for Trapezium Cluster Stars

Name (1)	(J-K) (2)	K (3)	Sp.Type(1) (4)	A _K (1) (5)	Excess(1) (6)	(J-K) _o (1) (7)	K _o (1) (8)	Sp.Type(2) (9)	A _K (2) (10)	Excess(2) (11)	(J-K) _o (2) (12)	K _o (2) (13)
JW684	2.60	10.28	M4	0.95	0.25	0.91 ±0.05	9.59					
JW687	2.69	9.60	K7	0.97	0.38	0.83 ±0.06	9.01					
JW690	1.31	10.54	M3	0.27	0.01	0.89 ±0.08	10.28					
HAB496	1.81	10.91	M6	0.56	0.00	0.95 ±0.03	10.35					
JW721	1.62	10.14	K2	0.54	0.19	0.62 ±0.09	9.79	K7	0.51	0.03	0.83 ±0.06	9.60
JW740	1.30	10.43	M6.5	0.00	0.18	1.12 ±0.14	10.61					
JW748	1.49	10.85	M4	0.35	0.05	0.91 ±0.07	10.55					
JW750	1.33	10.09	K4	0.33	0.15	0.69 ±0.08	9.91					
HAB535	1.16	12.12	M4	0.23	0.00	0.81 ±0.03	11.89					
JW766	2.01	9.00	M5	0.69	0.00	0.96 ±0.09	8.31					
JW775	2.27	10.35	M5	0.58	0.40	0.99 ±0.03	10.17					
JW776	1.63	9.89	K4	0.27	0.53	0.69 ±0.06	10.15					
JW777	2.35	9.23	K7	0.96	0.07	0.83 ±0.09	8.34					
JW782	2.42	9.66	K7	0.79	0.39	0.83 ±0.04	9.26					
JW791	2.37	9.25	G6	1.15	0.09	0.54 ±0.04	8.19	M1	0.92	0.11	0.87 ±0.03	8.22
JW792	1.77	9.74	K4	0.72	0.00	0.68 ±0.02	9.03	M0	0.60	0.00	0.86 ±0.03	9.14
JW793	2.23	10.10	K7	0.87	0.07	0.83 ±0.10	9.29					
JW799	1.11	8.61	F3	0.61	0.01	0.17 ±0.05	8.01	M2	0.12	0.05	0.88 ±0.05	8.44
JW825	3.05	10.11	M3	1.44	0.00	0.87 ±0.09	8.67					

Table 2.8: De-Reddening Parameters for Outer Annulus Stars

Name (1)	$(J-K)$ (2)	K (3)	Sp.Type(1) (4)	$A_K(1)$ (5)	Excess(1) (6)	$(J-K)_o(1)$ (7)	$K_o(1)$ (8)	Sp.Type(2) (9)	$A_K(2)$ (10)	Excess(2) (11)	$(J-K)_o(2)$ (12)	$K_o(2)$ (13)
JW71	1.31	12.29	M5	0.11	0.18	0.97 ± 0.08	12.36					
JW75	0.94	8.93	M3	0.08	0.00	0.81 ± 0.01	8.85					
JW77	1.12	11.03	M3	0.16	0.00	0.88 ± 0.07	10.87					
JW81	1.13	10.48	K5	0.26	0.00	0.73 ± 0.02	10.22	M1.5	0.17	0.00	0.87 ± 0.04	10.31
JW83	1.12	11.03	M4	0.41	0.05	0.45 ± 0.10	10.67					
JW86	2.46	11.63	K7	0.81	0.42	0.82 ± 0.07	11.24					
JW90	1.20	12.51	M5	0.07	0.11	0.98 ± 0.06	12.54					
JW92	1.21	12.55	M6	0.07	0.03	1.07 ± 0.01	12.51					
JW98	1.23	11.58	M4	0.20	0.03	0.91 ± 0.09	11.41					
JW99	1.27	10.02	M4	0.21	0.05	0.91 ± 0.10	9.86					
JW104	1.43	11.98	A0.5	0.94	0.04	-0.04 ± 0.01	11.08	M3	0.20	0.23	0.89 ± 0.01	11.55
JW106	0.98	11.14	M3	0.03	0.04	0.90 ± 0.08	11.15					
JW113	1.70	10.37	K7	0.35	0.34	0.83 ± 0.01	10.36					
JW116	0.85	10.17	K5	0.08	0.00	0.73 ± 0.01	10.08	M0.5	0.02	0.00	0.83 ± 0.03	10.15
JW117	1.48	10.28	K7	0.35	0.12	0.83 ± 0.03	10.05					
JW118	0.89	12.21	M5	0.00	0.00	0.89 ± 0.09	12.21					
JW123	1.85	9.72	K7	0.38	0.45	0.83 ± 0.01	9.80					
JW124	0.95	11.54	M4	0.00	0.06	0.89 ± 0.08	11.60					
JW134	1.54	12.23	M4	0.49	0.00	0.80 ± 0.06	11.74					
JW138	1.18	11.95	M3	0.13	0.09	0.89 ± 0.00	11.91					
JW141	1.39	11.92	M4	0.33	0.00	0.89 ± 0.01	11.59					
JW144	1.14	12.61	M5	0.13	0.00	0.94 ± 0.08	12.48					
JW147	1.06	12.03	M5	0.00	0.13	0.93 ± 0.10	12.16					
JW148	1.83	11.06	M3	0.64	0.00	0.86 ± 0.04	10.42					

Table 2.8 (continued): De-Reddening Parameters for Outer Annulus Stars

Name (1)	$(J-K)$ (2)	K (3)	Sp.Type(1) (4)	$A_K(1)$ (5)	Excess(1) (6)	$(J-K)_o(1)$ (7)	$K_o(1)$ (8)	Sp.Type(2) (9)	$A_K(2)$ (10)	Excess(2) (11)	$(J-K)_o(2)$ (12)	$K_o(2)$ (13)
JW149	1.50	12.16	M3	0.34	0.10	0.89 ± 0.02	11.93					
JW150	2.30	9.25	A3	1.32	0.30	-0.01 ± 0.05	8.23	M3	0.59	0.52	0.89 ± 0.05	8.15
JW155	1.07	12.01	M5	0.07	0.00	0.97 ± 0.05	11.94					
JW158	1.16	10.52	M3	0.24	0.00	0.79 ± 0.05	10.28					
JW164	1.33	11.17	G1.5	0.64	0.00	0.36 ± 0.01	10.53	M1.5	0.26	0.05	0.88 ± 0.01	10.86
JW177	1.74	11.07	K2	0.55	0.27	0.64 ± 0.02	10.79	M0	0.39	0.28	0.87 ± 0.00	10.40
JW188	0.85	12.06	M3	0.00	0.02	0.83 ± 0.10	12.08					
JW207	1.60	11.93	M4	0.31	0.23	0.90 ± 0.06	11.86					
JW209	1.00	12.08	A5	0.55	0.09	0.08 ± 0.02	11.62	F5	0.40	0.13	0.27 ± 0.02	11.55
JW218	1.16	12.25	M4	0.06	0.16	0.90 ± 0.02	12.35					
JW222	1.62	10.56	G0.5	0.80	0.07	0.34 ± 0.02	9.83	M1.5	0.41	0.13	0.87 ± 0.03	10.03
JW232	1.15	9.10	M1.5	0.18	0.00	0.87 ± 0.01	8.92					
JW235	1.72	10.36	K7	0.29	0.44	0.84 ± 0.02	10.51					
JW239	1.22	10.14	G1.5	0.57	0.00	0.36 ± 0.01	9.57	M1.5	0.19	0.06	0.87 ± 0.01	9.89
JW307	1.07	13.11	M1.5	0.11	0.02	0.88 ± 0.01	13.02					
JW329	1.16	12.42	G0.5	0.53	0.03	0.33 ± 0.04	11.92	M2	0.13	0.08	0.88 ± 0.04	12.21
JW364	0.97	8.65	M4	0.04	0.01	0.91 ± 0.01	8.62					
JW371	1.16	11.82	M4	0.17	0.00	0.90 ± 0.08	11.65					
JW380	1.05	11.12	M4	0.08	0.02	0.91 ± 0.01	11.07					
JW381	1.65	9.74	G1.5	0.95	0.06	0.15 ± 0.06	8.85	M2	0.38	0.21	0.87 ± 0.09	9.15
JW383	1.22	11.42	M4	0.20	0.01	0.91 ± 0.11	11.23					
JW386	1.91	9.58	M3	0.67	0.00	0.89 ± 0.09	8.91					
JW388	1.39	10.37	M1.5	0.33	0.03	0.86 ± 0.02	10.07					
JW416	0.95	11.68	M3	0.10	0.00	0.80 ± 0.07	11.58					

Table 2.8 (continued): De-Reddening Parameters for Outer Annulus Stars

Name (1)	(J-K) (2)	K (3)	Sp.Type(1) (4)	A_K (1) (5)	Excess(1) (6)	(J-K) _o (1) (7)	K_o (1) (8)	Sp.Type(2) (9)	A_K (2) (10)	Excess(2) (11)	(J-K) _o (2) (12)	K_o (2) (13)
JW421	1.54	8.84	K2	0.32	0.43	0.63 ±0.02	8.95	M0	0.17	0.44	0.85 ±0.03	8.23
JW428	1.10	11.45	K5	0.26	0.00	0.71 ±0.02	11.20	M1	0.17	0.00	0.85 ±0.02	11.28
JW517	0.96	12.40	M5	0.00	0.08	0.88 ±0.07	12.48					
JW528	2.00	10.65	G6	0.86	0.15	0.55 ±0.04	9.94	M1	0.63	0.18	0.87 ±0.03	9.84
JW566	2.87	8.65	F1	1.75	0.08	0.14 ±0.06	6.99	M2	1.17	0.22	0.87 ±0.09	7.26
JW590	1.05	11.91	M6	0.00	0.00	1.05 ±0.03	11.91					
JW601	0.72	10.95	K1	0.07	0.04	0.57 ±0.00	10.92					
JW612	1.46	11.65	F2	0.77	0.12	0.17 ±0.07	11.00	M2	0.20	0.28	0.87 ±0.08	11.16
JW633	2.19	11.19	M3	0.86	0.00	0.89 ±0.07	10.33					
JW655	1.87	8.03	M3	0.65	0.00	0.88 ±0.02	7.38					
JW664	1.49	10.65	K5	0.51	0.00	0.72 ±0.01	10.14					
JW673	1.62	9.86	K4	0.32	0.43	0.70 ±0.06	9.97					
JW727	1.57	10.74	K1.5	0.52	0.20	0.58 ±0.02	10.42	M0	0.34	0.20	0.85 ±0.01	10.20
JW729	1.42	11.61	G6	0.58	0.10	0.45 ±0.00	11.13	M0.5	0.26	0.17	0.86 ±0.03	11.19
JW747	0.76	9.46	G1.5	0.29	0.00	0.32 ±0.01	9.16	K5	0.01	0.01	0.74 ±0.04	9.43
JW753	1.26	10.66	K3	0.38	0.05	0.62 ±0.01	10.32	M0	0.23	0.05	0.86 ±0.01	10.37
JW788	1.43	11.04	M3	0.26	0.15	0.88 ±0.00	10.93					
JW789	1.26	12.73	M5.5	0.12	0.06	1.02 ±0.03	12.67					
JW805	1.83	11.01	A5.5	1.16	0.00	0.06 ±0.05	9.85	M3	0.49	0.18	0.90 ±0.07	10.34
JW812	1.22	11.02	M4	0.16	0.08	0.90 ±0.02	10.93					
JW824	2.40	9.61	M6.5	0.59	0.35	1.15 ±0.02	9.37					
JW836	1.57	10.31	K3	0.47	0.21	0.65 ±0.02	10.05	M0	0.32	0.22	0.87 ±0.03	9.77
JW843	1.04	11.33	M1	0.18	0.00	0.77 ±0.05	11.16					
JW854	1.81	10.69	A4	1.18	0.00	0.01 ±0.02	9.50	M3	0.49	0.16	0.90 ±0.05	10.03

Table 2.8 (continued): De-Reddening Parameters for Outer Annulus Stars

Name (1)	$(J-K)$ (2)	K (3)	Sp.Type(1) (4)	$A_K(1)$ (5)	Excess(1) (6)	$(J-K)_o(1)$ (7)	$K_o(1)$ (8)	Sp.Type(2) (9)	$A_K(2)$ (10)	Excess(2) (11)	$(J-K)_o(2)$ (12)	$K_o(2)$ (13)
JW863	1.62	10.73	F5	0.82	0.12	0.26 ± 0.06	10.02	M1.5	0.36	0.21	0.87 ± 0.06	10.16
JW878	1.01	11.35	M6	0.00	0.00	1.01 ± 0.02	11.35					
JW880	0.96	11.76	M3	0.02	0.03	0.89 ± 0.02	11.77					
JW883	1.27	10.30	M3	0.23	0.03	0.89 ± 0.14	10.10					
JW886	1.68	9.87	M3	0.59	0.00	0.79 ± 0.01	9.28					
JW889	0.60	12.02	G3	0.16	0.00	0.36 ± 0.03	11.86					
JW898	1.09	11.21	M4	0.09	0.06	0.90 ± 0.12	11.18					
JW907	0.87	10.91	M1.5	0.02	0.00	0.84 ± 0.01	10.89					
JW910	1.59	12.07	M4	0.34	0.16	0.92 ± 0.01	11.89					
JW916	0.95	11.97	M4	0.02	0.01	0.91 ± 0.00	11.96					
JW930	1.01	11.67	M2	0.12	0.00	0.83 ± 0.05	11.55					
JW931	2.90	8.76	M5	1.26	0.01	0.97 ± 0.14	7.51					
JW933	1.05	11.15	M3	0.06	0.07	0.89 ± 0.13	11.16					
JW942	1.90	12.10	K5	0.81	0.00	0.68 ± 0.02	11.30	M1.5	0.71	0.00	0.82 ± 0.04	11.39
JW945	1.46	8.87	M4	0.32	0.06	0.91 ± 0.03	8.61					
JW950	0.52	11.12	G0	0.16	0.00	0.28 ± 0.03	10.96					
JW951	1.70	11.75	M4	0.38	0.22	0.90 ± 0.08	11.59					
JW954	1.51	11.06	A0.5	0.95	0.10	-0.03 ± 0.01	10.21	M3	0.21	0.30	0.90 ± 0.01	10.55
JW962	1.39	10.14	K7	0.27	0.16	0.83 ± 0.04	10.04					
JW969	2.01	11.29	K7	0.43	0.53	0.83 ± 0.01	11.40					
JW980	1.31	10.77	A4	0.83	0.01	0.04 ± 0.03	9.95	M3	0.14	0.20	0.90 ± 0.04	10.44
JW981	1.06	10.65	K3	0.27	0.03	0.62 ± 0.03	10.41	M0	0.09	0.07	0.86 ± 0.05	10.50
JW990	0.96	11.54	M4	0.03	0.00	0.91 ± 0.01	11.51					
JW998	1.08	11.02	K3	0.29	0.02	0.62 ± 0.04	10.75	M0	0.11	0.05	0.87 ± 0.06	10.86

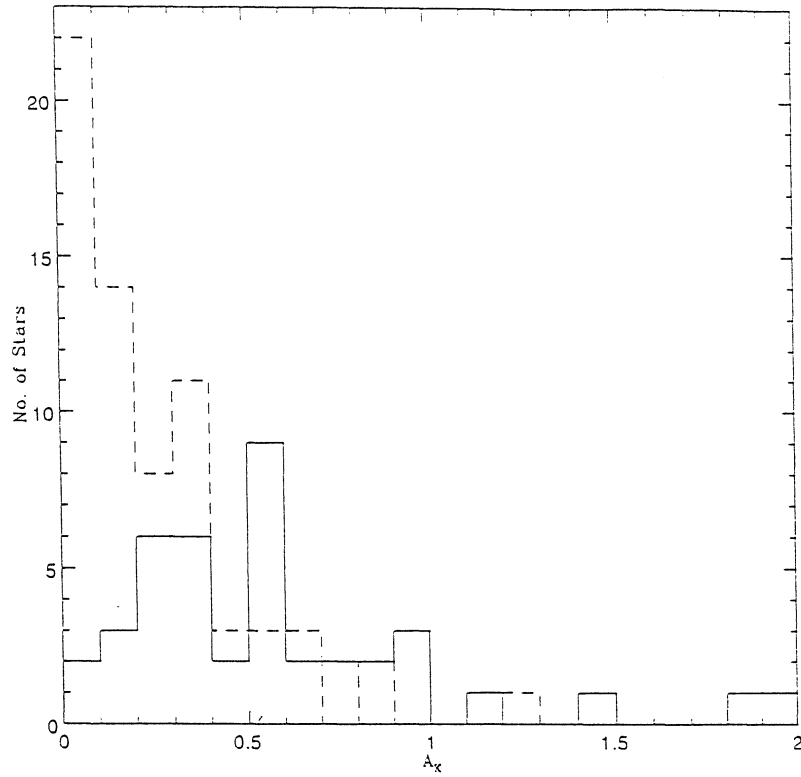


Figure 2.13: Histogram of Trapezium Cluster stars (solid line) and outer annulus stars (dashed line) as a function of A_K for sample members which have been successfully dereddened.

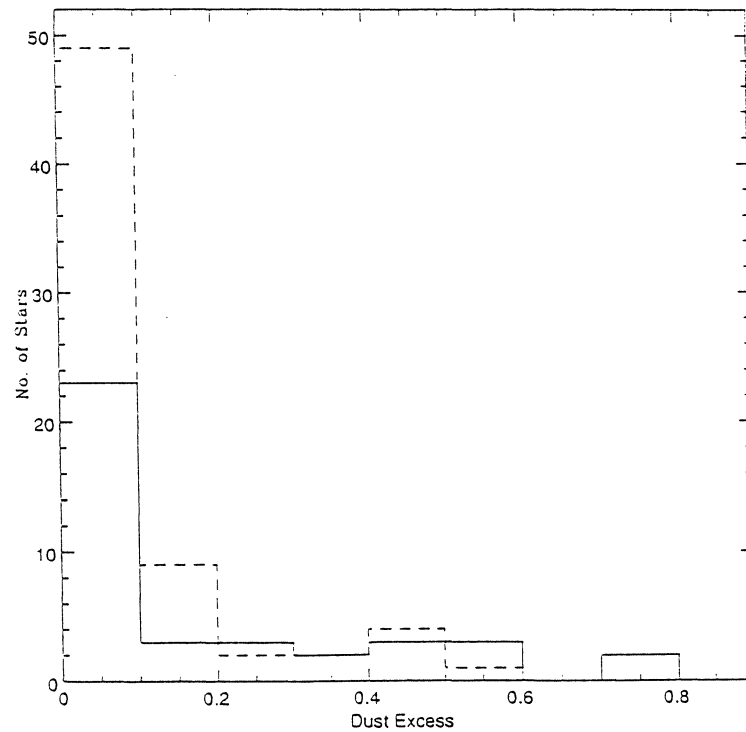


Figure 2.14: Histogram of Trapezium Cluster stars (solid line) and outer annulus stars (dashed line) as a function of dust excess for sample members which have been successfully dereddened.

the tables of $(J-K)$ measurements of dwarfs covering spectral types from B8–M6 given by Bessell & Brett (1988) to convert the T_{eff} values to $J-K$ colors. In order to obtain K magnitudes from the M_{bol} values, we used the K bolometric correction function of Bessell & Wood (1984) obtained for oxygen-rich stars in the LMC and Galaxy:

$$BC_K = 0.72 + 2.65(J - K) - 0.67(J - K)^2 : 0.6 < (J - K) < 2 \quad (2.7)$$

We applied the bolometric corrections provided by Johnson (1966) outside this $(J-K)$ range. Mazzitelli (1989) has critically reviewed the accuracy of theoretical PMS evolutionary tracks, including those of Vandenberg (1983). He claims that errors in such models have the effect of producing overly large estimates of mass and age, due to the nature of the inputs into these models. The errors in mass for PMS stars correspond to $\sim \pm 0.1 M_\odot$, and in age of $\sim 20\text{--}30\%$ for stars younger than 10^7 yr. Uncertainties of this magnitude are insignificant compared with the uncertainties in our photometry.

Thirty-nine Trapezium Cluster stars were dereddened to a unique spectral type (filled circles; Figure 2.15). Comparison with the PMS evolutionary tracks suggests that the majority of these are $\sim 10^6$ yr or younger in age, with some stars apparently even younger than 10^5 yr. The stars are all less massive than $1.3 M_\odot$. Consideration of the full sample of 59 stars shows that the range in age could extend to a few $\times 10^6$ yr, with the mass range potentially up to $\sim 5 M_\odot$, due mainly to the possible presence of $\sim$ five stars earlier than G in spectral type in our sample.

The Outer Annulus Sample

The K_o , $(J-K)_o$ diagram of the 96 dereddened outer annulus stars is given in Figure 2.16. Here, 67 stars have been unambiguously dereddened. Judging from the PMS tracks given, the mean age of this sample is also 10^6 yr or younger, as for the Trapezium Cluster sample. However, the range in age extends to more than 10^7 yr, reaching to the main sequence itself. The mass range is the same as found for the Trapezium Cluster sample, with a maximum stellar mass of $\sim 1.3 M_\odot$. These results do not change significantly when the whole sample is taken into account, apart from the mass range again increasing to nearly $5 M_\odot$.

It is evident from Figures 2.15 and 2.16 that the Trapezium Cluster and outer annulus populations are similar in their spectral types, mean age, and mass range. However, we find a number of older stars at the radii of our outer annulus region which are not observed in the inner Trapezium Cluster sample. The outer annulus sample includes stars at fainter K magnitude than could be observed and dereddened from the Trapezium Cluster, so selection effects may be responsible for our non-detection of older, low luminosity stars in the Trapezium Cluster itself. Comparison

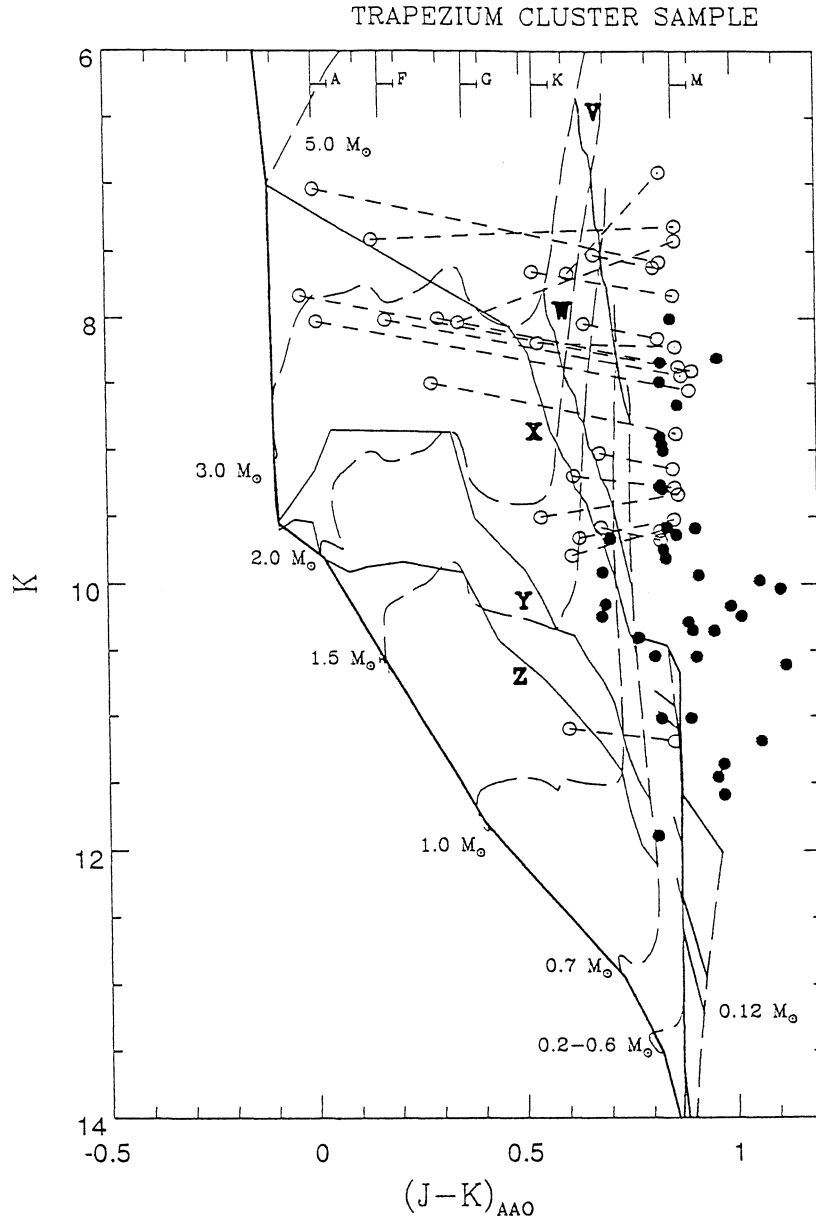


Figure 2.15: K_0 vs $(J-K)_0$ diagram for the Trapezium Cluster sample. The solid line bounding the diagram to the left represents the main-sequence locus in this plane. Dashed lines are given for PMS evolutionary tracks from 0.12 to 3 $M_{\odot}$ (VandenBerg 1991; see text) and for a 5 $M_{\odot}$ star (Iben & Talbot 1966). Solid lines marked V to Z correspond to isochrones such that V: 10^5 yr; W: 5×10^5 yr; X: 10^6 yr; Y: 5×10^6 yr; Z: 10^7 yr. The figure includes lines marking the observed $J-K$ colors for A- to M-type dwarfs (Bessell & Brett 1988), along the top axis. The positions of the dereddened stars are indicated by solid circles where only one spectral type has been confidently derived to reasonable accuracy. In cases where two spectral types are possible, the two feasible positions are shown with open circles connected by dashed lines.

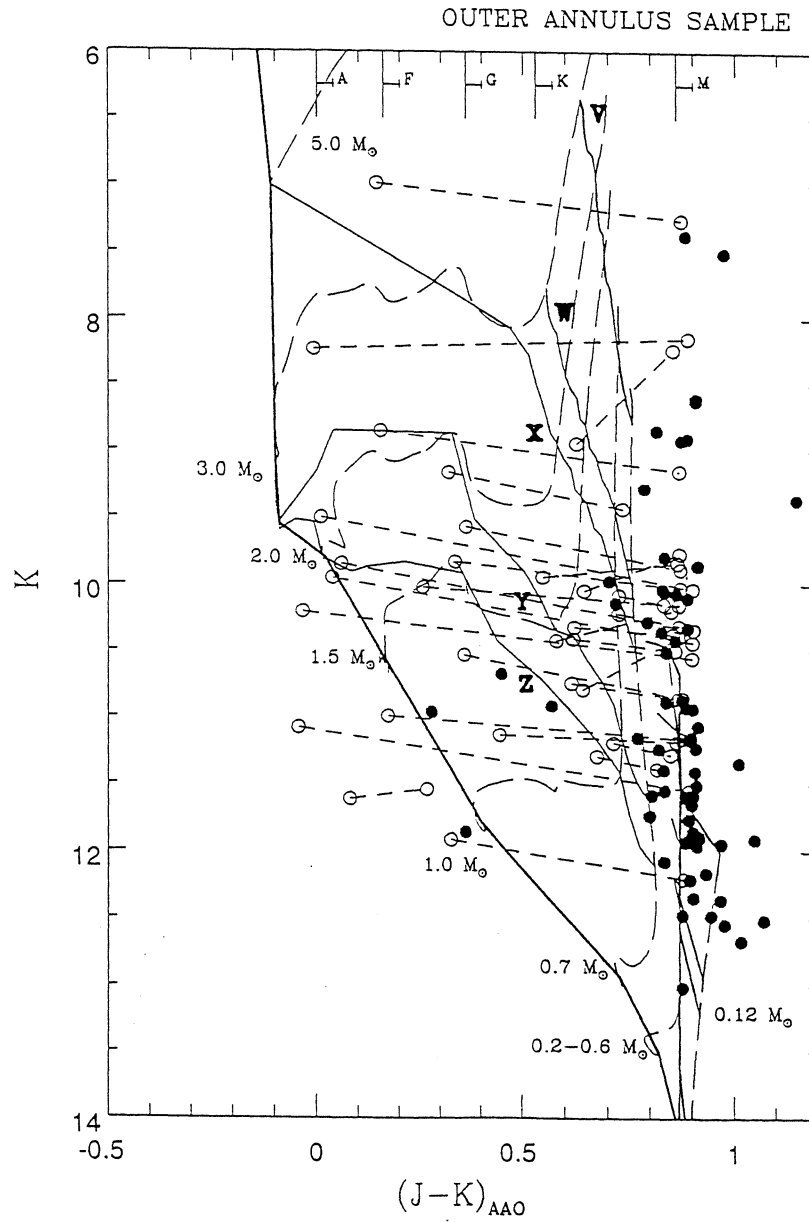


Figure 2.16: K vs $(J-K)$ diagram for the outer annulus sample. All features are as described for Figure 2.12.

of the two figures shows that the difference in our two samples corresponds to a larger number of Trapezium Cluster stars being either high on their Hayashi tracks and therefore younger, or being near-main-sequence stars of high mass, compared with outer annulus stars. While the uncertainties in our dereddening process limit any definitive statement regarding the suggested age and mass spreads, we have shown that the method has led to reasonable solutions for many of our objects. We explore the implications of our results further in §2.4.

2.4 Discussion

2.4.1 The Age Distribution

On the basis of the results obtained in the current work we find that the Trapezium Cluster and outer annulus stars studied are almost exclusively in the PMS phase of stellar evolution, the majority being 10^6 yr or younger. The outer annulus stars observed display a larger age spread, a few stars being unequivocally dereddened as far as the main sequence. These have comparable ages to the ages estimated for giant molecular clouds, $\sim 3 \times 10^7$ yr (Blitz & Shu 1980). We conclude that star formation has continued in the Trapezium Cluster from $\sim 10^6$ yr to the present. While it remains to be seen whether older stars are also present in the cluster, we note that older stars are found in close proximity, within $8'$ radius of the Trapezium OB stars.

The results obtained here agree with the qualitatively derived cluster age of between $1\text{--}2 \times 10^6$ yr obtained by Zinnecker et al. (1992), based on interpretation of the K luminosity function. The age estimates given above are also in good agreement with those of Herbig & Terndrup (1986) for 68 optically visible Trapezium Cluster stars. These authors find the majority of their sample to be no older than 10^6 yr. The main difference between the methods of analysis of Herbig & Terndrup and the work presented here is in the dereddening method used. Herbig & Terndrup have used a *mean* extinction value corresponding to $A_K \sim 0.3$ mag for all their stars. We calculate the extinction for each star individually, with the average of our infrared-selected sample determined to be $A_K \sim 0.5$ mag in the Trapezium Cluster vicinity. Our dereddening procedure has highlighted the non-uniform nature of the extinction suffered by sources in the Trapezium Cluster area and hence the need to estimate extinctions and dust excesses associated with these stars on an individual basis.

The high mass Trapezium OB stars located at the center of the Trapezium Cluster are claimed to be approximately zero-age main sequence stars (Warren & Hesser 1978). Thus, only a lower limit to their ages of $\sim 6 \times 10^4$ yr (Iben 1965) can be estimated, using theoretical models of PMS evolution for high mass stars. Comparison with the ages determined here for the low mass stars demonstrates that

the OB stars could be among the youngest stars in the region. Consequently, the question of whether low mass star formation has been inhibited by the formation of the OB stars is subject to the uncertainty in the age determination for the OB stars. If they *have* been on the main sequence for some time, the fact that low mass cluster stars with ages of $< 10^5$ yr are observed would demonstrate that low mass star formation has not been inhibited by the formation of these high mass stars. The BN-KL nebula, located $\sim 1\text{-}1.5'$ distant from the Trapezium OB stars, includes BN, an early B-type zero-age main sequence star (Scoville et al. 1983), and IRC2. These are both estimated to have ages of $\leq 10^4$ yr (see for example Scoville et al. 1983; Mundy et al. 1986). Comparison with the ages determined here for the Trapezium Cluster low mass stars lends support to the widely-held notion (Genzel & Stutzki 1989; Zinnecker et al. 1992; and references therein) that star formation in the BN-KL region is, overall, a more recent occurrence than in the Trapezium Cluster as a whole. The work of Cohen & Kuhl (1979) included stars from the Orion Nebula Cluster (the 1c sub-group), a few of which lie very close to our outer annulus. Their 21 Orion Nebula Cluster stars have an age spread from $\sim 3 \times 10^4$ yr to $\sim 6 \times 10^6$ yr, with a mean age of $\sim 10^6$ yr. Thus, while the average is in excellent agreement with our results for the Trapezium Cluster, a larger number of older stars have been identified in this extended region than we observe in our sample of Trapezium Cluster stars. It is of interest to determine if older stars are also present in the central Trapezium Cluster, since this will address the question of whether the two cluster populations are the product of the same triggering event.

Moving further afield, work on the dark cloud L1630 located in the northern extent of the Orion Molecular Cloud (OMC) complex (Lada & Lada 1991; and references therein) give ages of $< \text{a few} \times 10^5$ yr for the embedded stars. These stars are observed to form in a clustered mode of star formation similar to that found in the Trapezium Cluster. Cohen & Kuhl (1979), Strom et al. (1989), and Chen et al. (1992), among others, have investigated embedded stars in L1641, in other regions than the Orion Nebula. The ages determined for these stars are less than 3×10^6 yr with a mean age of $\sim 10^6$ yr. The ages estimated for the L1630 and L1641 low mass stellar populations are comparable with those obtained here for our two samples. Thus, several major star formation events appear to have been triggered essentially simultaneously. The common ages determined for these star formation events in the OMC complex may eventually help in understanding the nature of the triggering mechanism(s) involved (for example, Zinnecker et al. 1992; Chen et al. 1992).

2.4.2 The Mass Distribution

The stars in both our Trapezium Cluster and outer annulus samples range from ~ 0.1 to $\sim 1.3 M_{\odot}$, with a mean mass of around $0.5 M_{\odot}$. The masses derived are of course subject to the uncertainties in our dereddening method, and are used here as an initial solution to the problem of the nature of the low mass Trapezium Cluster population. We note that the detection limit of our observations has prevented faint, lower mass stars in the Trapezium Cluster from being included in this study.

Zinnecker et al. (1992) show that the peak of the K luminosity function for the infrared Trapezium Cluster corresponds to a stellar mass of $\sim 0.3 M_{\odot}$. However, as they state, the transformation between luminosity and mass is not straightforward for PMS stars, so means such as those used in the present study are necessary to derive an accurate cluster mass function. The optical photometry study of the Trapezium Cluster conducted by Herbig & Terndrup (1986) finds stellar masses of up to $3 M_{\odot}$. This mass range is in good agreement with our results. Cohen & Kuhn (1979) also determine a mass range from ~ 0.35 to $3 M_{\odot}$ for their Orion Nebula Cluster stars, but obtain a mean mass of $\sim 1 M_{\odot}$. This is higher than the mean stellar mass found here for the Trapezium Cluster. We note that our sample includes low mass stars not known to Cohen & Kuhn. However, in general these comparisons show that the low mass PMS population in this region has the same mass function out to at least $18'$ in radius from the Trapezium OB stars.

For a mean mass of $\sim 0.5 M_{\odot}$ the mass of the infrared cluster of ~ 562 stars is $\sim 281 M_{\odot}$. If we consider the same volume as that used by Herbig & Terndrup (1986) for comparison purposes, then the mass density obtained here is $\sim 4330 M_{\odot} \text{ pc}^{-3}$. Adding the contribution from the Θ^1 Ori stars of $\sim 84 M_{\odot}$, we obtain a mass density of $\sim 5620 M_{\odot} \text{ pc}^{-3}$. In a closed system with $\sim 100\%$ star formation efficiency, this amount of mass would have formed from gas of density $\sim 1.1 \times 10^5 \text{ H}_2 \text{ molecules cm}^{-3}$. Gas densities of this order are supported by density measurements of 10^5 – 10^6 cm^{-3} in dense cores of the Orion Molecular Cloud (Snell et al. 1984; Mezger, Wink & Zylka 1990) as well as in ultra-compact H II regions, the birthplaces of OB clusters (Churchwell 1991; Cesaroni et al. 1991). The densities determined by Herbig & Terndrup (1986) are $\sim 3000 M_{\odot} \text{ pc}^{-3}$ including the Θ^1 Ori stars, or $\sim 0.6 \times 10^5 \text{ H}_2 \text{ molecules cm}^{-3}$. Thus, our estimates are around 1.8 times as much as their values. This is not unexpected since we are including many optically obscured stars not known to Herbig & Terndrup. We note that the stellar mass density of the Trapezium Cluster is significantly larger than has been observed by Chen et al. (1992) for PMS populations in L1641, but more comparable with the newly revealed clusters in regions such as L1630 (Lada & Lada 1991) and S106 (Hodapp & Rayner 1991). Larger stellar mass densities have been proposed for clusters in the Serpens molecular cloud (Eiroa & Casali 1989) and L1641 (Strom, Margulis & Strom 1989).

The spectral types derived here are between late K and M, with a mean of M3. This range agrees with the spectral type range measured for the Orion Nebula Cluster stars observed by Cohen & Kuhi (1979). However, Cohen & Kuhi find a mean spectral type of around K for their Orion Nebula Cluster stars. Based on different mean spectral types found in various star forming regions (Herbig 1977; Appenzeller, Jankovics & Krautter 1983), it has been proposed that star-forming regions such as Orion and NGC 2264 are forming more massive low mass stars ($\sim 1 M_{\odot}$) than places such as Taurus-Auriga, Chamaeleon, or Lupus, all of which have an average spectral type of M0 which translates to a mean mass of $\sim 0.5 M_{\odot}$. The results obtained in the present work (including many low mass stars unknown to Cohen & Kuhi) provide no evidence that the Trapezium Cluster low mass stars are any more massive than low mass stars in these other regions, but rather suggest that they have comparable masses and spectral types. This result is dependent on the reddening estimates for the stars. Thus, further work is needed to ascertain whether there is in fact a difference between the masses of low mass stars in the Orion region and low mass stars in dark clouds.

2.4.3 The Bound Nature of the Trapezium Cluster

The question of whether the Trapezium Cluster is bound or not has been much debated (Genzel & Stutzki 1989, and references therein). Comparison of the observed velocity dispersion of Trapezium Cluster stars of 2.3 kms^{-1} (Jones & Walker 1988) with the velocity dispersion obtained using previously estimated cluster masses (most recently Herbig & Terndrup 1986) have led to the conclusion that the cluster is not in fact bound. We redo the calculation for the entire HAB infrared cluster. Firstly, an estimate of the gas mass in the cluster volume can be made by using the maximum $A_K \sim 2.0 \text{ mag}$ for our sample in the following relationship (see Dickman 1978):

$$\frac{N_{H_2}}{A_V} = 1.25 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \quad (2.8)$$

Considering the area covered by the HAB survey, the extinction estimates correspond to $\sim 400 M_{\odot}$ of gas within our cluster volume. We use the combined mass of gas and stars in the binding equation:

$$\sigma = \sqrt{\left(\frac{GM}{2r}\right)} \quad (2.9)$$

where r is the radius containing half the mass of the cluster. An accurately derived mass function is required to determine this half-mass radius. We assume a uniform distribution of low mass stars as a crude first-order approximation, such that $r \sim 9.3 \times 10^{17} \text{ cm}$ ($\sim 140''$). The value of σ , the velocity dispersion, is then

determined here to be $\sim 2.3 \text{ kms}^{-1}$, exactly equivalent to that measured observationally. Thus, including the estimated gas mass in the cluster, we find that the Trapezium Cluster is at present a bound system. Consideration of the stars alone would not be sufficient to bind the cluster, based on the first-order estimates of stellar masses used here. In this interpretation future loss of gas from the Trapezium Cluster region, via ultraviolet radiation and stellar winds from the OB stars (Garay et al. 1987), will be sufficient to unbind the system. Our analysis highlights the importance of an accurate determination of the mass distribution of the entire cluster in ascertaining the dynamical state of the system.

An order-of-magnitude estimate of the star formation efficiency in the Trapezium Cluster can be made using the cluster gas mass calculated above. Using the total mass determined here for the low mass stars of $\sim 281 M_{\odot}$, and $\sim 84 M_{\odot}$ for the mass of the high mass OB stars, the total stellar mass in the cluster region is $\sim 365 M_{\odot}$. Thus, the star formation efficiency:

$$SFE = \frac{M_{star}}{M_{star} + M_{gas}} \quad (2.10)$$

is $\sim 48 \%$. Similarly high star formation efficiencies of between 20 and 42 % are determined for embedded clusters in NGC 2071, NGC 2068 and NGC 2024 (Lada 1990) in L1630, and for the embedded ρ Oph cluster (Wilking, Lada & Young 1989). As might be expected, high star formation efficiencies are producing dense stellar clusters in many regions. This may be compared with regions such as Taurus where the derived star formation efficiency is $< 5 \%$ (for example, Myers 1982), and the observed stellar density is comparatively low.

2.4.4 The Spatial Distribution

We have established that the Trapezium Cluster stars sampled have an average extinction of $A_K \sim 0.5 \text{ mag}$. This is most likely a minimum estimate for the total low mass Trapezium Cluster of more than 550 stars, since our dereddened sample is biased to those objects detected at I . The mean extinction obtained here suggests that our sample is more deeply embedded on average than the optical sample of Herbig & Terndrup (1986), with $\overline{A_K} \sim 0.3 \text{ mag}$. Our Trapezium Cluster sample is also more reddened than stars from the outer annulus, which have a mean extinction of $A_K \sim 0.2 \text{ mag}$. We conclude that the Trapezium Cluster stars in our sample are in general more embedded within the molecular cloud material than stars as close radially as the outer annulus stars observed here.

The Orion Nebula H II region is estimated to have a mean A_K of $\sim 0.2 \text{ mag}$ (Greve et al. 1989). This is of the order of the extinction estimated towards the Θ^1 Ori stars of between $A_K \sim 0.1\text{--}0.3 \text{ mag}$ (Warren & Hesser 1978; Garay, Moran

& Reid 1987). Comparison of the extinction determined towards the Θ^1 Ori stars with the extinction towards the H II region places these high mass stars at the near-face of the molecular cloud. In relation to this, our extinction estimates for the low mass stellar population indicate that the low mass stars are generally more deeply embedded in the cloud than the high mass stars.

The *maximum* extinction associated with our samples is $A_K \sim 2$ mag. for $\sim$ seven Trapezium Cluster stars. Thus, it is unlikely that any of the stars observed here are members of a more embedded low mass cluster associated with the BN-KL region (Lonsdale et al. 1982), given extinction estimates towards this region of $A_K \sim 2-5$ mag (Gillett et al. 1975; Joyce, Simon & Simon 1978; Scoville et al. 1983; Beckwith 1982; Hyland et al. 1984; Minchin et al. 1991).

We have used arguments similar to those of Herbig & Terndrup (1986) in order to gain an understanding of the spatial extent of the Trapezium Cluster through the molecular cloud. Herbig & Terndrup address this issue using the stellar density of their optical sample with the K luminosity function obtained by Hyland et al. (1984), assuming a cloud depth of 4 pc and varying degrees of total cloud extinction. Their results indicate that the cluster is in fact local to the near-face of the cloud, rather than being uniformly distributed throughout the cloud. We study the problem using the complete HAB infrared sample (maximum radius ~ 0.6 pc) together with the cloud depth inferred by Bally et al. (1987) from ^{13}CO emission maps of 0.5–2 pc. Firstly, we consider the cloud to be composed of cylindrical slabs, each of radius $r = 0.6$ pc and depth $2r$. The K luminosity function (KLF) for a uniform distribution of stars through the cloud is then derived in the following way. We assume that each slab has the same stellar density and intrinsic KLF as the infrared cluster observed. The intrinsic KLF is approximated by dereddening the observed K luminosity function (HAB) using the mean cluster extinction estimated here of ~ 0.5 mag. Hence, we attenuate this intrinsic KLF by increasing increments for each slab considered, based on the total cloud extinction assumed. The contributions from each slab are then summed to make up the total predicted KLF. This is then compared with the observed function. Figure 2.17 shows our results for a cloud depth of ~ 2.4 pc and total cloud extinction of $A_K \sim 2$ mag and 4 mag. We find that a geometry where the cluster is spread at its observed density through the cloud predicts more stars than are observed, although the predicted K luminosity function is closer to the observations for larger values of cloud extinction. We conclude, on the basis of updated parameters for the Trapezium Cluster region, that the cluster is most likely to be local to the near-face of the cloud, in agreement with the finding of Herbig & Terndrup (1986; see also Genzel & Stutzki 1989; Zinnecker et al. 1992).

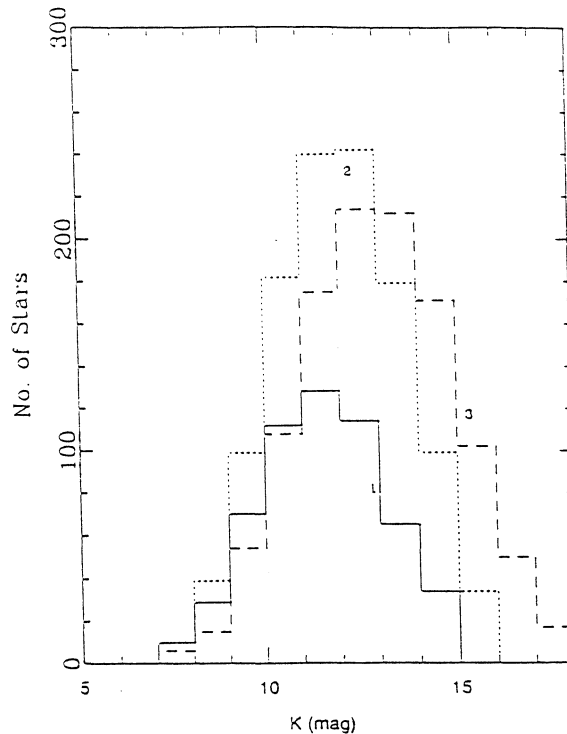


Figure 2.17: The K Luminosity Function for (1) the observed infrared cluster; (2) a cluster spread through a cloud of depth 2.4 pc and total cloud extinction ~ 2 mag; (3) a cluster spread through a cloud of depth 2.4 pc and total cloud extinction ~ 4 mag.

2.4.5 Infrared Excess Stars

Our results demonstrate that around half the stars in both the Trapezium Cluster and outer annulus samples have significant infrared excesses. Furthermore, we determine that stars in our Trapezium Cluster sample have slightly larger infrared excesses than those in the outer annulus region overall. Our data suggest that disk-stripping via star-star interactions, proposed by Herbig & Terndrup (1986; see also Zinnecker et al. 1992), is unlikely to be a significant process in this extremely dense region, at least for the inner-disk regions detected at near-infrared wavelengths. This is not unreasonable because the inner-disk regions responsible for near-infrared excess are the most tightly bound disk material. Our result does not rule out significant interactions between the extended outer disk regions which are best studied at millimeter wavelengths. The proportion of classical T Tauri stars (with infrared excesses) compared with naked T Tauri stars (no infrared excess) determined here is similar to that found in other young stellar populations such as Taurus-Auriga and ρ Oph (Walter 1986; Walter et al. 1988) and Chamaeleon (Hartigan 1993). Thus, in this sense, the PMS population in the Trapezium Cluster is comparable with less populous star forming regions.

We point out that the values of infrared excess and interstellar extinction estimated here are subject to the assumptions of the dust models used. As an example,

these models assume a spherically symmetric distribution of circumstellar material around the star. We adopt these models as a good approximation to the form of the circumstellar dust (Hyland et al. 1982), noting that other geometries for this material are possible.

2.5 Conclusions

The study of Trapezium Cluster stars using near-infrared photometry methods has provided the following information about the stellar population. The Trapezium Cluster stars sampled here out to $\sim 8'$ predominantly range in age from $\sim 10^6$ yr to the present. Thus, the lower limit to the ages of the OB stars of $\sim 6 \times 10^4$ yr (Iben 1965) imply that they could be among the more youthful of the stars in the region. Alternatively, if the OB stars have been on the main sequence for some time, then our estimation of low mass cluster stars with ages of $< 10^5$ yr suggests that low mass star formation has not been inhibited by the formation of the high mass stars. We find $\sim$ four stars older than $\sim 10^7$ yr at the radial distance ($8'$) of our outer annulus. It remains to be seen whether any stars in the central Trapezium Cluster have similar ages. We concur with the picture presented in previous studies (Genzel & Stutzki 1989, and references therein) that the small number of embedded BN-KL sources are likely to have been triggered even more recently than the Trapezium Cluster. The stars observed here have masses between ~ 0.1 and $1.3 M_{\odot}$, in good agreement with the findings of Herbig & Terndrup (1986) for their Trapezium Cluster sample, and the Orion Nebula Cluster sample of Cohen & Kuhl (1979). Thus, there is no evidence for a mass gradient with increasing radius. For a mean mass of $\sim 0.5 M_{\odot}$, the mass density of the cluster is determined to be $\sim 5620 M_{\odot} \text{ pc}^{-3}$, corresponding to $\sim 1.1 \times 10^5 \text{ H}_2 \text{ molecules cm}^{-3}$. Regions in the Orion Molecular Cloud of this gas density have been detected (for example, Snell et al. 1984; Mezger, Wink & Zylka 1990). Our densities are approximately 1.8 times the estimates of Herbig & Terndrup (1986) of $\sim 3000 M_{\odot} \text{ pc}^{-3}$, or $0.6 \times 10^5 \text{ H}_2 \text{ molecules cm}^{-3}$. The total mass obtained here for the low mass stars is combined with the gas mass determined from our extinction estimates to show that the cluster is at present bound, if both gas and stars are taken into account. The derived mean mass for the low mass cluster stars suggests a high star formation efficiency of $\sim 48 \%$ in this region. However, the cluster parameters derived from our mass estimates are subject to the errors in our dereddening process. An accurate determination of the cluster mass distribution will help constrain the findings of the present investigation.

The average extinction to our sample of Trapezium Cluster stars is $A_K \sim 0.5$ mag, suggesting that our sample stars are more extincted than the optical stars observed by Herbig & Terndrup (1986) with $A_K \sim 0.3$ mag. We have used our extinction

determinations to address the question of the extent to which the Trapezium Cluster is distributed through OMC-1. We find that the infrared cluster is best modelled as being located in close proximity to the Θ^1 Ori stars at the near-face of the cloud. Such a geometry for the cluster is that predicted by Herbig & Terndrup (1986), Genzel & Stutzki (1989) and Zinnecker et al. (1992), among others. The number of stars with significant infrared excesses in our Trapezium Cluster sample is comparable with the proportions found in other less populous star-forming regions such as Taurus-Auriga, ρ Oph and Chamaeleon (Walter 1986; Walter et al. 1988; Hartigan 1993).

Chapter 3

Optical Spectroscopy of Trapezium Cluster Stars

3.1 Introduction

The Trapezium Cluster at the core of the Orion Nebula is important in being a prototype of a mode of star formation where high and low mass stars are forming in embedded clusters. The Trapezium Cluster consists of more than 550 low mass stars immediately surrounding the Trapezium OB stars in the Orion Nebula (Hyland, Allen & Bailey 1993, hereafter HAB). It covers a radial extent of ~ 0.6 pc ($\sim 5'$: HAB; see also Herbig & Terndrup 1986). Situated as it is at the centre of the Orion Nebula, the cluster is associated with bright nebulosity which has severely obstructed photographic observations of individual stars. Observations using CCDs with large dynamic range have been more successful. This method has been used in the present spectroscopic study of the Trapezium Cluster to obtain spectral types for cluster stars in order to locate the stars in the HR diagram and hence derive stellar masses and ages.

In Chapter 2, near-infrared photometry measurements of Trapezium Cluster stars were used to derive mass and age estimates for the stars. The shape of the initial mass function (IMF) of embedded clusters provides valuable information regarding the processes by which such clusters form from their natal molecular clouds. Knowledge of the relative ages of the cluster stars helps determine whether low and high mass stars form at the same time in these regions. However, the results of our infrared program were limited by the difficulties of separating the contributions of interstellar reddening and circumstellar dust emission. These problems led to ambiguities in the intrinsic values obtained for a number of stars. The difficulties highlight the more fundamental issue that theoretical tracks for young low mass stars lie close together in temperature in the color-magnitude diagram. Thus, accu-

rate stellar temperatures are required to distinguish between tracks of different mass stars. It was clear that accurate spectral type information of as many Trapezium Cluster stars as possible was needed to define their stellar temperatures and obtain more accurate estimates of stellar extinctions, masses, and ages. In the following work we discuss these data.

As well as its significance to the initial mass function of the cluster, knowledge of the mass distribution provides information on the degree of mass segregation among cluster stars. Such segregation is suggested by the high mass Trapezium OB stars, which are concentrated towards the centre of the cluster in our line of sight. However, it is not yet clear whether mass segregation is present among the lower mass cluster members. A possible age spread was found among the Trapezium Cluster stars from the results of our infrared photometry program, from $< 10^5$ yr to a few $\times 10^6$ yr. Here, we will probe the reality of this age range.

Published spectral types exist for very few cluster stars. Spectroscopic data of twelve of the brighter Trapezium Cluster members were presented by Herbig & Terndrup (1986). A mean spectral type of G5 was found for this small sample. Two Trapezium Cluster stars are included in the sample of Orion Nebula Cluster stars classified by Walker (1983) as K0? and K4. Other spectroscopic studies in the vicinity of the Trapezium Cluster concentrate on the more accessible Orion Nebula population. Parsamian & Chavira (1982) find that the predominant spectral class of the 49 Orion Nebula Cluster stars in their sample is K-type, in agreement with the result of Cohen & Kuhl (1979) for their sample of more than 80 Orion Nebula Cluster stars.

The work of Herbig & Terndrup (1986) is the most extensive analysis of the Trapezium Cluster undertaken to date. These authors used narrow-band CCD photometry to observe 68 Trapezium Cluster stars and, due to the paucity of spectral type information, were forced to resort to a mean value of $A_V \sim 2.4$ mag ($A_K \sim 0.26$) for the stars without spectral classifications. They place the stars on a color-magnitude diagram to derive mass and age estimates, finding a mass range for their sample from < 0.7 to $3 M_\odot$, and ages generally less than 4×10^6 yr, with most stars being not more than 10^6 yr in age. Our infrared photometry program has demonstrated the variations in amounts of extinction toward Trapezium Cluster stars and hence the need to estimate extinctions on a star-by-star basis.

The mass density of the Trapezium Cluster is estimated to be $\geq 1800 M_\odot \text{ pc}^{-3}$ (Herbig & Terndrup 1986). This is one of the highest-known mass densities for young clusters. Whether or not the Trapezium Cluster is dynamically bound is the subject of much ongoing debate (Strand 1958; Vasilevskis 1971; Fallon, Gerola & Sofia 1977; Herbig & Terndrup 1986; van Altena et al. 1988; Jones & Walker 1988, hereafter JW; Gatley et al. 1991). Mathieu (1983), Lada, Margulis & Dearborn

(1984), and Verschueren (1990) all calculate that star formation efficiencies greater than 50 % are required for the formation of bound clusters with O-type stars in locations where rapid gas removal occurs. Genzel & Stutzki (1989) suggest that the Trapezium Cluster will in fact disperse due to the removal of binding gaseous material by the local OB stars. JW conducted a proper motion survey of a $\sim 2 \text{ pc} \times 2 \text{ pc}$ ($15' \times 15'$) region centred on the Trapezium Cluster. They derive a velocity dispersion of $\sim 2.3 \text{ kms}^{-1}$ for approximately 900 cluster members, a value which they found to be roughly constant within 1.6 pc (12') of the Trapezium OB stars. This velocity dispersion is much higher than the 0.8 kms^{-1} predicted (JW) using the optically observed cluster mass of Herbig & Terndrup (1986). Such calculations suggest that the cluster is in fact unbound and in the process of dissipating. However, the recently revealed large numbers of optically invisible stars in the Trapezium Cluster (McCaughrean 1988; HAB) provide additional binding mass. Proper accounting for the mass of embedded stars is necessary to adequately address the question of the dynamical state of the cluster.

In §3.2, details of the observational method and sample selection are given. The analysis of the data and the resultant spectral type classifications are presented in §3.3. §3.4 begins with a comparison of our results with previous classifications of Trapezium Cluster stars. We then describe the means by which temperature classifications are used to deredden our sample in the color-magnitude plane. The intrinsic locations of stars in the color-magnitude diagram provide information on stellar extinctions, dust excesses, ages and masses. The values obtained for these parameters form the basis of our discussion of the dynamical state and star formation history of the Trapezium Cluster.

3.2 Observations

3.2.1 Sample A

Optical spectra have been obtained for 44 Trapezium Cluster stars in the wavelength range $\sim 6000\text{--}8750 \text{ \AA}$. This range contains the temperature-sensitive TiO absorption bands, to be used here for spectral classification. The 44 stars observed are referred to as sample A in the following analysis and are listed in Table 3.1. The data were acquired using the Reynolds spectrograph and RCA CCD on the ANU 1.9m telescope at Mount Stromlo Observatory, and on the 1m telescope at Siding Spring Observatory, during the period from 1989 October to 1990 January. A 300 l/mm grating was used, providing a nominal dispersion of $219 \text{ \AA/mm}$. The slit width was set to $350 \text{ }\mu\text{m}$ to give a resolution of $\sim 4.8 \text{ \AA}$ at the detector. Sample A consists of stars identified as members of the Orion Nebula Cluster by JW, bright enough to be visible on the television monitor, and as close as possible to the central core region

of the Trapezium Cluster. Stars identified as variables are noted, with references for these identifications given. The data were reduced using the Starlink FIGARO routines. Comparison spectra of dwarfs selected from the Bright Star Catalogue were obtained on the same nights. We have chosen dwarf standards even though the Trapezium Cluster stars are pre-main-sequence objects (Herbig & Terndrup 1986, McCaughrean 1988; Chapter 2), and therefore would have luminosities between those of dwarfs and giants. In addition to these data, two giant standards have also been included in our analysis for completeness, from earlier observations made in 1988 April to May with the ANU 1m telescope at Siding Spring Observatory, using the Reynolds Spectrograph and RCA CCD. These standards have been observed over the wavelength range $\sim 4950\text{--}7700\text{ \AA}$. The detector resolution was $\sim 4.8\text{ \AA}$, using the same grating and slit width described above.

3.2.2 Sample B

Titanium oxide absorption is only present in stars cooler than M0. Thus, in order to classify hotter stars we have also acquired optical spectra of a sample of 37 Trapezium Cluster stars in the range $\sim 5150\text{--}5640\text{ \AA}$ during the period 1990 September to 1991 January, as well as 1991 December. These stars are listed in Table 3.1. The data were obtained using the 1.9m MSO telescope with the Coudé spectrograph and CCD. A 600 l/mm grating was used with the 80cm camera, to give a nominal dispersion of $20\text{ \AA/mm}$. The slit width was set to $370\text{ }\mu\text{m}$ corresponding to a resolution of $\sim 0.5\text{ \AA}$ at the detector. These $5150\text{--}5640\text{ \AA}$ spectra were measured with two different CCD chips on separate observing runs, an RCA (416×578 pixel) detector and a Thompson (1024×1024 pixel) detector. The resultant spectra cover different sections of this wavelength regime, $5156\text{--}5455\text{ \AA}$ and $5166\text{--}5640\text{ \AA}$.

Obtaining accurate photospheric spectral types for T Tauri stars is problematic due to the veiling of the photospheric spectrum by envelope emission. Finkenzeller & Basri (1987) demonstrated that the *weak* absorption lines between $5100\text{--}6000\text{ \AA}$ observed in the spectra of T Tauri stars in the Chamaeleon and Lupus dark clouds resemble very closely the photospheric absorption features seen in standard dwarf spectra. Thus, accurate spectral types can be obtained for pre-main-sequence stars, as long as we restrict ourselves to consideration of weak absorption features. Dwarf star standards were again observed in order to classify the sample B stars. As above, JW sources with visible identification and close proximity to the Θ^1 Ori stars were selected. The data were reduced using the IRAF reduction packages.

Table 3.1: Spectral Classification of Trapezium Cluster Stars

Name (1)	Par.No. (2)	Sample (3)	SpT(A) (4)	SpT(B) (5)	SpT(IR) (6)	SpT(Other) (7)	Var. (8)	Vsin i (kms ⁻¹) (9)	Comment (10)
JW75	1587	B		K2	M3				
JW232	1727	B		K1-K2	M1.5		yes(JW)		
JW248		B		K4-M0					
JW249	1737	B		M0,M4			yes(JW)		
JW273	1746	A	<M0			K0(J;PC);K3(CK);K4(W)	yes(JW)		Ca II emission
JW291	1754	B		K4-M0	K7				
JW337	1771	A,B	<M0	K4-M0			yes(JW;MH)		
JW345	1783	A	M0-M2						
JW347	1782	A,B	<M0	K2-K4	K4		yes(MH)	14.(MH)	
JW348	1785	A	<M0				yes(JW)		
JW352	1784	A,B	<M0	K2-K3	K5-M1.5	K2(HT)	yes(JW;MH)	13.(MH)	
JW365	1800	A,B	<M0	K2-K3			yes(JW)		
JW378	1808	B		M0			yes(MH)	11.(MH)	
JW385	1807	A	<M0			K1(HT)	yes(JW)		
JW391	1806	B		K0					
JW401		A	<M0		A2-M3				Ca II emission
JW409	1824	A	<M0				yes(JW;MH)		
JW423	1819	A,B	<M0	M0,M4	G0.5-M1.5		yes(JW)		
JW431	1823	A	<M0						

Table 3.1(ctd): Spectral Classification of Trapezium Cluster Stars

Name (1)	Par.No. (2)	Sample (3)	SpT(A) (4)	SpT(B) (5)	SpT(IR) (6)	SpT(Other) (7)	Var. (8)	Vsin i (kms ⁻¹) (9)	Comment (10)
JW437	1826	A,B	M0-M1	K4					
JW448	1839	A,B	M0-M1.5	K3-K4					
JW454	1840	A,B	<M0	K4-M0					
JW457	1837	A,B	<M0	K3-K4	K2-M0		yes(JW)		
JW478	1872	A,B	K7-M1	K4			yes(JW)		
JW480	1871	A	<M0		K7		yes(JW)		
JW482		A	<M0		M4		yes(JW)		Ca II emission
JW504	1859	A,B	<M0	K2-K4					
JW515	1895	A	<M0						
JW526	1896	B		K2-K3			yes(MH)		
JW529	1886	A,B	M0-M1	M0			yes(JW)		
JW531	1885	A,B	<M0	<F5		A2(T;GS)	yes(JW)	≥225(S)	
JW536	1887	A	<M0						
JW544	1884	A,B	<M0	K3	G5.5,M1	K5III(HT)	yes(JW;MH)		
JW548	1909	A	<M0				yes(JW;MH)		
JW551		A	<M0						
JW561	1907	A	<M0						
JW567	1910	A,B	<M0	K2-K3	A5.5-M2	K3-4(HT)	yes(JW;MH)	12.(MH)	
JW581	1913	A	<M0				yes(MH)		

Table 3.1(ctd): Spectral Classification of Trapezium Cluster Stars

Name (1)	Par.No. (2)	Sample (3)	SpT(A) (4)	SpT(B) (5)	SpT(IR) (6)	SpT(Other) (7)	Var. (8)	Vsin i (kms ⁻¹) (9)	Comment (10)
JW589	1925	A	<M0		K4-M0	G8-K0(HT)	yes(JW;MH)	7.(MH)	
JW595	1922	A,B	<M0	K0		F8(HT)	yes(JW)	≥150(S)	
JW608	1923	A,B	<M0	<F7		B-A(HT)			
JW613	1936	B		K2					
JW622	1940	A	<M0		K7				Ca II emission
JW631	1938	A	<M0						
JW637	1939	A	<M0						
JW640	1937	A,B	<M0	F7-G2		G0(HT);K0(H)	yes(JW)		
JW660	1956	A,B	<M0	<F5		B0(J);B2(LA;HT)	yes(MH)	17.(MH); ≥225(S)	
JW669	1961	A,B	<M0	K1-K2			yes(MH)		
JW678	1974	B		K1-K2	K5-M1.5		yes(JW;MH)		
JW706	1972	B		K2-K4					
JW721	1990	A	<M0		K2-K7		yes(JW;MH)		
JW747	2001	B		K1	G1.5-K5		yes(JW)		
JW750	2012	B		K0-K2	K4		yes(JW)		
JW766		A	<M0		M5				
JW769	2008	A,B	<M0	K2-K4					
JW799	2032	B		K1,M3	F3-M2	G0III(HB)	yes(JW)		
JW810		A,B	<M0	K4					
JW831	2058	A,B	<M0	<F5		A0(J);B9.5(LA)		≥225(S)	

CK: Cohen & Kuhi 1979; GS: Greenstein & Struve 1946; H: Herbig 1950; HB: Herbig & Bell 1988; HT: Herbig & Terndrup 1986; J: Johnson 1965;
 JW: Jones & Walker 1988; LA: Levato & Abt 1976; MH: Mandel & Herbst 1989; PC: Parsamian & Chavira 1982; S: Samuel 1993 (present Chapter);
 T: Trumpler 1931; W: Walker 1983

Table 3.2: Equivalent Widths of M Standards

Name (1)	EW(TiO λ 7100) (2)	SpT (3)
GL 79	40.0 $\pm$ 14.0	M0
GL 887	46.5 $\pm$ 15.9	M1
π Leo	70.1 $\pm$ 9.8	M2
3 Aqr	98.4 $\pm$ 4.1	M3
GL 876	132.2 $\pm$ 15.0	M4
GL 866	161.5 $\pm$ 16.0	M5.5

Table 3.3: TiO Equivalent Widths of Trapezium Cluster Stars

Name (1)	EW(TiO λ 7100) (2)	SpT (3)
JW345	51.1 $\pm$ 22.0	M0-M2
JW437	37.5 $\pm$ 5.0	M0-M1
JW448	45.5 $\pm$ 13.0	M0-M1.5
JW478	36.0 $\pm$ 10.3	K7-M1
JW529	37.2 $\pm$ 6.7	M0-M1

3.3 Results

3.3.1 The 6000–8750 Å Spectra

Five Trapezium Cluster stars in sample A have detectable TiO absorption, and are determined here to be late-K to early-M in spectral class. The spectra of these stars are given in Figure 3.3, along with derived spectral types. The standard-star spectra pertaining to the 6000–8750 Å wavelength range are presented in Figure 3.1. Also indicated in this figure is feature A, the ~ 7100 Å TiO absorption band used here for spectral classification. The equivalent widths of this feature measured from the standard stars are tabulated in Table 3.2, and plotted against spectral type in Figure 3.2. Here, the line of best fit (heavy line) has been used in combination with the error bars shown to classify the five Trapezium Cluster stars. The measured 7100 Å TiO equivalent widths of these five cluster stars are given in Table 3.3. The remaining 39 stars of sample A are interpreted here to be of earlier spectral type, therefore requiring alternative means of classification.

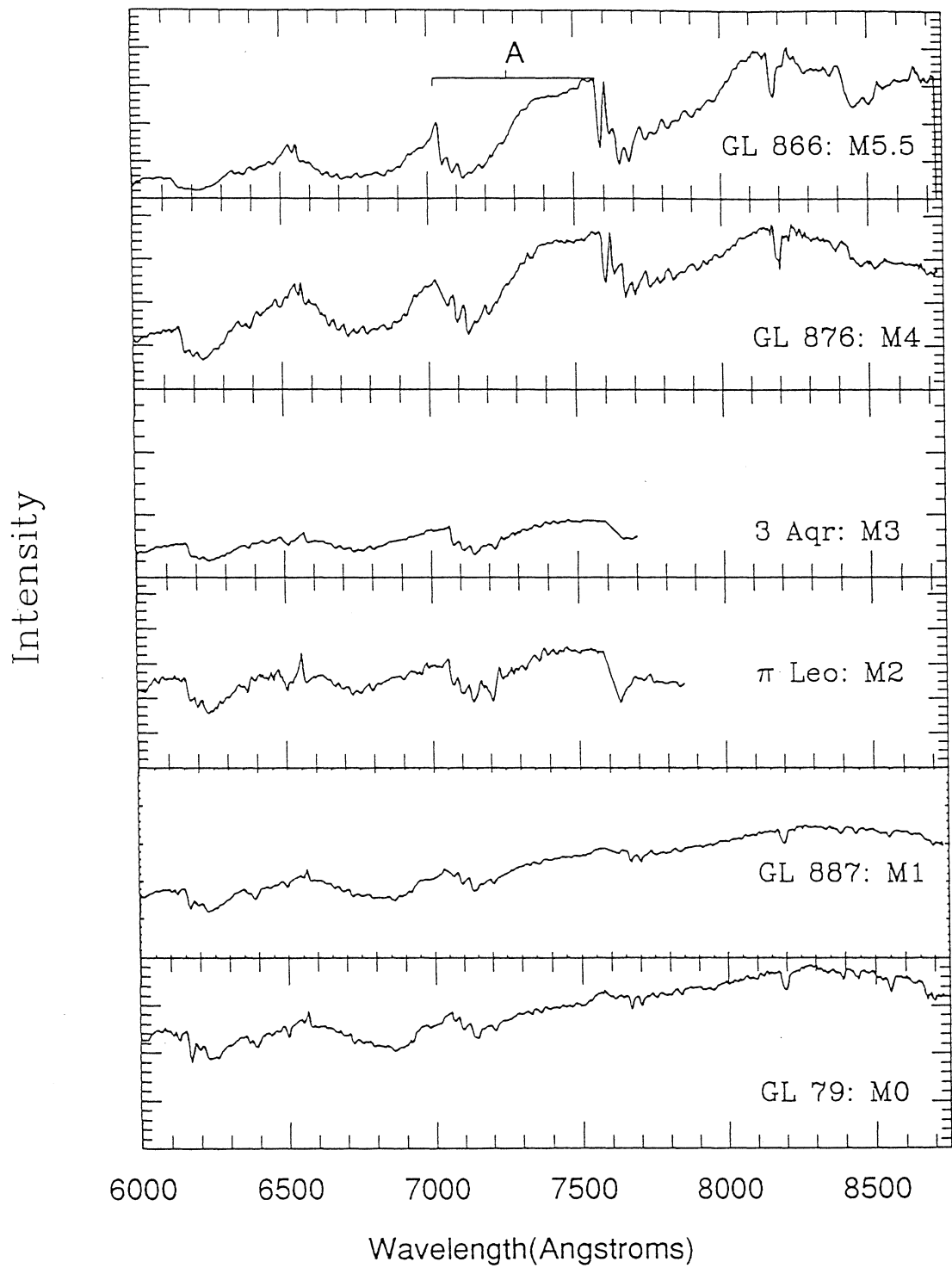


Figure 3.1: Spectra of M standards between ~ 6000 – 8750 Å. The 7100 Å TiO absorption band used for spectral classification is marked as Feature A.

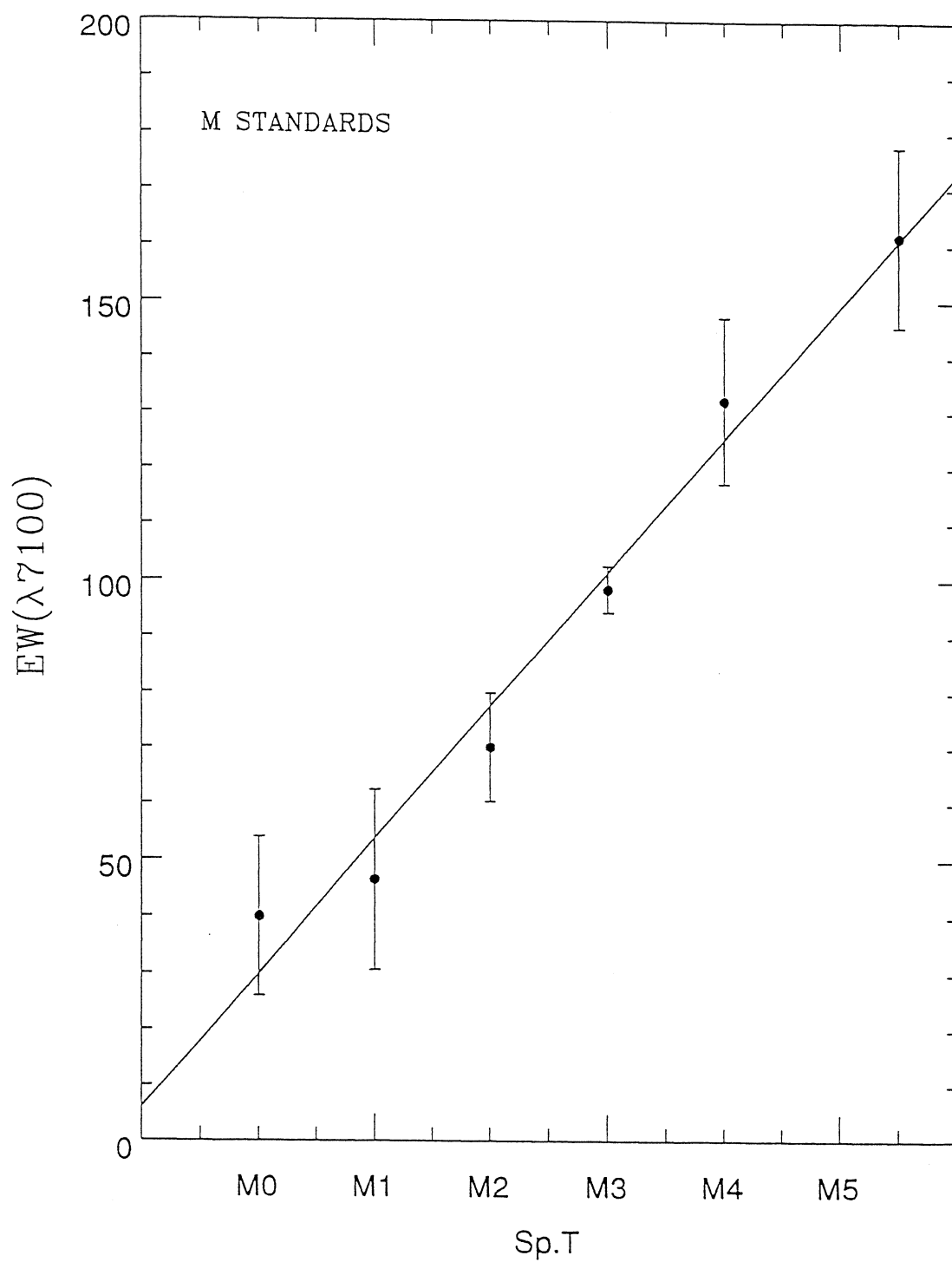


Figure 3.2: Equivalent width of Feature A (7100 Å TiO) vs. Spectral Type.

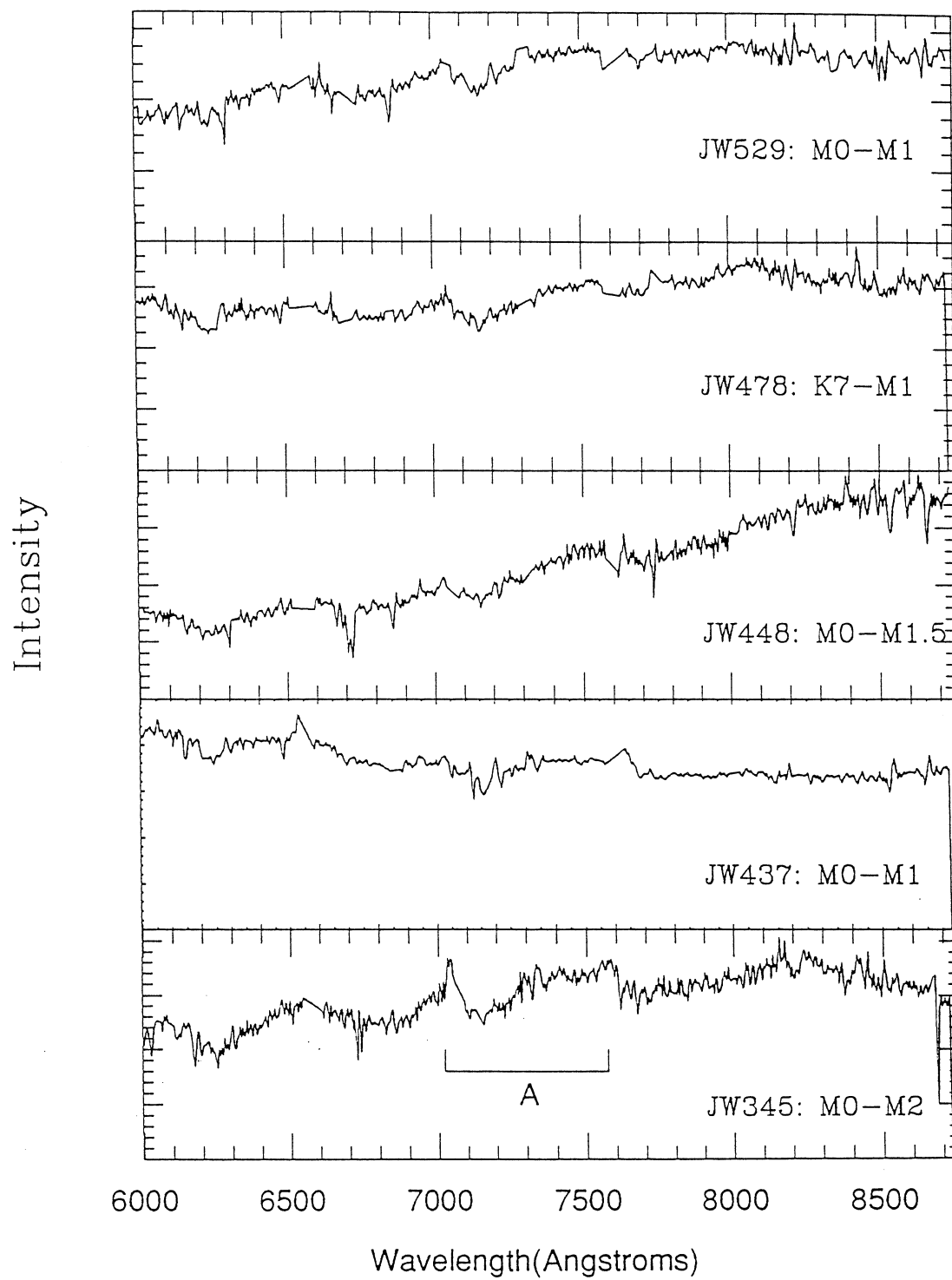


Figure 3.3: Spectra of Trapezium Cluster objects with measurable TiO absorption, marked as Feature A, between ~ 6000 – 8750 Å.

3.3.2 The 5150–5640 Å Spectra

Figures 3.4 and 3.5 are standards and object spectra respectively covering the wavelength range 5156–5455 Å, while Figures 3.6 and 3.7 are standards and object spectra from 5166–5640 Å. The Trapezium Cluster stars of sample B have been spectral typed using a combination of the Mg b triplet absorption lines ($\lambda\lambda\lambda$ 5168, 5172, and 5183), and blended atomic absorption lines defined collectively as features B (5203–5220 Å), C (5259–5278 Å), and D (5358–5457 Å). We note that veiling may affect the observed strengths of the strong Mg b features; due to this they have been used only in the following manner. A comparison between the standard spectra shows that the three distinct Mg b triplet lines are replaced by broad molecular bands of MgH and TiO for stars cooler than M0. Thus, the presence of the Mg b triplet provides a qualitative means of differentiating between stars later and earlier than M0. The blended features B, C and D are composed of Fe I and II, Cr I, and Ca I atomic absorption lines. All features used for spectral classification are marked in the standard and object spectra given.

The mean equivalent widths of features B, C, and D measured for our standard stars are presented in Tables 3.4, 3.5, and 3.6. Figure 3.8 shows graphs of these equivalent widths as a function of spectral type. The error bars reflect the standard deviation of measurements for a number of standards of the same spectral type. The variation of equivalent width with spectral type seen here for all three features demonstrates the usefulness of these features for spectral classification. In all three instances, the equivalent widths increase with spectral type to $\sim$ K4. It is clear from Figure 3.8 that a marked difference exists in the equivalent widths of features B, C and D between G-type stars and K- and M-type stars. Distinguishing between early K- and M-type stars is less straightforward. Here, if the Mg b triplet lines were not included in the stellar spectrum, alternative means of classification were required. We have noted that the 5167 Å TiO absorption band produces a drop towards the blue end of the spectrum in the M standards observed here compared with the standards of earlier spectral type (see Figure 3.4). Therefore, we have extrapolated the stellar continuum in the relevant sample B spectra at this end of the wavelength range. If a drop is seen, we have classified the star as M-type.

The equivalent widths of features B, C, and D measured in our Trapezium Cluster sample (B) are tabulated in Tables 3.7, 3.8, and 3.9, together with derived spectral types for each case. Combination of the results from all three features is used to estimate the most accurate stellar spectral type. Spectral types for our sample B stars based on the equivalent widths of each feature separately were found to be in good agreement overall. These have been listed in Table 3.1 and are included in the spectra of the objects given (Figures 3.5 and 3.7).

We classify 37 Trapezium Cluster stars using this procedure. Sample B consists

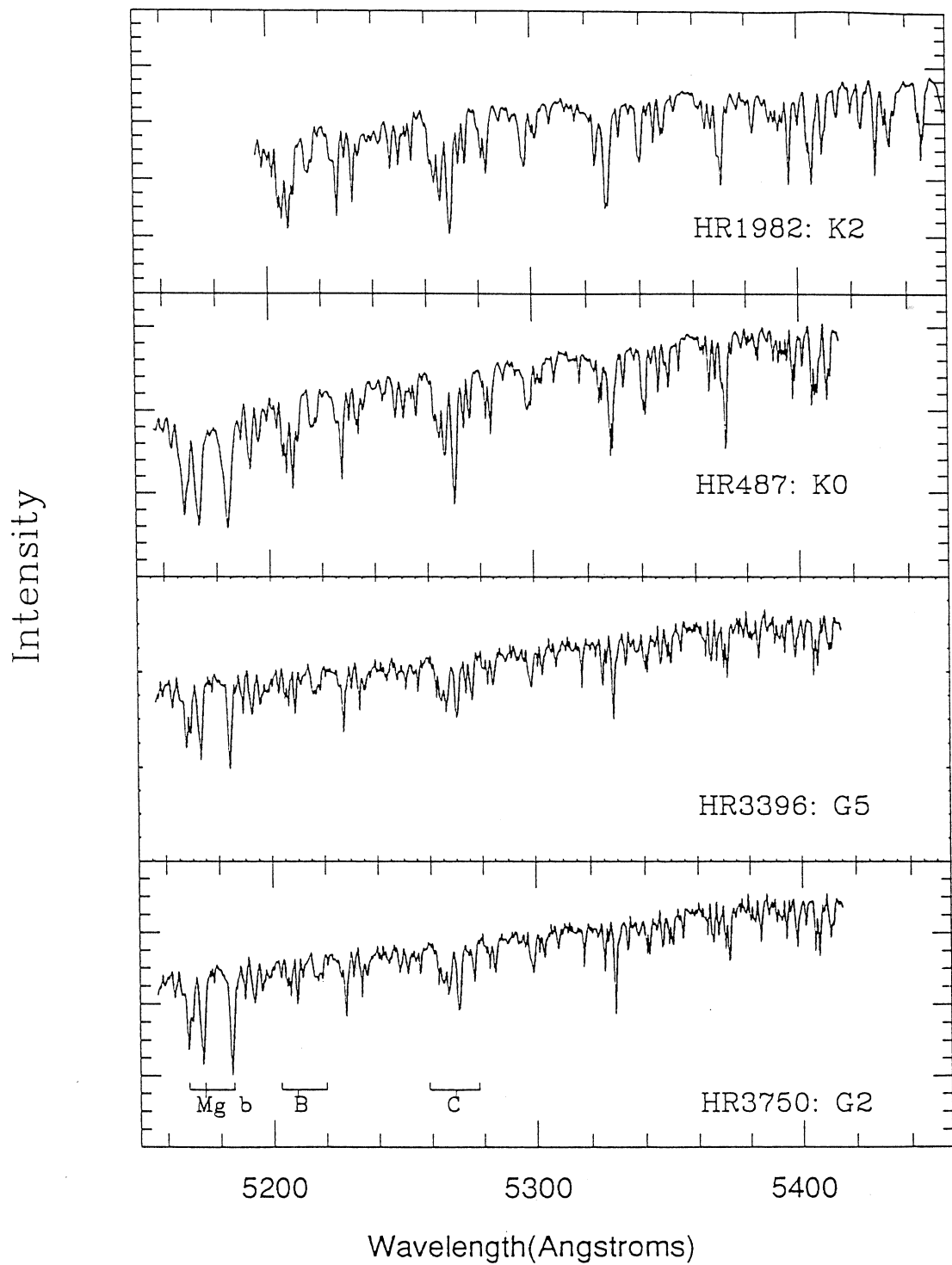


Figure 3.4: Spectra of standards between ~ 5156 – 5455 Å. The Mg b absorption lines and Features B and C used for spectral classification are marked.

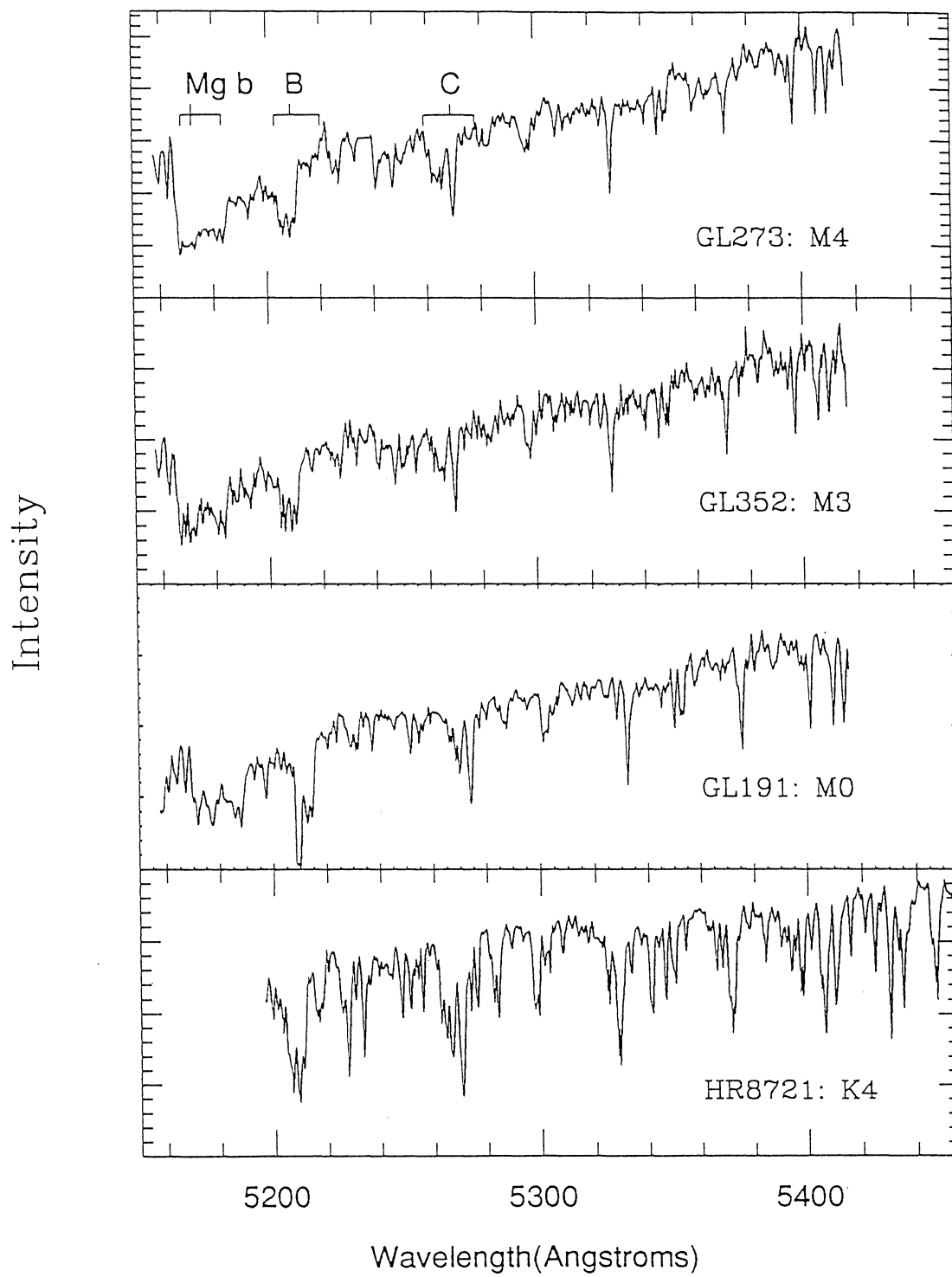


Figure 3.4: *cont.*

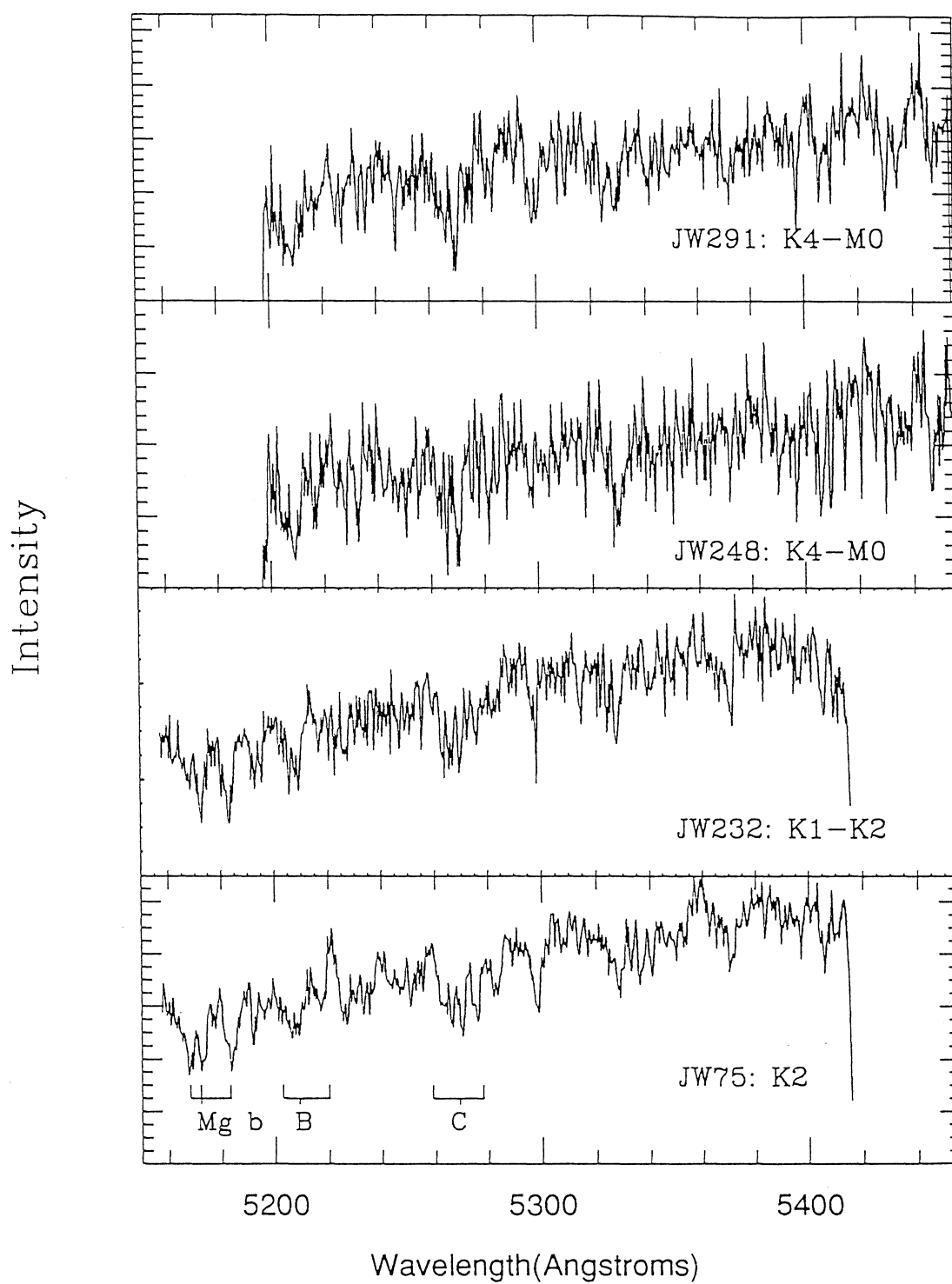


Figure 3.5: Spectra of Trapezium Cluster objects between ~ 5156 – 5455 Å, with Mg b lines and Features B and C marked. Derived spectral types are also given.

Intensity

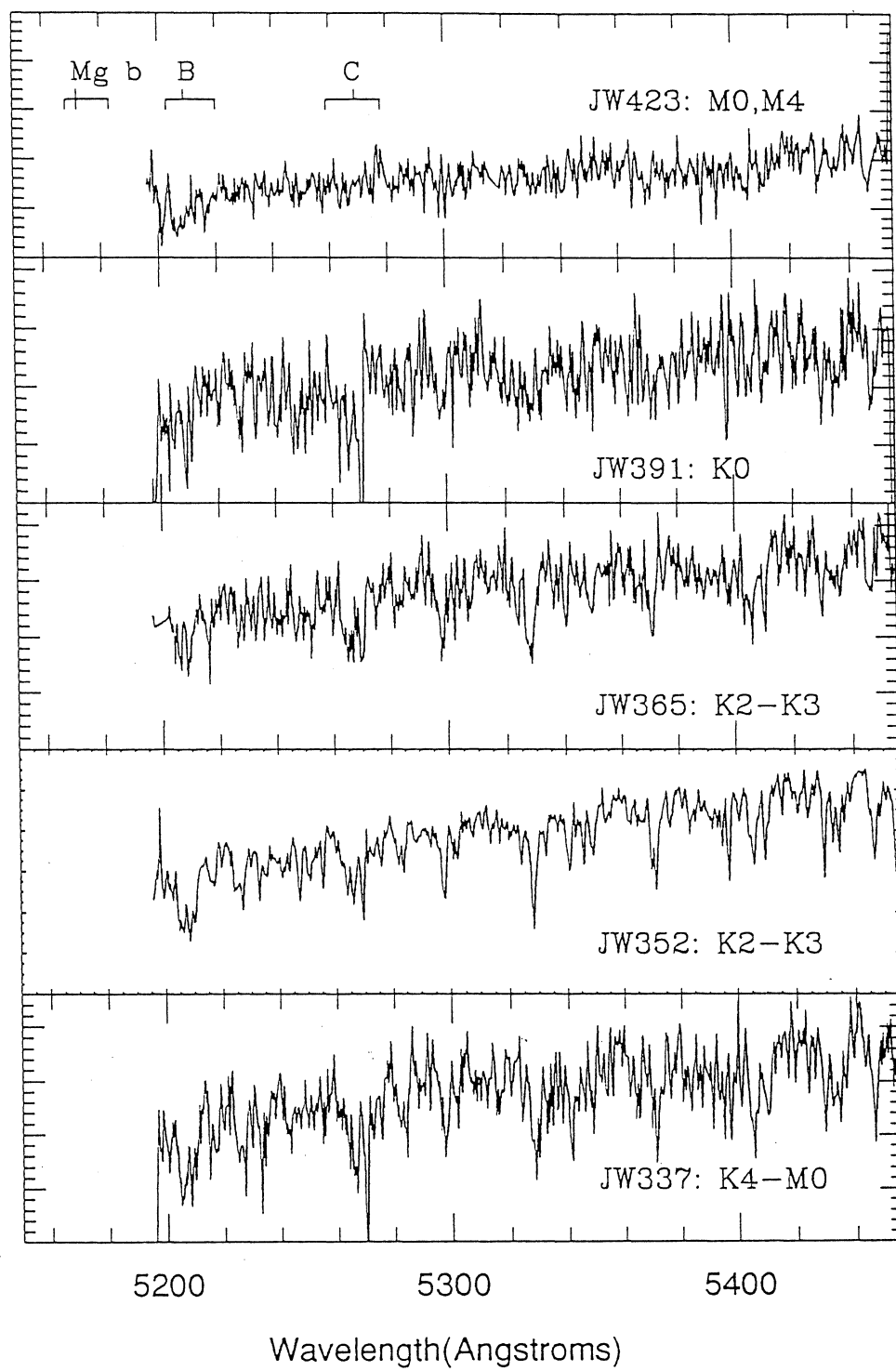


Figure 3.5: *cont.*

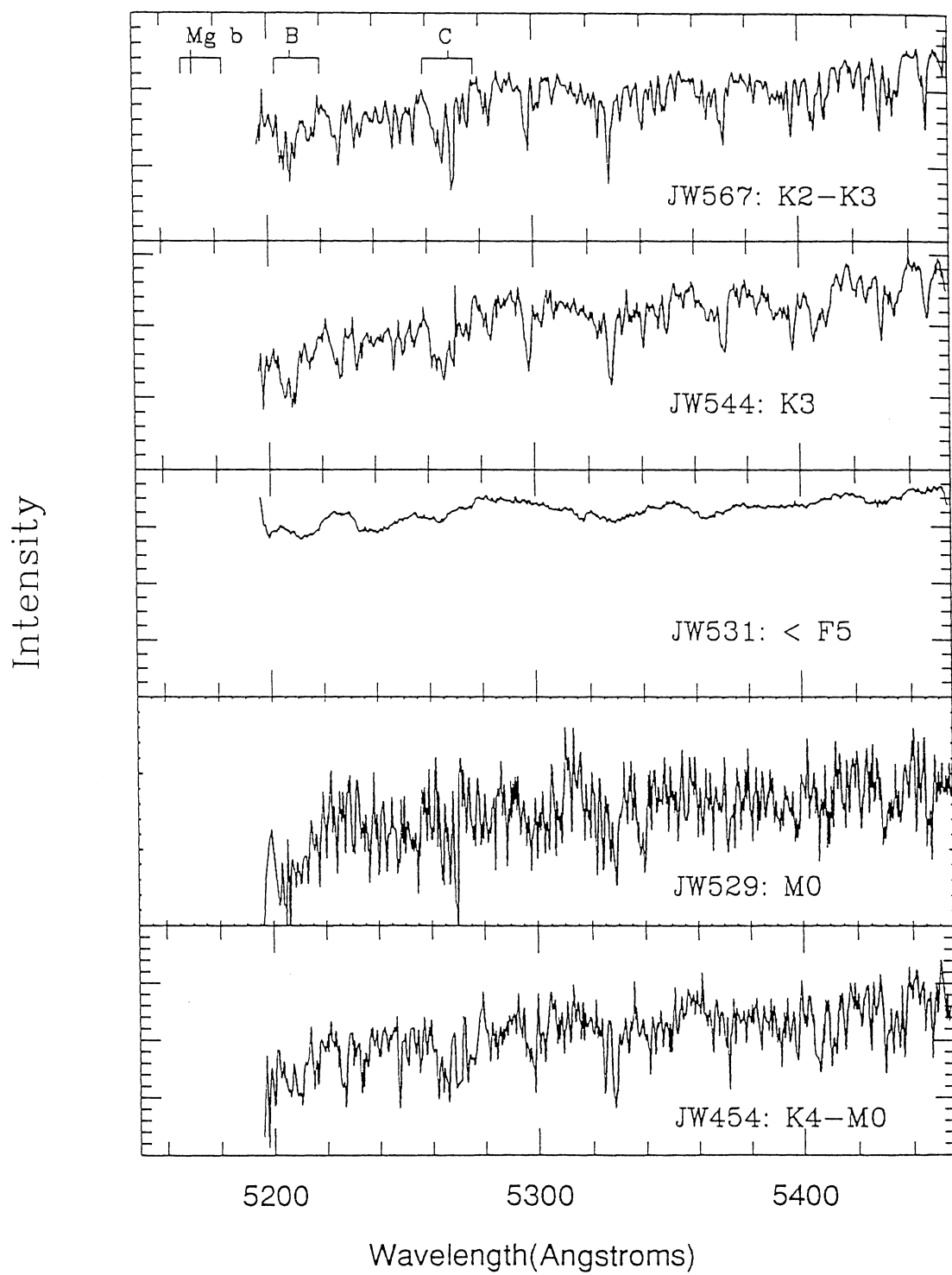


Figure 3.5: *cont.*

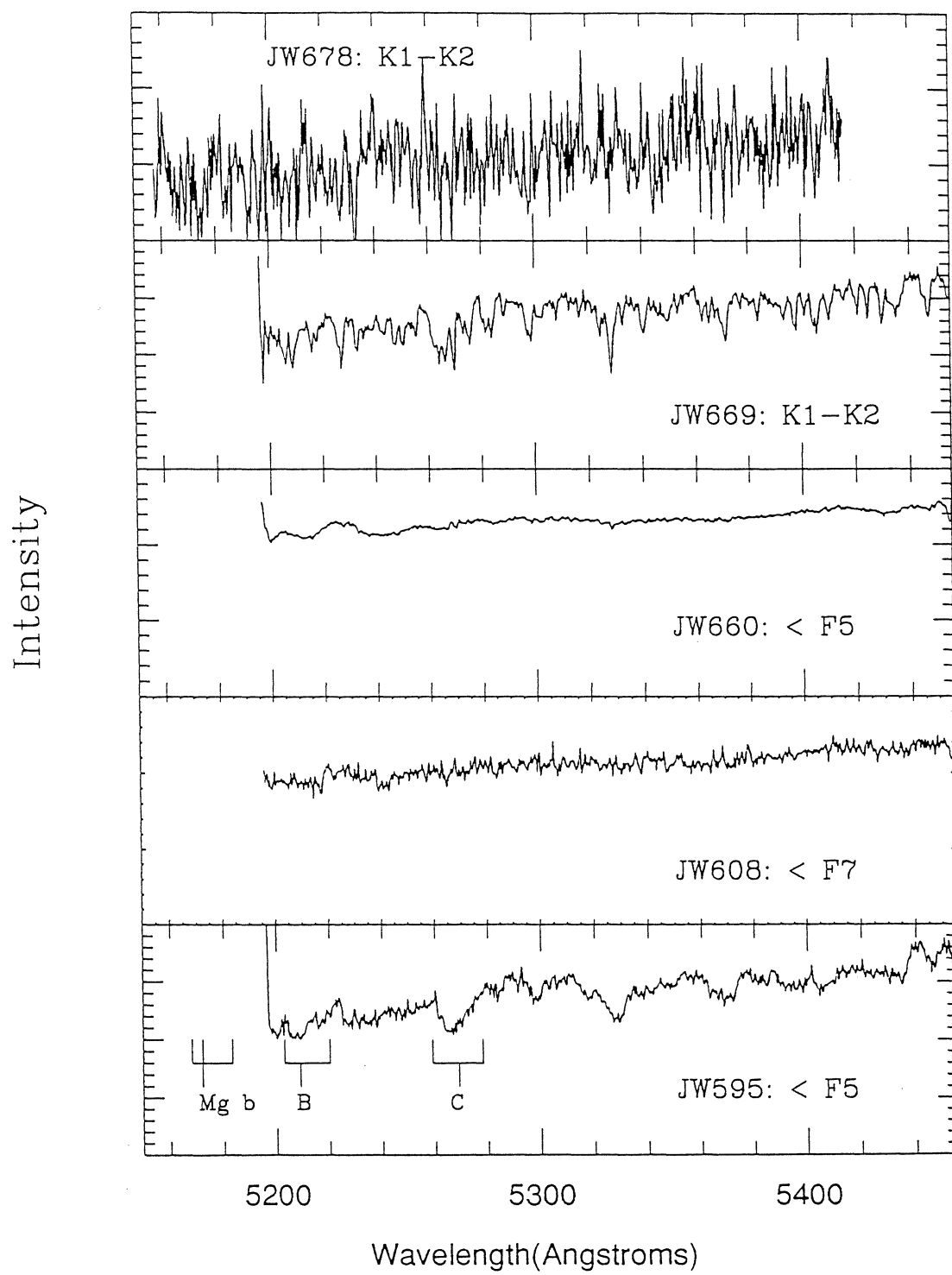


Figure 3.5: *cont.*

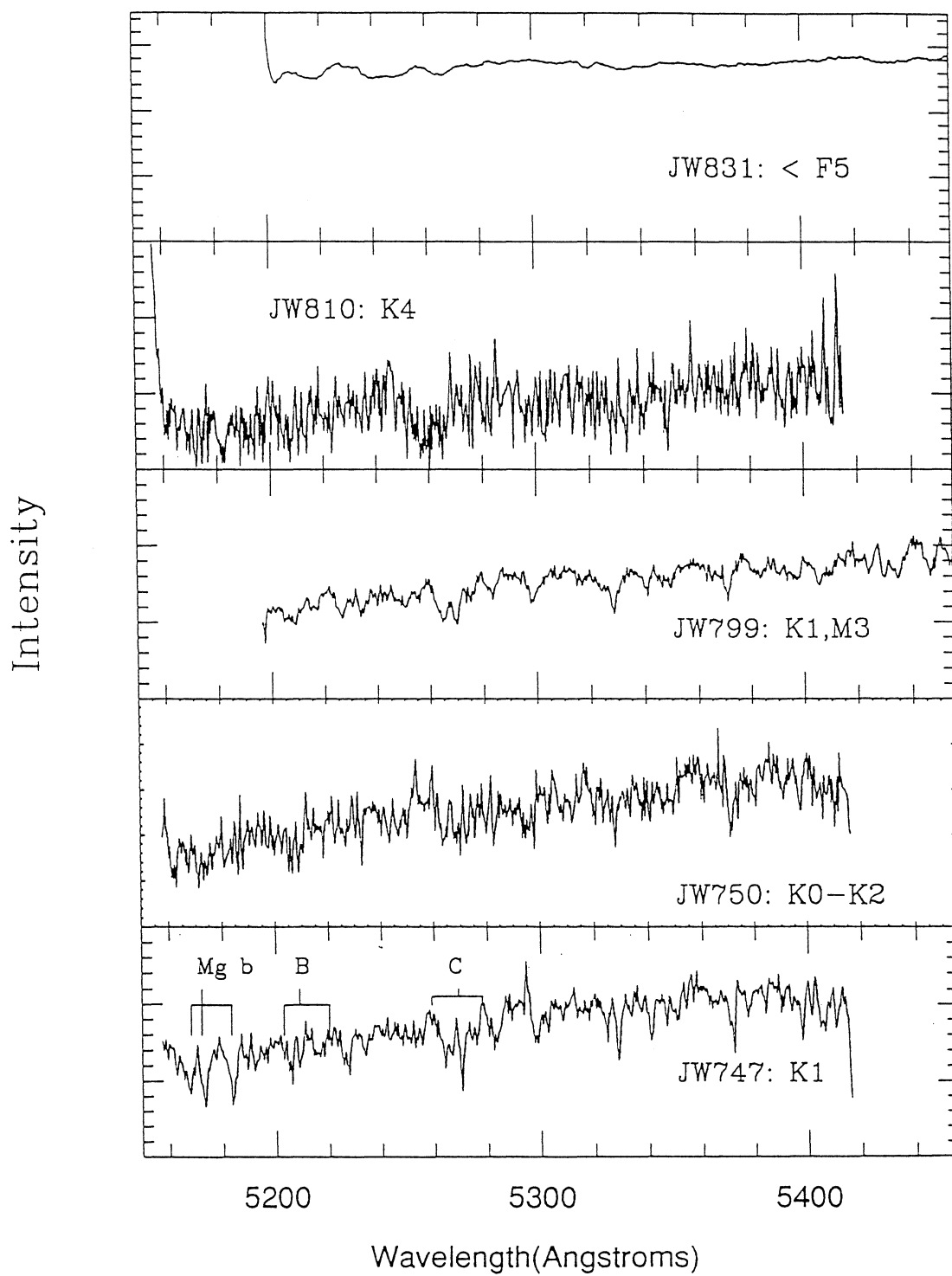


Figure 3.5: *cont.*

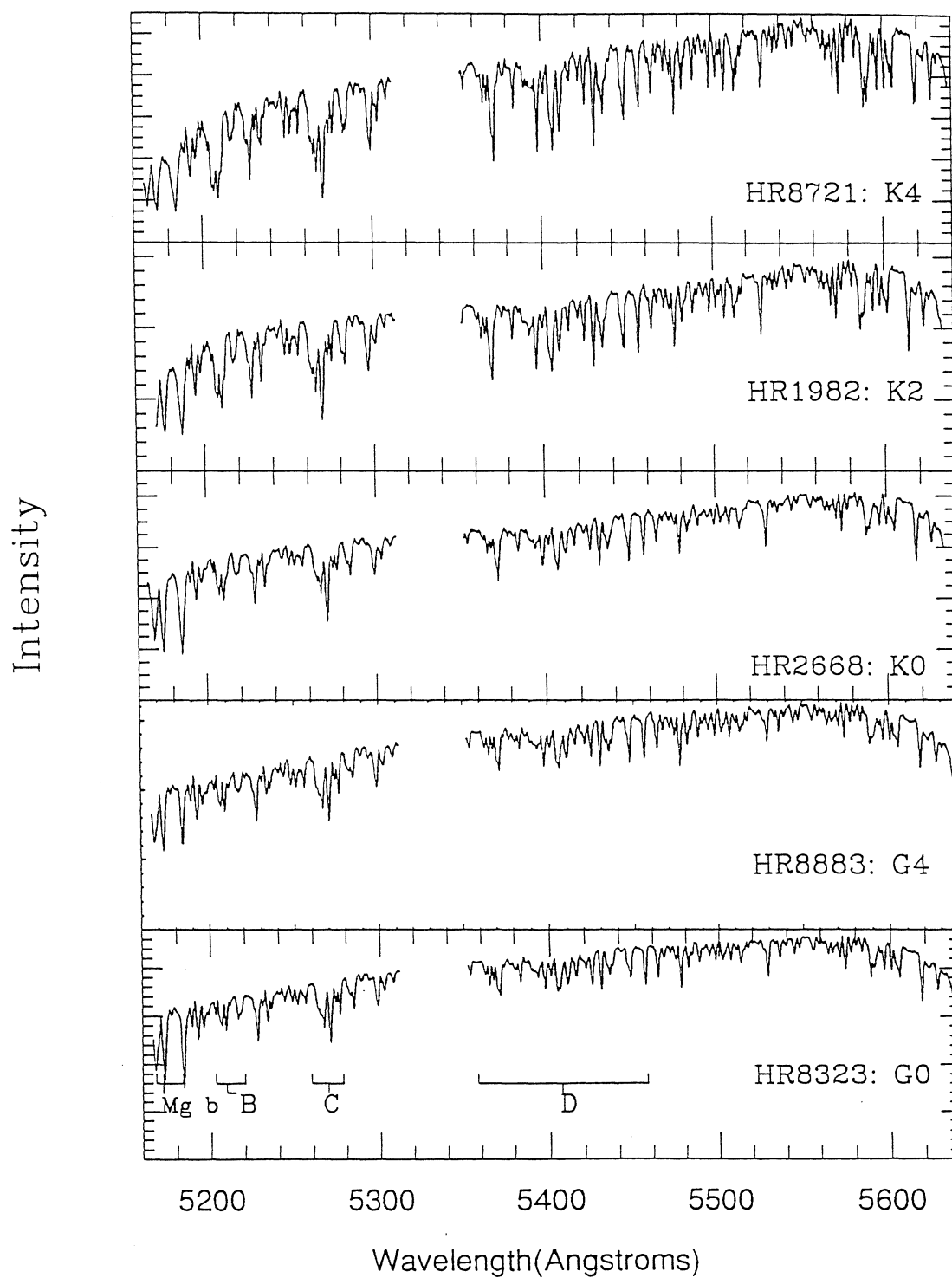


Figure 3.6: Spectra of standards between ~ 5166 – 5640 Å. The Mg B absorption lines and Features B, C and D used for spectral classification are marked.

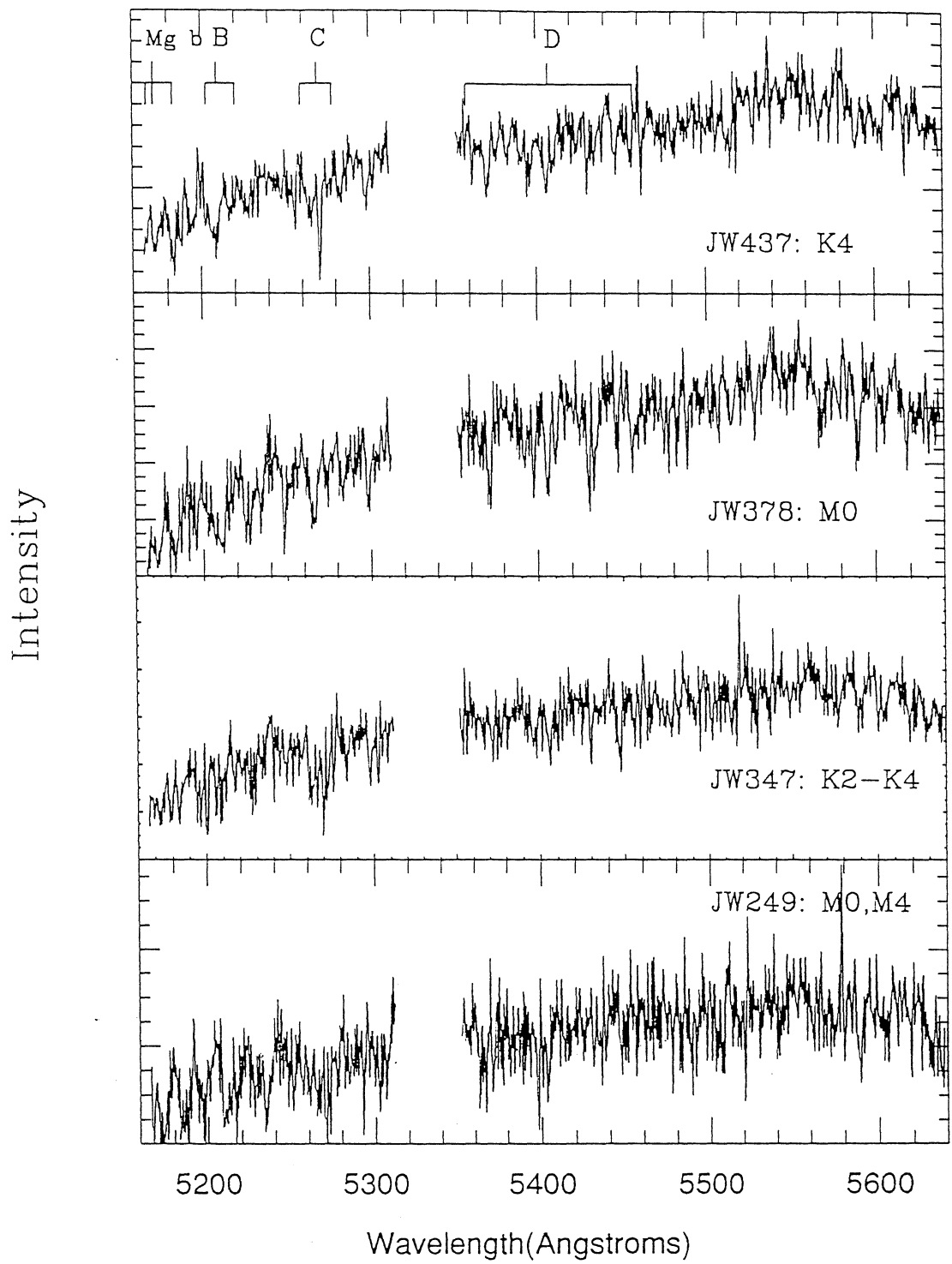


Figure 3.7: Spectra of Trapezium Cluster objects between ~ 5166 – 5640 Å, again with Mg b lines, and Features B, C and D marked. Derived spectral types are also given.

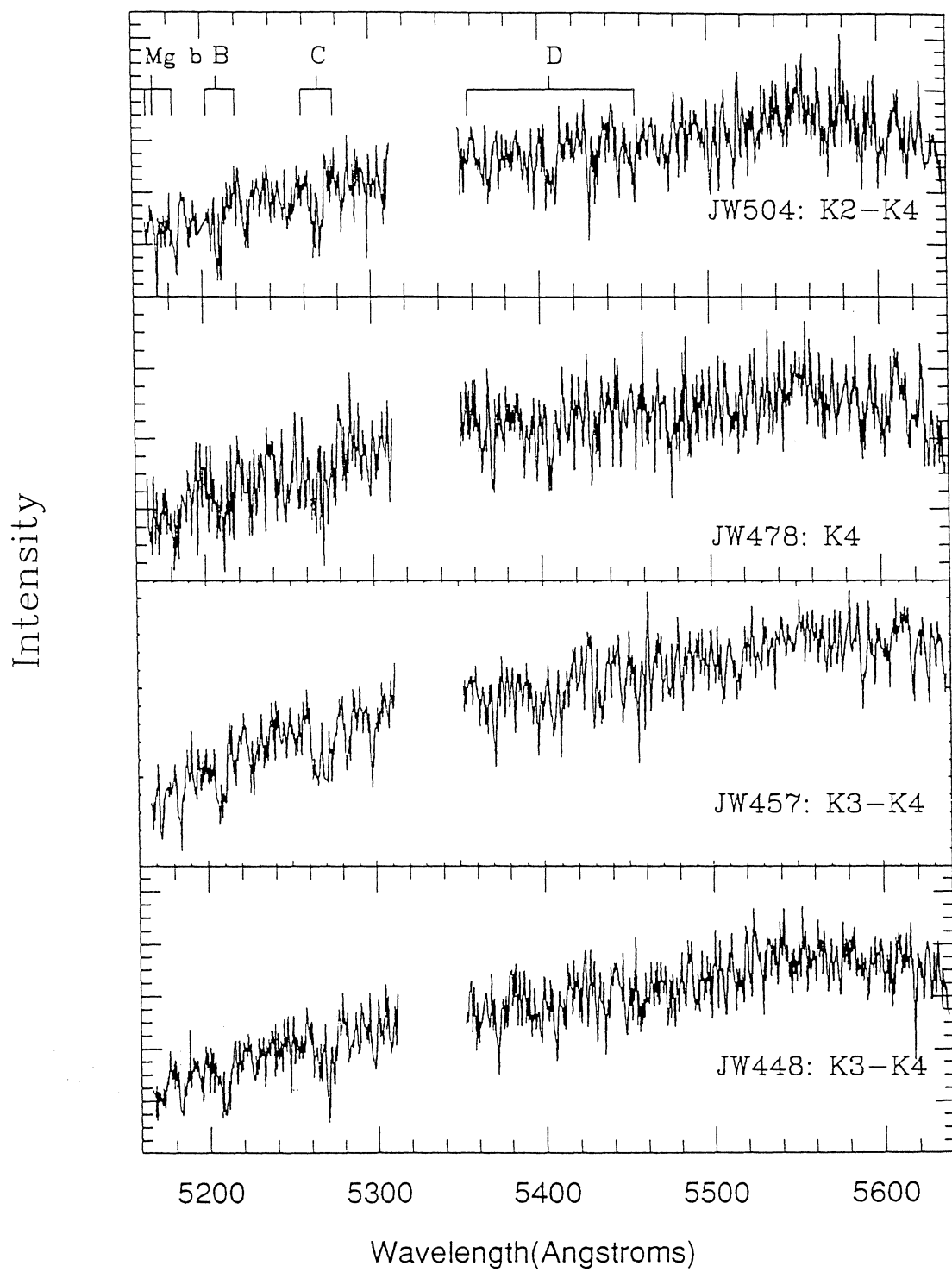


Figure 3.7: *cont.*

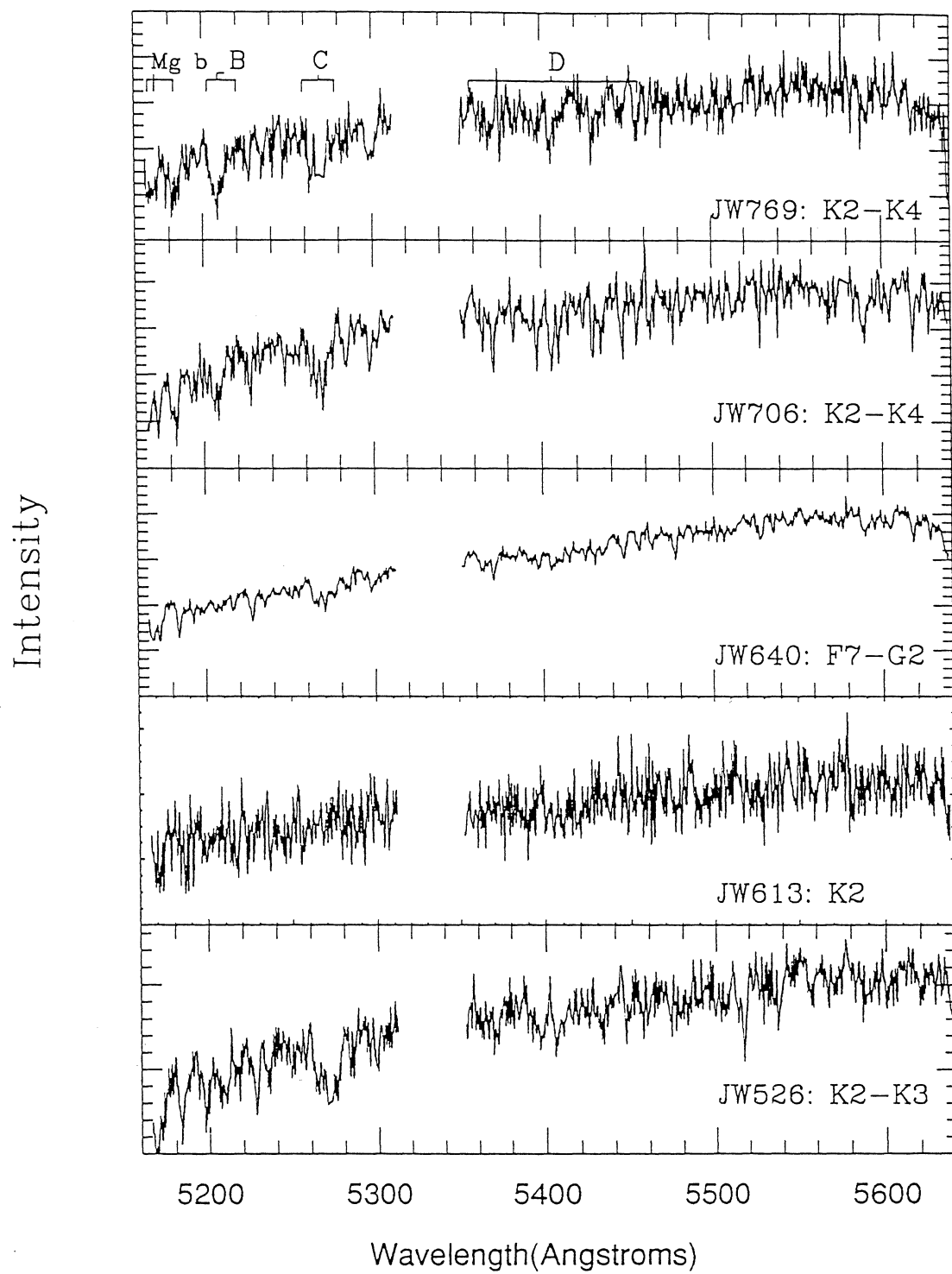


Figure 3.7: *cont.*

Table 3.4: Standard Equivalent Widths for Feature B (Averaged)

SpT (1)	EW(B) (2)
F7	2.25 ± 0.04
G0	2.58 ± 0.05
G1	2.37 ± 0.25
G2	2.56 ± 0.17
G4	2.95 ± 0.12
G5	2.77 ± 0.15
G8	2.87 ± 0.22
K0	3.33 ± 0.04
K2	4.65 ± 0.27
K4	5.52 ± 0.06
M0	3.59 ± 0.38
M3	3.45 ± 0.26
M4	3.62 ± 0.50

Table 3.5: Standard Equivalent Widths for Feature C (Averaged)

SpT (1)	EW(C) (2)
F7	1.42 ± 0.23
G0	1.76 ± 0.27
G1	1.98 ± 0.02
G2	1.66 ± 0.25
G4	1.86 ± 0.23
G5	1.92 ± 0.24
G8	1.97 ± 0.14
K0	2.35 ± 0.16
K2	3.65 ± 0.55
K4	5.45 ± 0.39
M0	6.07 ± 0.48
M3	3.36 ± 0.85
M4	5.52 ± 0.96

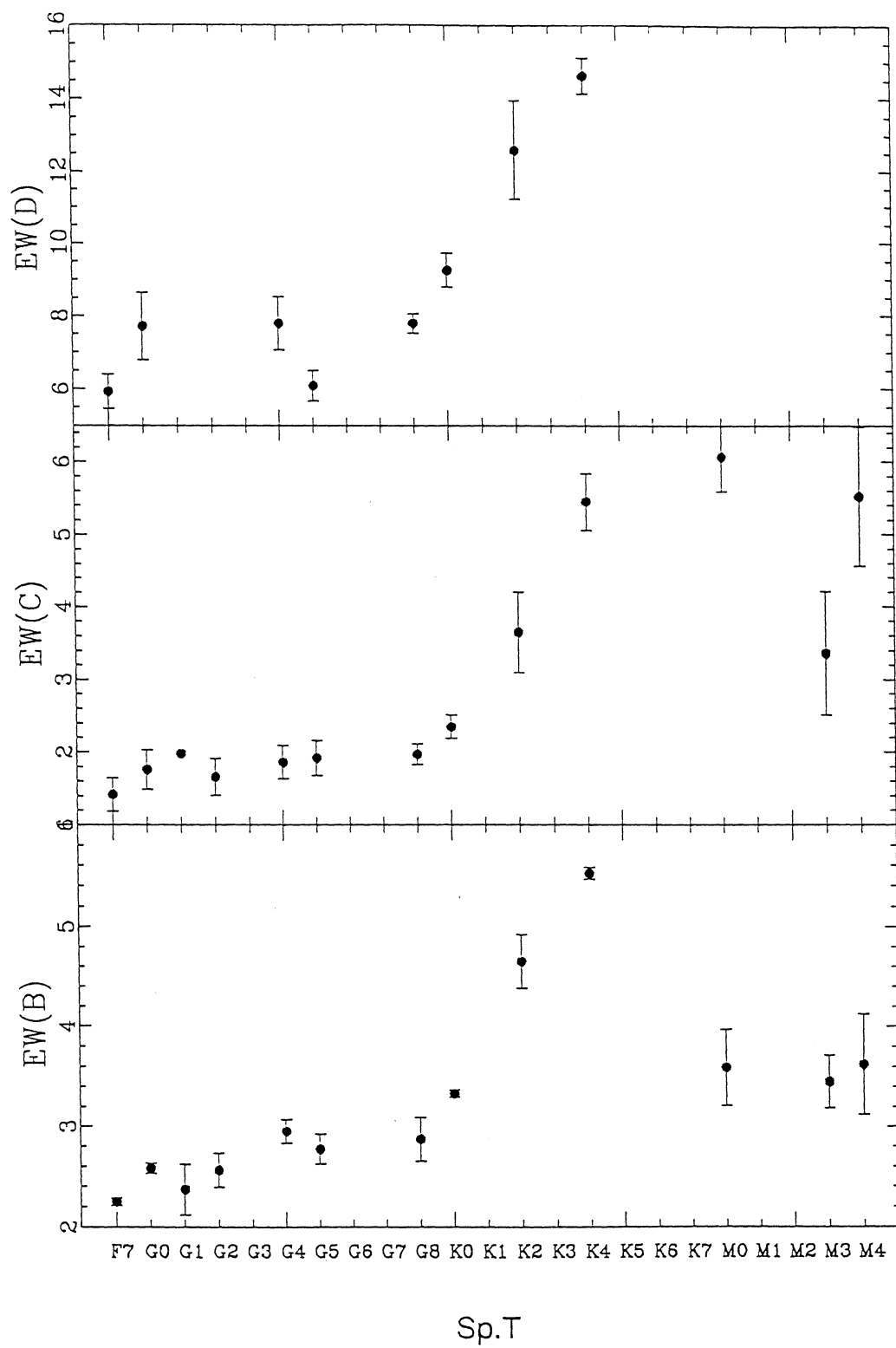


Figure 3.8: Equivalent widths of Features B, C and D vs. Spectral Type.

Table 3.6: Standard Equivalent Widths for Feature D (Averaged)

SpT (1)	EW(D) (2)
F7	5.93 ± 0.47
G0	7.72 ± 0.93
G4	7.79 ± 0.74
G5	6.09 ± 0.41
G8	7.79 ± 0.27
K0	9.26 ± 0.47
K2	12.58 ± 1.37
K4	14.62 ± 0.49

of 26 stars between K0 and M0, four stars which are M0 or later, and five stars earlier than G5. One star is classified more ambiguously as being either a K1 or M3 star. The mean spectral type for the sample is $\sim K3$. Errors involved in the classification process are represented by the range in spectral type given for each star.

The results obtained for the 23 stars included in both samples A and B are generally in good agreement. JW423 is the only notable exception, with no detectable TiO absorption in its redward spectrum but being classified as M0 or M4 by our analysis of its spectrum at bluer wavelengths. The star is known to vary (Table 3.1); further observations are necessary to monitor its variability and determine whether TiO absorption is indeed present. JW423 is left out of the current analysis because of these uncertainties.

3.3.3 Calcium Triplet Emission

An important result obtained with the observations of sample A is the detection of Ca II infrared triplet emission in four stars (see Figure 3.9). The triplet lines occur at $\lambda 8498$, $\lambda 8548$ and $\lambda 8662$ Å. Figure 3.9 shows that in all four stars the triplet emission lines are of almost equal intensity. The fact that the line ratios expected for optically thin emission are 1:9:5 indicates that the emission in these objects is optically thick.

Table 3.7: Equivalent Widths of Trapezium Cluster Stars - Feature B

Object (1)	EW(B) (2)	SpT (3)
JW75	4.09±0.76	K0-K4
JW232	3.24±0.92	G0-K0
JW248	5.56±0.58	K4
JW273	3.51±0.26	K0, M0-M4
JW291	7.18±0.49	K4
JW347	6.19±0.63	K4
JW352	4.52±0.36	K2
JW364	3.91±0.18	K2
JW365	4.19±0.52	K2, M0-M4
JW409	3.36±0.56	G4-K0
JW421	5.69±0.59	K4
JW437	5.67±0.90	K4
JW448	5.74±0.22	K4
JW504	4.61±0.57	K2
JW589	5.03±0.20	K4
JW608	0.62±0.28	<F7
JW640	2.74±0.30	G2-G8
JW641	4.86±1.02	K2-K4
JW669	4.39±0.28	K2, M4
JW678	3.86±0.31	K1
JW683	3.96±0.75	K0-K2, M0-M4
JW706	5.52±0.38	K4
JW747	4.03±0.28	K1
JW750	3.57±0.93	G2-K2
JW769	4.06±0.47	K2
JW795	3.44±0.42	G8-K1
JW799	3.54±0.22	K0-K1, M0-M4
JW810	8.46±2.01	K4
JW813	5.40±1.23	K4
JW826	4.04±1.05	K2
JW852	6.51±1.37	K4

Table 3.8: Equivalent Widths of Trapezium Cluster Stars - Feature C

Object (1)	EW(C) (2)	SpT (3)
JW75	4.71±0.50	K2
JW232	2.71±0.18	K1
JW248	6.60±0.37	M0, M4
JW249	6.36±0.57	M0, M4
JW268	3.03±0.72	K0-K2, M3
JW273	4.23±0.41	K2-K3, M3
JW291	6.93±0.23	M0, M4
JW337	5.40±0.68	K4-M0, M4
JW347	3.09±0.73	K0-K2
JW352	4.76±0.13	K3
JW364	1.68±0.28	F7-G8
JW365	4.91±0.30	K3
JW378	8.56±0.34	M0, M4
JW391	2.58±0.25	K0
JW409	2.91±0.46	K0-K2
JW421	2.52±0.23	K0-K1, M3
JW423	6.21±0.24	M0, M4
JW437	6.88±0.67	K4
JW448	4.12±0.98	K2-K3, M3
JW454	5.77±0.04	K4-M0, M4
JW457	4.16±0.30	K2-K3
JW478	5.48±0.27	K4
JW526	3.80±0.48	K2-K3
JW529	9.07±0.77	M0, M4
JW544	4.87±0.18	K3
JW567	4.42±0.53	K2-K3
JW589	2.88±0.18	K1
JW608	1.07±0.44	<F7
JW613	3.07±0.27	K2
JW640	1.11±0.61	<F7
JW641	5.69±0.46	K4-M0, M4
JW669	1.96±0.83	<F7-K1, M3
JW678	4.95±1.29	K2-K4
JW683	6.19±0.19	M0, M4
JW698	4.13±0.15	K2-K3, M3
JW706	3.55±0.06	K2
JW747	2.67±0.40	K0-K1
JW750	2.70±0.29	K0-K2
JW769	4.95±0.65	K3-K4, M4
JW795	2.90±0.10	K1
JW799	3.29±0.23	K1-K2, M3
JW810	5.14±0.44	K4
JW813	4.27±0.76	K2-K3
JW826	5.84±0.76	K3-K4
JW852	5.74±0.18	K4

Table 3.9: Equivalent Widths of Trapezium Cluster Stars - Feature D

Object (1)	EW(D) (2)	SpT (3)
JW249	20.53 ± 1.20	>K4
JW347	17.29 ± 1.67	>K4
JW378	16.63 ± 1.15	>K4
JW409	17.72 ± 2.14	>K4
JW437	16.88 ± 1.97	>K4
JW448	12.57 ± 2.47	K1-K4
JW457	17.5 ± 1.22	>K4
JW478	15.12 ± 0.83	$\geq$ K4
JW504	17.82 ± 1.64	>K4
JW526	13.62 ± 2.30	K1->K4
JW589	13.07 ± 1.20	K2-K4
JW613	13.64 ± 1.65	K2-K4
JW640	8.49 ± 0.68	G0-G4, G8-K0
JW706	22.45 ± 1.23	>K4
JW769	15.79 ± 1.24	$\geq$ K4

Observations of optically thick Ca II triplet emission have been well-documented for many stars including T Tauri stars (Herbig 1962; Herbig & Soderblom 1980), Be stars (Polidan 1980), and high mass protostars (McGregor, Persson & Cohen 1984). Herbig & Soderblom (1980) proposed that the similarity of the Ca II triplet lines in T Tauri stars with solar observations is supportive of a chromospheric origin for the emission. Hamann & Persson (1992; HPA) find that the correlation observed between calcium triplet emission and infrared excess suggests a circumstellar disk origin for the triplet lines. They determine that observed triplet features narrower than $\sim 40 \text{ kms}^{-1}$ ($\sim 1.2 \text{ \AA}$) are chromospheric, while broad features $> 100 \text{ kms}^{-1}$ ($\sim 3 \text{ \AA}$) originate in the disk. We investigate the strengths of triplet emission observed and the frequency of PMS stars with Ca II infrared triplet emission in the Trapezium Cluster at greater length in Chapter 4 of this dissertation.

3.3.4 Rotational Velocities of Trapezium Cluster Stars

Four Trapezium Cluster stars, JW531, JW595, JW660, and JW831, have spectra in the range 5155–5455 $\text{\AA}$ with extremely broad lines (Figure 3.10). The line broadening may be due to the effects of high stellar rotational velocities. We have attempted to model this situation by convolving standard star spectra corresponding to a variety of spectral types with the profile for rotational broadening given by Unsöld

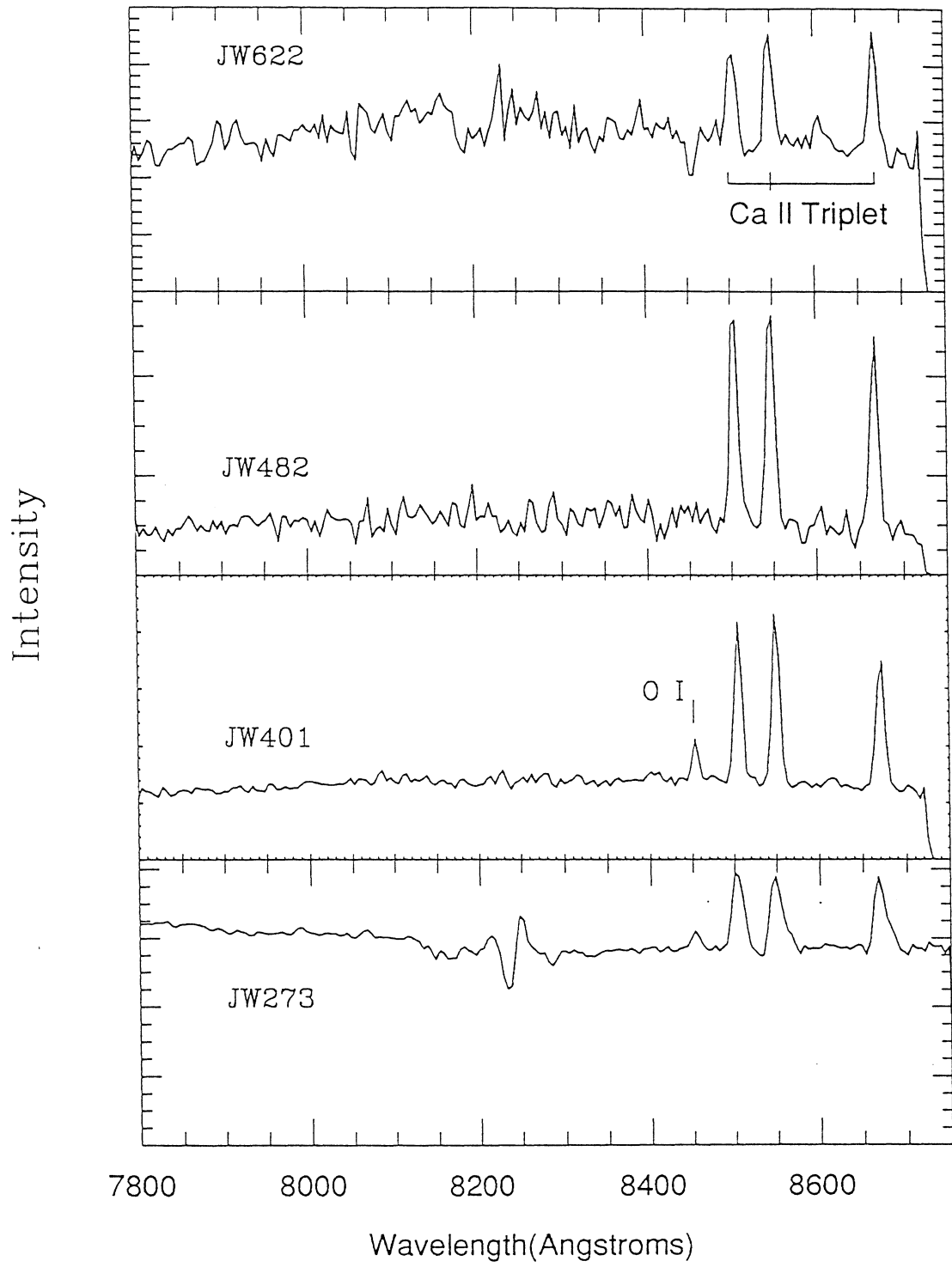


Figure 3.9: Spectra of 4 Sample A stars with Ca II IR triplet emission, between 7800–8750 Å. The O I λ 8446 emission feature is marked.

(1955). Comparison of the artificially broadened standard spectra with the spectra of the four Trapezium Cluster stars (Figure 3.10) supports a high rotational-velocity interpretation of $\geq 225 \text{ kms}^{-1}$ for the observed spectral broadening in three of the four stars. These three stars appear to be earlier than F5 in spectral type. This interpretation agrees with the well-known correlation between stellar rotational velocity and spectral type where stars of early-type are found to rotate more rapidly than cooler stars (Hauck & Slettebak 1989, and references therein). We find that the remaining star, JW595, is more comparable to a K0 star with the lower rotational velocity of $\sim 150 \text{ kms}^{-1}$. Late-type PMS stars with high rotational velocities ($> 100 \text{ kms}^{-1}$) have also been observed in the Orion Nebula Cluster by Walker (1983).

JW660 is the only star of the four whose rotational period has previously been measured. Mandel & Herbst (1991) have determined a period of 6.2 days for this star. For a typical stellar radius of $\sim 2 R_{\odot}$ for PMS stars (Bertout 1989; Walker 1983), this period corresponds to a rotational velocity for JW660 of $\sim 17 \text{ kms}^{-1}$. This estimate is considerably different from the value of $\geq 225 \text{ kms}^{-1}$ obtained here. It is not apparent why the two velocity estimates should be so disproportionate, although we conjecture that Mandel & Herbst may in fact be probing spots on the stellar surface rotating at different rates to the star itself. Further monitoring of this star to confirm the stellar rotational velocity will help resolve this issue. The periods of the seven stars measured by Mandel & Herbst (1991) range from 6.2 to 14.3 days, or, assuming stellar radii of $\sim 2 R_{\odot}$, from 7 kms^{-1} to 17 kms^{-1} . Herbig & Terndrup (1986) found that the absorption lines in the spectrum of JW595 are very broad, but do not make any rotational velocity estimates based on these observations. Duncan (1991) has measured rotational velocities of stars in the Orion Nebula Cluster population. Typical $v \sin i$ values he found are between 15 and 30 kms^{-1} for his sample of ~ 20 Orion Nebula Cluster stars. These results differ from those of Walker (1983). Walker derived rotational velocities of between 45 and 279 kms^{-1} for five pre-main-sequence stars in the Orion Nebula Cluster region. In summary, the situation regarding the rotational velocities of PMS stars in this star-forming region is confused. Stars of both low and high rotational rates are measured. Monitoring observations of the fast rotators in our sample will help clarify the status of these stars. High rotational velocities have been modelled for PMS stars (Endal & Sofia 1981; Terebey, Shu & Cassen 1984; Larson 1984) as due to small angular momentum loss rates over the PMS evolutionary phase. The observation of a few high rotational velocity stars indicates that angular momentum transfer during collapse stages has been less efficient in these stars. However, while some of the early-type stars in our sample appear to have higher velocities typical of early-type main sequence stars, in general the Trapezium Cluster stars are slow rotators with velocities of less than 20 kms^{-1} (the resolution of our data). This is consistent with earlier findings (for example,

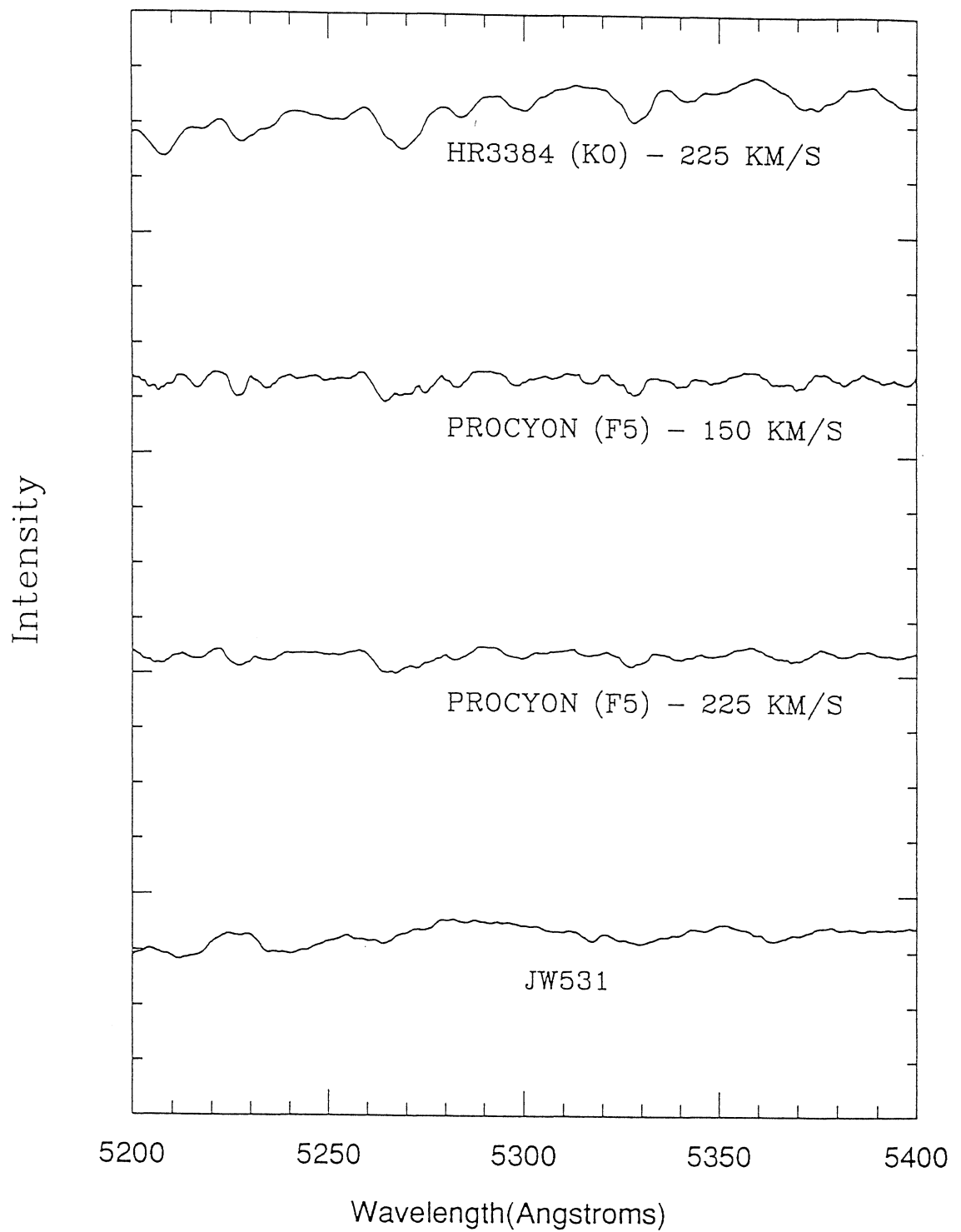


Figure 3.10: Spectra of Four Trapezium Cluster stars with Broadened Features Compared with Spectra of Artificially-Broadened Standard Stars.

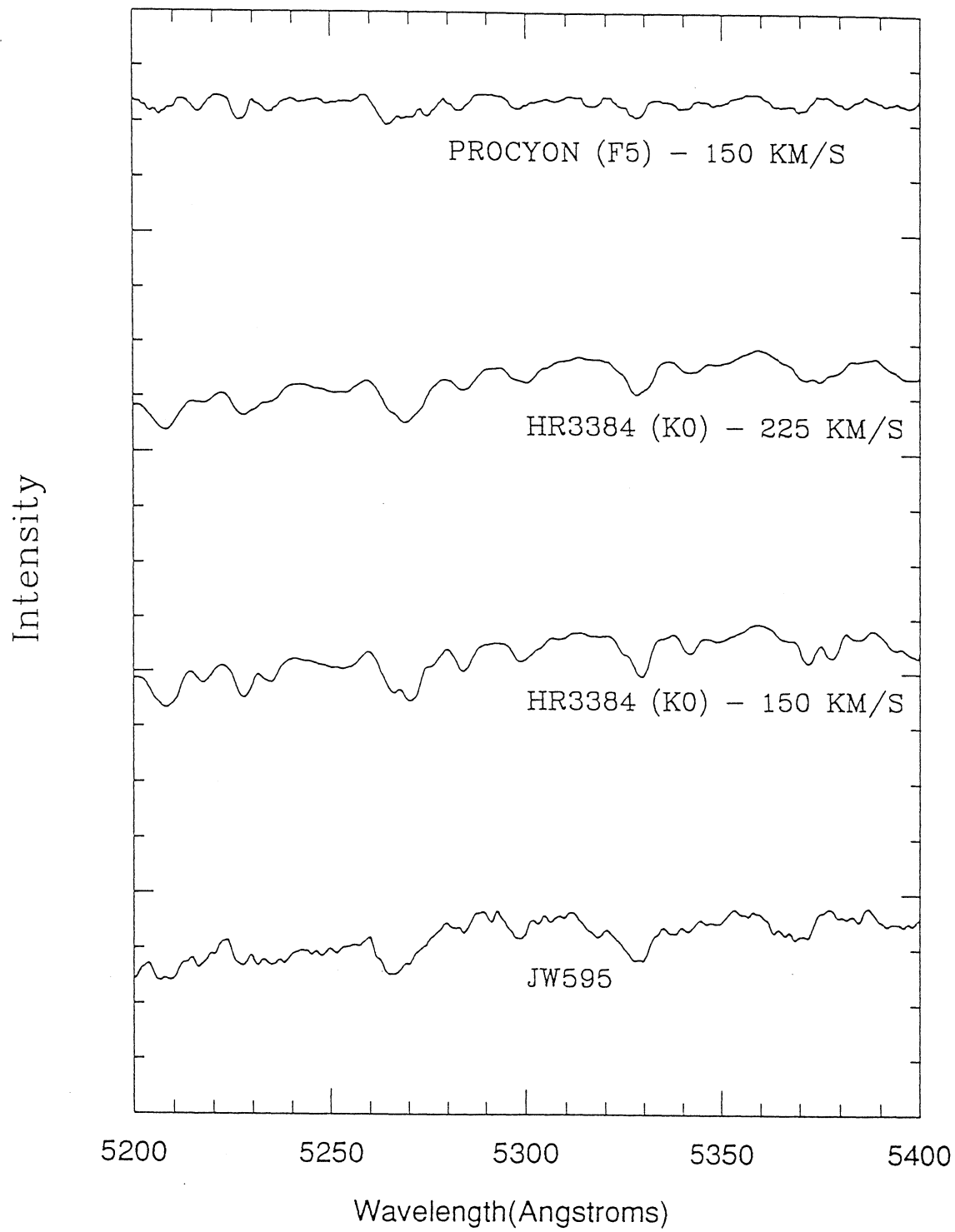


Figure 3.10: *cont.*

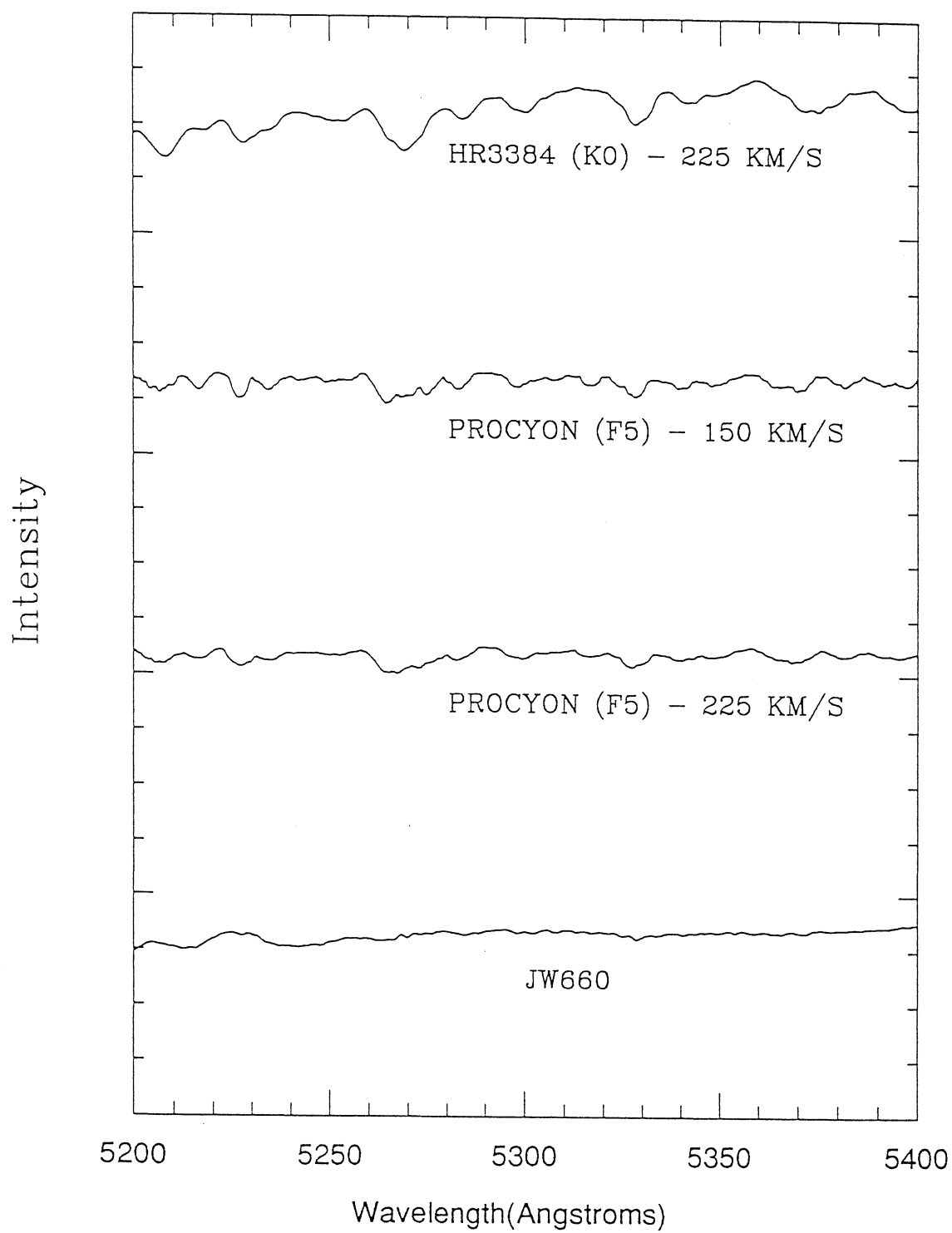


Figure 3.10: *cont.*

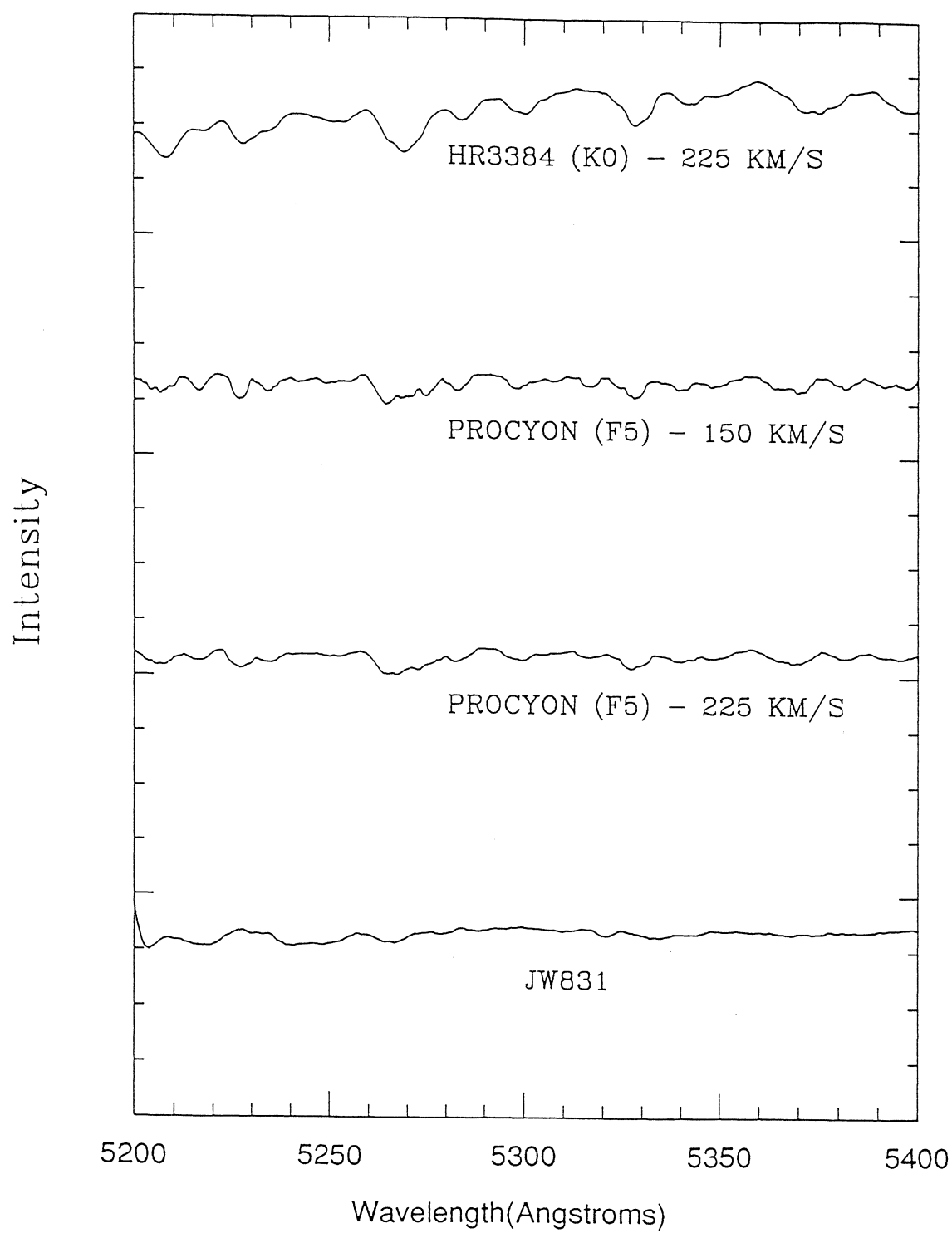


Figure 3.10: *cont.*

Vogel & Kuhi 1981; Hartmann et al. 1986; Bouvier et al. 1986; Stauffer 1988) that the rotational velocities of T Tauri stars are typically $\leq 20\text{--}25 \text{ kms}^{-1}$. Thus, our data provide more evidence that, contrary to some model predictions, angular momentum loss must occur predominantly before the T Tauri stage (Bertout 1989).

3.4 Discussion

3.4.1 Spectral Classification of Trapezium Cluster Sample

In total, 58 Trapezium Cluster stars have been examined in this program. The spectral types obtained are given in columns 4 and 5 of Table 3.1. The mean spectral type of our samples is $\sim K3$. Only five of the 58 are positively identified as being M-type stars. Five stars are classified as earlier than G5.

Table 3.1 also includes a listing of spectral types inferred from our parallel infrared photometry program (Chapter 2; column 6), and from other programs (column 7). The spectral types obtained for fifteen of the twenty stars classified in both our infrared and spectroscopic programs are in reasonable agreement. However, the uncertainties in the spectral classes inferred from the infrared photometry data dominate comparisons with the current results. Herbig & Terndrup (1986) give spectral classes for eleven of the brighter Trapezium Cluster stars. The mean spectral type obtained for these eleven stars is G5. The spectroscopic study of Orion Nebula stars undertaken by Walker (1983) includes nine JW stars. Two of these, JW273 and JW364, are also included in our sample. Walker's study finds an average spectral type of K3, which is consistent with our results. Parsamian & Chavira (1982) surveyed 5 degrees² centred on the Trapezium high mass stars. They classified 49 stars, finding thirteen of G-type or earlier, 29 K stars, and seven M stars, again in agreement with our results. Further spectral classifications in the vicinity of the Trapezium Cluster were made by Cohen & Kuhi (1979). Of the 109 Orion Molecular Cloud stars in their study, 11 are JW stars and thus within 15' of M42, and 41 are within 0.5 degrees of the Trapezium. Cohen & Kuhi find an average spectral type for the 11 JW stars of K4, and an average of K6 for the 41 members at greater distances, also agreeing with the results obtained here. Thus, we update the value of mean spectral type derived in Chapter 2, using more accurate spectroscopic data, and determine that the low mass stars of the Trapezium Cluster appear to be representative of the larger Orion population with no evidence for a significant radial gradient in their mean spectral type. In the case of PMS stars, this consistency in spectral type can be interpreted as a consistency in stellar mass.

3.4.2 The K_o , $J-K_o$ Diagram

I , J , and K magnitudes of ~ 0.1 mag accuracy were measured for 25 of the Trapezium Cluster stars included in the present study, in our infrared photometry program (Chapter 2). Where these parameters have not been estimated from our photometric survey for a particular star, recourse has been made to the less accurate JW I magnitudes and J and K magnitudes obtained by HAB. These values have been used to obtain $I-J$ vs $J-K$ colors for the stars studied here, and hence to deredden the stars onto the K_o , $(J-K)_o$ diagram. The $I-J$ vs $J-K$ diagram for our sample is plotted in Figure 3.11. The form of the intrinsic main sequence locus in the $I-J$, $J-K$ plane is such that late spectral classes are more distinct from each other compared with their positions in the $J-H$, $H-K$ plane (see Chapter 2, Figure 2.5). Thus, this factor, combined with the fact that *late* spectral types are determined for our sample, has led to our preference for using this plane rather than the $J-H$, $H-K$ plane in which to deredden the stars. The extinction and dust excess values corresponding to the stellar spectral type determined in the present investigation are calculated in the $(I-J)$, $(J-K)$ plane, following the procedure described in detail in Chapter 2 (§2.3.2). These extinctions and excesses are then applied to deredden the star in the K_o , $J-K_o$ plane.

The K_o , $J-K_o$ diagram is given in Figure 3.12. Three stars, JW531, JW608, and JW660, are plotted with arrows. JW531 and JW660 are found here to have broadened absorption spectra corresponding to high rotational velocities. The arrows indicate that the plotted positions of these three stars represent the latest possible spectral types for the stars. Table 3.10 lists the observed $I-J$, $J-K$ and K values for the 33 stars which were successfully dereddened, their spectral types as determined in the present work, the corresponding extinctions and dust excesses evaluated in the dereddening process, and the final dereddened $J-K_o$ and K_o values. Locating these stars in the K_o , $(J-K)_o$ diagram from spectral type information allows more accurate determinations of their associated extinctions, dust excesses, stellar masses, and ages than has been possible in the past using other methods (Herbig & Terndrup 1986; McCaughrean 1988; Chapter 2).

Extinction and Dust Excess Measurements

We calculate a mean extinction of $A_K \sim 0.3$ mag for our Trapezium Cluster sample. This is in good agreement with the value of $A_K \sim 0.27$ mag calculated by Herbig & Terndrup (1986). Our present estimate is slightly smaller than the mean A_K of 0.5 mag determined from our infrared photometry program, which can be accounted for by the fact that we have included optically obscured, potentially more embedded stars in our photometry program. The extinctions measured here range from

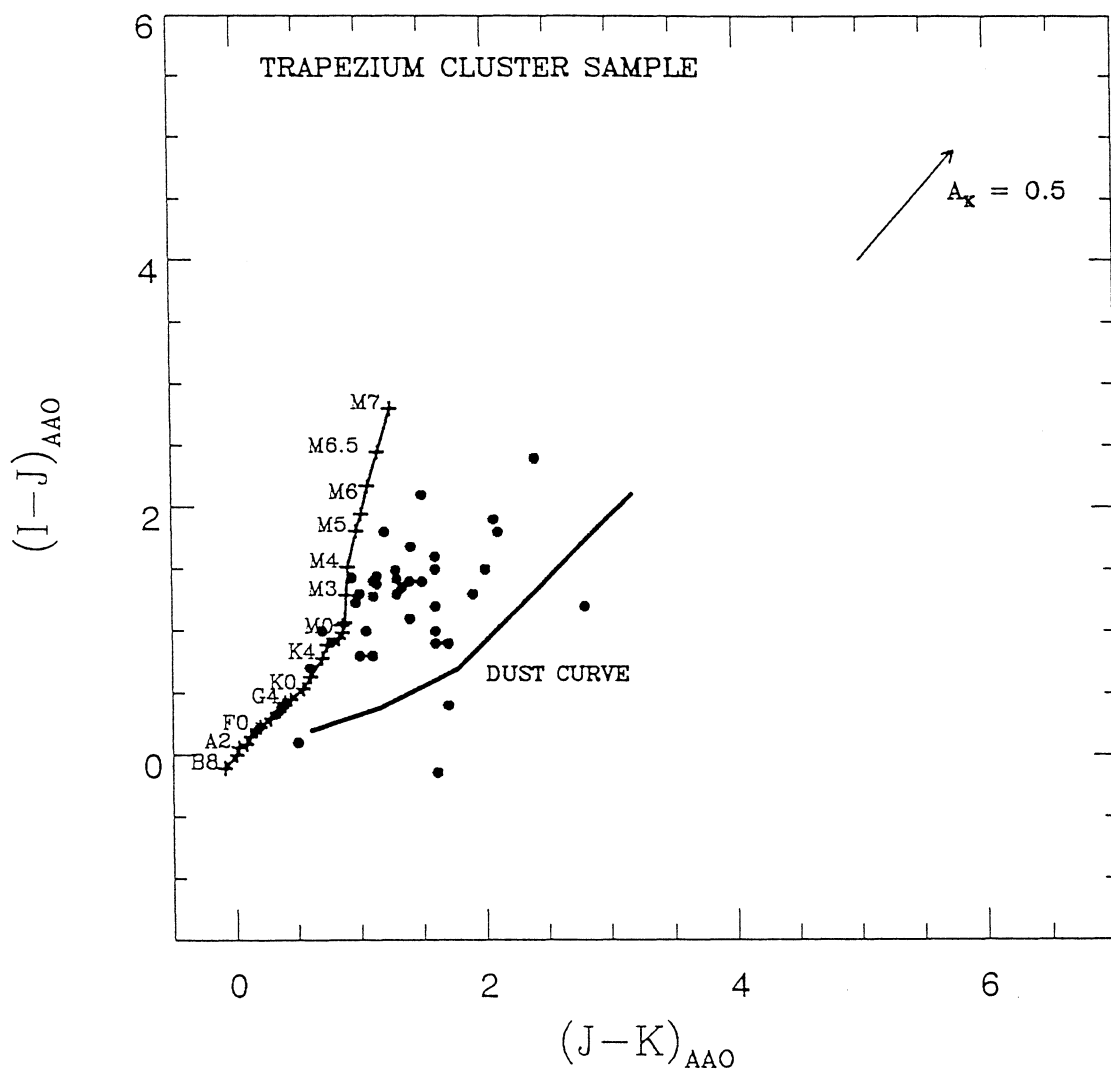


Figure 3.11: $(I-J)$ vs $(J-K)$ diagram for Trapezium Cluster stars, given by filled circles. The locus for B8–M7 dwarfs (Bessell & Brett 1988; Bessell 1991) is represented by the solid heavy line to the left of the diagram, with spectral types marked. The position of a (5400 K photosphere+dust) curve (Hyland et al. 1982) used in the dereddening process is also indicated. The extinction vector given corresponds to $A_K = 0.5$ mag, and assumes a normal reddening law (Rieke & Lebofsky 1985).

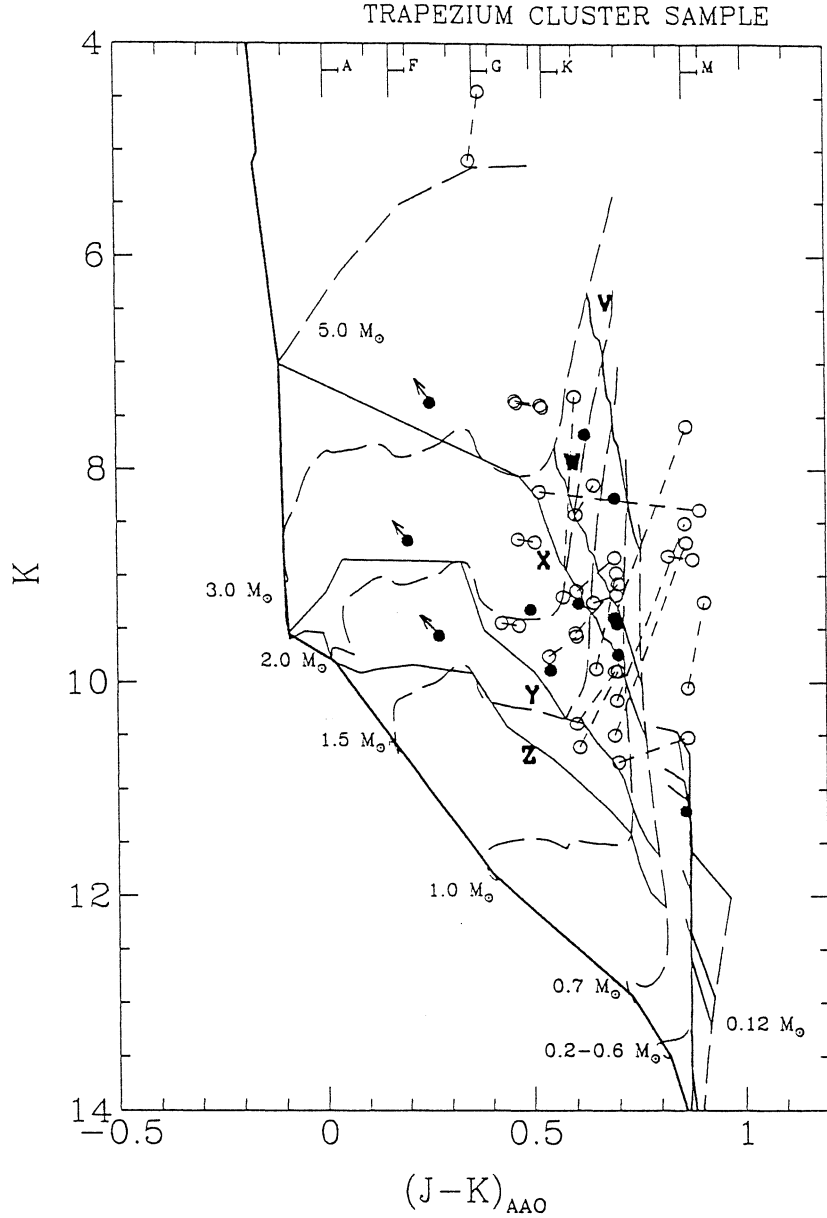


Figure 3.12: K_0 vs $J-K_0$ diagram for the Trapezium Cluster sample. The main-sequence locus is indicated by the solid line in the left of the diagram. Dashed lines give PMS evolutionary tracks from 0.12 to 3 $M_{\odot}$ (VandenBerg 1991; see Chapter 2, §2.3.4) and for a 5 $M_{\odot}$ star (Iben & Talbot 1966). Solid lines marked V to Z correspond to isochrones such that V: 10^5 yr; W: 5×10^5 yr; X: 10^6 yr; Y: 5×10^6 yr; Z: 10^7 yr. The figure includes lines marking the observed $J-K$ colors for A- to M-type dwarfs (Bessell & Brett 1988), along the top axis. Filled circles represent stars for which a unique spectral class has been derived. Those stars whose spectral types were not so well constrained are shown as open circles connected by a dashed line, corresponding to the two extremes in spectral class determined for each star.

Table 3.10: De-Reddening Parameters for Trapezium Cluster Stars

Name	$(I-J)$	$(J-K)$	K	SpT(1)	$A_K(1)$	Excess(1)	$(J-K)_o(1)$	$K_o(1)$	SpT(2)	$A_K(2)$	Excess(2)	$(J-K)_o(2)$	$K_o(2)$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
JW232	1.38	1.14	9.1	K1	0.44	0.00	0.47	8.66	K2	0.42	0.00	0.51	8.68
JW248	1.30	1.90	9.7	K4	0.16	0.96	0.69	10.50	M0	0.04	0.97	0.87	8.69
JW249	1.50	1.60	10.0	M0	0.27	0.32	0.87	10.05	M4	0.00	0.86	0.91	9.25
JW291	1.00	1.05	10.7	K4	0.12	0.17	0.70	10.75	M0	0.00	0.18	0.87	10.52
JW337	1.00	1.60	9.3	K4	0.01	0.88	0.70	10.17	M0	0.00	0.90	0.86	8.51
JW345	1.68	1.41	9.2	M0	0.39	0.00	0.82	8.81	M2	0.34	0.01	0.88	8.85
JW347	1.40	1.50	9.7	K2	0.42	0.26	0.60	9.54	K4	0.33	0.29	0.70	9.08
JW352	1.44	1.14	7.8	K2	0.45	0.00	0.46	7.35	K3	0.41	0.00	0.52	7.39
JW378	1.00	0.70	9.4	M0	0.00	0.00	0.70	9.40					
JW391	1.30	1.30	10.2	K0	0.43	0.11	0.54	9.88					
JW437	1.20	1.60	9.0	K4	0.18	0.63	0.70	9.45					
JW448	1.10	1.40	9.6	K3	0.19	0.46	0.65	9.87	K4	0.15	0.48	0.70	8.97
JW454	1.30	1.90	8.6	K4	0.16	0.96	0.69	9.40	M0	0.04	0.97	0.87	7.59
JW457	1.42	1.30	9.6	K3	0.40	0.05	0.65	9.25	K4	0.36	0.06	0.70	9.18
JW478	1.60	1.60	8.5	K4	0.45	0.22	0.70	8.27					
JW504	1.60	1.60	9.5	K2	0.54	0.18	0.61	9.14	K4	0.45	0.22	0.70	8.83
JW526	1.40	1.40	8.7	K2	0.43	0.15	0.60	8.42	K3	0.38	0.17	0.65	8.15

Table 3.10(ctd): De-Reddening Parameters for Trapezium Cluster Stars

Name	(I-J)	(J-K)	K	SpT(1)	A _K (1)	Excess(1)	(J-K) _o (1)	K _o (1)	SpT(2)	A _K (2)	Excess(2)	(J-K) _o (2)	K _o (2)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
JW529	0.90	1.70	9.7	M0	0.00	1.24	0.86	11.20					
JW531	0.10	0.50	9.0	<F5	0.00	0.43	0.27	9.56					
JW544	1.49	1.29	8.1	K3	0.44	0.00	0.63	7.66					
JW567	1.40	1.11	7.8	K2	0.43	0.00	0.46	7.37	K3	0.39	0.00	0.53	7.42
JW608	1.30	1.00	9.2	<F7	0.53	0.00	0.20	8.67					
JW613	1.80	2.10	9.3	K2	0.61	0.57	0.61	9.26					
JW640	2.40	2.40	5.9	F7	1.13	0.33	0.35	5.10	G2	1.10	0.35	0.38	4.45
JW660	0.70	0.60	7.6	<F5	0.23	0.00	0.27	7.35					
JW669	0.90	1.60	8.3	K1	0.05	0.95	0.57	9.20	K2	0.02	0.97	0.60	7.31
JW678	1.23	0.97	9.8	K1	0.36	0.00	0.43	9.44	K2	0.33	0.00	0.47	9.47
JW706	0.80	1.00	10.2	K2	0.08	0.27	0.60	10.39	K4	0.00	0.31	0.70	9.89
JW747	0.91	0.77	9.5	K1	0.18	0.00	0.50	9.32					
JW750	1.35	1.34	10.1	K0	0.46	0.11	0.54	9.76	K2	0.40	0.13	0.61	9.57
JW769	0.80	1.10	10.3	K2	0.07	0.38	0.61	10.61	K4	0.00	0.42	0.70	9.90
JW799	1.28	1.11	8.6	K1	0.39	0.00	0.52	8.21	M3	0.00	0.23	0.90	8.38
JW810	1.50	2.00	9.2	K4	0.30	0.84	0.70	9.74					

$A_K \sim 0.0$ – 1.1 mag. These values may be compared with the estimated extinction towards the high mass Θ^1 Ori stars of $A_K \sim 0.1$ – 0.3 mag (Warren & Hesser 1978; Garay, Moran & Reid 1987; Chapter 2). Combined with the fact that our sample of Trapezium Cluster stars is optically selected, our results suggest that the low mass Trapezium Cluster stars are in general at least *as* embedded and possibly more embedded in the molecular cloud than the high mass Trapezium OB stars. The BN-KL star formation complex is estimated to be extinguished by A_K between 2 and 5 mag (Gillett et al. 1975; Joyce, Simon & Simon 1978; Scoville et al. 1983; Beckwith 1982; Hyland et al. 1984; Minchin et al. 1991), and is therefore much more deeply embedded in the molecular cloud than the Trapezium Cluster stars examined here. The mean extinction determined here of $A_K \sim 0.3$ mag for our sample of Trapezium Cluster stars, compared with the 0.5 mag determined from our infrared photometry program, strengthens our proposal of Chapter 2 (§2.4.4) that the low mass cluster is local to the front face of the cloud rather than being spread through it.

Approximately one-third of the stars in our sample (11 out of 33) have little or no dust excess (Table 3.10 and Figure 3.13). This is comparable with the statistics of dust-excess/no-excess stars found in ρ Oph, Taurus-Auriga, and Chamaeleon (Walter 1986; Walter et al. 1988; Hartigan 1993). Using our small sample, the results here confirm the finding of Chapter 2 that the proportion of PMS stars without dust excesses in the Trapezium Cluster is typical of young stellar populations, and that the inner-disk regions probed at near-infrared wavelengths have not been altered significantly via disk-disk interactions in this populous environment.

Age Estimates for Trapezium Cluster Sample

The 33 Trapezium Cluster stars plotted in Figure 3.12 occupy pre-main sequence positions as expected, with the majority found to be younger than 5×10^6 yr. The average age is $\sim 10^6$ yr, with stars younger than 10^5 yr included in our sample. Our age estimates are in excellent agreement with those of Herbig & Terndrup (1986) for their optical Trapezium Cluster sample. The range in age found here is larger than that found from our infrared photometry approach, but upholds the result obtained in Chapter 2 that no Trapezium Cluster stars older than 10^7 yr are observed. The lower limit to the ages of the Trapezium OB stars is $\sim 6 \times 10^4$ yr (Iben 1965). It remains unresolved whether or not a distinction exists between the times of low and high mass star formation, and whether the formation of high mass stars has terminated further low mass star formation (Herbig 1962; Elmegreen & Lada 1977; Silk 1977; Larson 1985). Cohen & Kuhn (1979) found that the average age of Orion Nebula Cluster stars is a few $\times 10^6$ yr, in reasonable agreement with our results. The ages estimated for the high mass BN-KL stars are $\leq 10^4$ yr (Scoville et al. 1983; Mundy et al. 1986), making these the youngest known sources in the region.

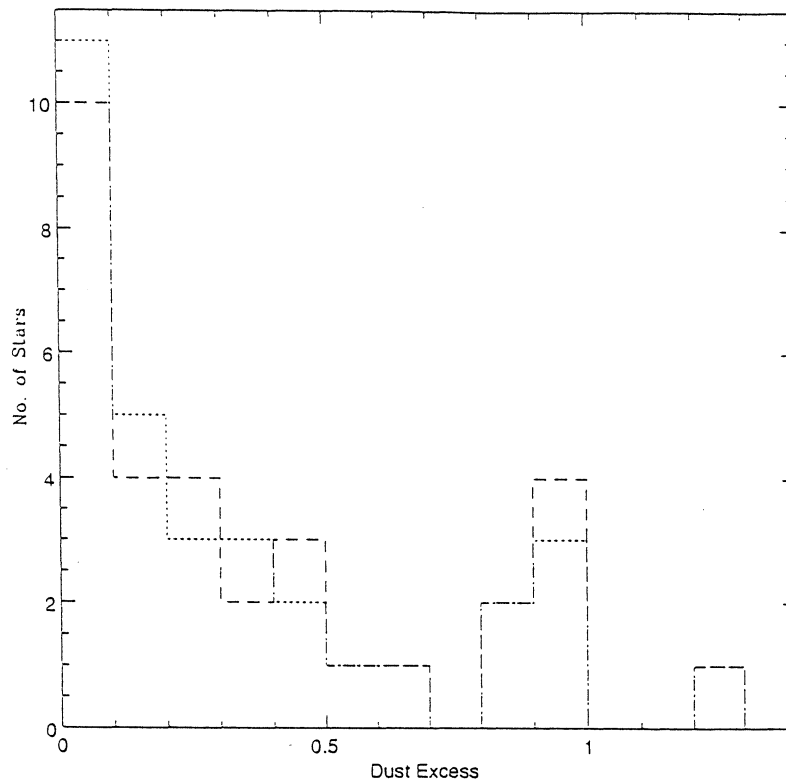


Figure 3.13: Histograms of dust excesses determined for Trapezium Cluster sample. The two histograms demonstrate the results obtained considering two spectral-type interpretations where appropriate (short dashes: spectral type 1; long dashes: spectral type 2).

Masses of Trapezium Cluster Sample

Masses for our sample of Trapezium Cluster stars are between 0.2 and $\sim 5 M_{\odot}$, although most stars are between 0.6 and $3 M_{\odot}$. We find the average mass of our sample to be $\sim 1.5 M_{\odot}$. We note that the sample of ~ 33 stars discussed here have been chosen on the basis of optical identification and as such are either high luminosity stars or objects with relatively small amounts of extinction. It is therefore necessary to place our sample in the context of the total Trapezium Cluster population before discussing their masses further.

3.4.3 Mass of the Complete Trapezium Cluster Population

The K luminosity function for a sample of PMS stars can be used to derive individual stellar masses and hence the initial mass function (IMF) (Zinnecker, McCaughrean & Wilking 1992). The transformation from K luminosity to mass for PMS stars is not straightforward and is a strong function of the stellar age (Zinnecker et al. 1992). If our accurate determination of the mean age of the Trapezium Cluster stars observed here is typical of the full population, it can be extended to the total cluster population and so remove much of the uncertainty in the K luminosity-to-mass transformation. Both Zinnecker et al. (1992) and HAB have produced K luminosity distributions for more than 450 low mass stars constituting the Trapezium Cluster.

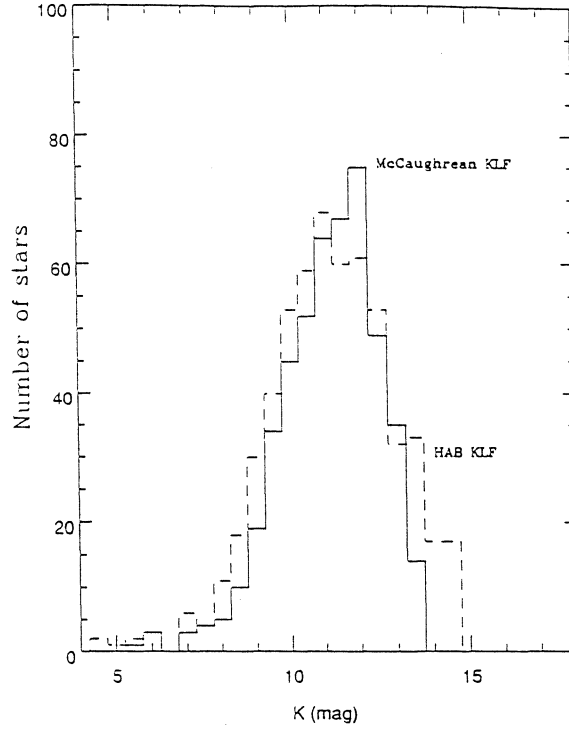


Figure 3.14: K Luminosity Functions for the Trapezium Cluster from the infrared surveys of McCaughrean (1988) and HAB.

Zinnecker et al. obtained their distribution function from infrared array data, while HAB used raster-scan techniques. Figure 3.14 shows both distributions. The two data-sets include the high mass OB stars in the region, and have good agreement. We determine the mass distribution of the infrared cluster from the HAB K luminosity function for which we have individual K magnitudes, for the cluster age of 10^6 yr found here. This procedure is based on the assumption that the stars have negligible dust excesses (Zinnecker et al 1992), and can be simply dereddened along the reddening vector back to the 10^6 yr isochrone. The distribution of dust excesses found in our investigation (Figure 3.13) is weighted towards the no-excess end of the spectrum, giving some justification for the application of this approach to obtain a first-order estimation. The resultant distribution is given in Table 3.11. Column (1) lists the observed K magnitude considered, column (2) gives the number of stars within this K magnitude bin, column (3) is the inferred mass for stars of this K magnitude based on position in the K_o , $(J-K)_o$ diagram (Figure 3.12) with respect to the 10^6 yr isochrone, column (4) gives the total mass in that bin, and column (5) lists the cumulative mass. Note that the inferred masses for stars more massive than $\sim 5 M_\odot$ are only order-of-magnitude estimates.

For the mean cluster age of $\sim 10^6$ yr, the ~ 562 low mass Trapezium Cluster stars included here, with masses $\leq 5 M_\odot$, have a total stellar mass of $\sim 491 M_\odot$. The average stellar mass is then $\sim 0.9 M_\odot$. The difference in mass between the results for our sample of $\sim 1.5 M_\odot$ and the mean stellar mass of the whole cluster highlights the fact that our sample of ~ 33 stars is biased towards the brighter members of

Table 3.11: Mass Distribution for Trapezium Cluster Stars (10^6 yr)

K_0 (1)	No. of Stars (2)	Mass (3)	M_{tot} (4)	Cumul. Mass (5)
4.5	2.0	30.0	60.0	60.0
5.0	1.0	20.0	20.0	80.0
5.5	2.0	16.0	32.0	112.0
6.0	3.0	10.0	30.0	142.0
6.5	0.0	7.0	0.0	142.0
7.0	6.0	5.0	30.0	172.0
7.5	4.0	4.0	16.0	188.0
8.0	11.0	3.0	33.0	221.0
8.5	18.0	2.5	45.0	266.0
9.0	30.0	2.0	60.0	326.0
9.5	40.0	1.5	60.0	386.0
10.0	53.0	1.0	53.0	439.0
10.5	59.0	0.7	41.3	480.3
11.0	68.0	0.65	44.2	524.5
11.5	60.0	0.6	36.0	560.5
12.0	61.0	0.5	30.5	591.0
12.5	53.0	0.4	21.2	612.2
13.0	32.0	0.3	9.6	621.8
13.5	33.0	0.2	6.6	628.4
14.0	17.0	0.12	2.04	630.4
14.5	17.0	0.12	2.04	632.5

the low mass cluster stars. The average mass derived from our infrared photometry program of $\sim 0.5 M_{\odot}$ is subject to the uncertainties in the dereddening process used, and is a first-order estimate based on a small sample. Considering the whole infrared sample (HAB), we note that if the mean cluster age has been overestimated here then the mean stellar mass calculated is too large. For a cluster age of $\sim 10^5$ yr, the mean stellar mass is $\sim 0.5 M_{\odot}$. An older cluster age of $\sim 5 \times 10^6$ yr gives larger mean mass of $\sim 1.2 M_{\odot}$. However, we consider that a cluster age of 10^6 yr is more probable based on the data presented here.

The peak of the K luminosity function used by Zinnecker et al. (1992) at ~ 11.5 mag (including the effects of extinction) is shown by these authors to correspond to a stellar mass of $\sim 0.3 M_{\odot}$. As they point out, errors are inherent in transforming directly from this peak value of K to a mean stellar mass. The results obtained here uphold the traditional view that giant molecular clouds such as Orion are forming more massive low mass stars than dark clouds such as Taurus-Auriga, Lupus, and Chamaeleon (Cohen & Kuhi 1979; Herbig 1977; Appenzeller, Jankovics & Krautter 1983; Larson 1991). The low mass populations of these dark clouds have estimated mean masses of $\sim 0.5 M_{\odot}$. Many stars less massive than $0.9 M_{\odot}$ exist in the Trapezium Cluster as is evident from the K luminosity function, but the individual masses of these stars are so low that the total mass in very low mass stars is relatively

small.

Cohen & Kuhi (1979) obtain a mean mass of $1 M_{\odot}$ for their sample of Orion Nebula Cluster stars. Thus, we find no significant difference between the average masses of the low mass population comprising the Trapezium Cluster and the more extended Orion Nebula Cluster. The two regions are mainly differentiated by the extreme mass density in the core. We calculate the mass density of the Trapezium Cluster using our values for average stellar mass ($0.9 M_{\odot}$) and number of stars (~ 245 stars; HAB) inside the same volume considered by Herbig & Terndrup (1986). The mass density obtained is $\sim 3400 M_{\odot} \text{pc}^{-3}$. Including the $\sim 84 M_{\odot}$ contributed by the Θ^1 Ori stars, this becomes $\sim 4690 M_{\odot} \text{pc}^{-3}$. This amount of mass can be put in terms of the amount of gas it would have formed from, assuming 100 % star formation efficiency and a closed system. The equivalent gas density is then $\sim 10^5 \text{ H}_2 \text{ molecules cm}^{-3}$ (compare with density measurements of 10^5 – 10^6 cm^{-3} in dense cores of the Orion Molecular Cloud: Snell et al. 1984; Mezger, Wink & Zylka 1990). Our estimate is ~ 1.5 times that of Herbig & Terndrup of $\sim 3000 M_{\odot} \text{pc}^{-3}$, or $0.6 \times 10^5 \text{ H}_2 \text{ molecules cm}^{-3}$, for the same volume. Clearly, a proper accounting of the entire infrared cluster makes a significant difference to density estimates for the cluster.

The mass function for the infrared cluster is plotted in Figure 3.15, derived using HAB K magnitudes and the K_o , $(J-K)_o$ diagram to estimate the number of stars per $\log$ Mass bin. While the mean determination of 10^6 yr obtained in this work is taken as the most likely age for the cluster stars, we also plot the mass function for cluster ages of 10^5 yr and 5×10^6 yr in order to gauge the level of uncertainty due to our age estimate. The mass functions obtained are compared with standard models. The earliest form of the initial mass function was derived by Salpeter (1955):

$$dN(\log M) \propto M^{-1.35} \quad (3.1)$$

Subsequent studies using recent observations suggest that a steeper slope of -1.7 is more realistic for low mass stars (Scalo 1986). Both of these functions are given in Figure 3.15 for comparison. We find that the mass function for a 10^6 yr cluster could be fit by either Salpeter or Scalo slopes to $\sim 0.5 M_{\odot}$, within the errors of our transformation from K magnitude to stellar mass. A cluster age of 5×10^6 yr gives a mass function which is better fit by the more recent Scalo slope. The mass function for a cluster age of 10^5 yr is too shallow to be well fit by either model. Here, a smaller number of stars is present in intermediate mass bins compared with the models, with the distribution weighted towards very low masses. This reflects the fact that for such a young age there are many very young PMS stars with brighter luminosities for their mass than would be true if the stars were older, as they are in the models. However, for the cluster age derived in this study, the numbers of low

mass stars being formed of different masses in the Trapezium Cluster corresponds to the standard models determined for stars in the solar neighbourhood, at least down to masses of $\sim 0.5 M_{\odot}$. Our result may be compared with the finding of Cohen & Kuhn (1979) that the Orion Nebula Cluster initial mass function is reasonably well fit by a Salpeter slope. This again demonstrates that, for our derived cluster age of 10^6 yr, there is no significant difference in the mass distributions of the central low mass Trapezium Cluster and the more extended low mass Orion Nebula Cluster. We note also that agreement, as found here between the observed mass function and the field IMFs, is also seen in regions of low mass star formation such as Taurus-Auriga (Cohen & Kuhn 1979). Thus, the presence of high mass stars in the Trapezium Cluster region does not appear to have affected their distribution of lower mass stars with mass, at least for the cluster age estimated here.

The reality of a truncation at the low mass end of the mass function is currently the subject of much debate (Scalo 1986). The IMFs of several young clusters are observed to be truncated (Gatley et al. 1991; Rayner et al. 1991; Lada et al. 1991; among others) but it is not clear whether the turnovers are intrinsic to the stellar populations or caused by a lack of completeness in the observations, with very faint sources undetected. The existence of a turnover in the initial mass function remains one of the outstanding questions of star formation.

A detailed knowledge of the mass distribution of Trapezium Cluster stars is necessary in order to quantify the dynamics of the region. Thus, the data provided above are a vital precursor to the following analysis of the dynamical evolution of the Trapezium Cluster.

3.4.4 Dynamics of the Trapezium Cluster Star Formation Region Dynamical Evolution Time-scales

The most fundamental parameters with which to probe the dynamical state of a stellar system are the time-scales over which dynamical evolution occurs. The relevant equations have been derived from modelling systems with an arbitrary number of particles (Chandrasekhar 1942; Spitzer 1987 and references therein).

An initial approximation made in our analysis is that we are dealing with a single-mass population. This is an assumption used extensively in theoretical work on N-body systems (for example, Spitzer & Hart 1971; Aarseth & Lecar 1975; Binney & Tremaine 1987; Spitzer 1987). However, models have also been developed which deal with realistic populations covering a range in stellar mass. These models have so far mainly dealt with globular cluster systems which are considerably more evolved than the Trapezium Cluster (however, see Terlevich 1987). The evolutionary time-scales pertaining to stars of different mass are considered, as well as the effects of

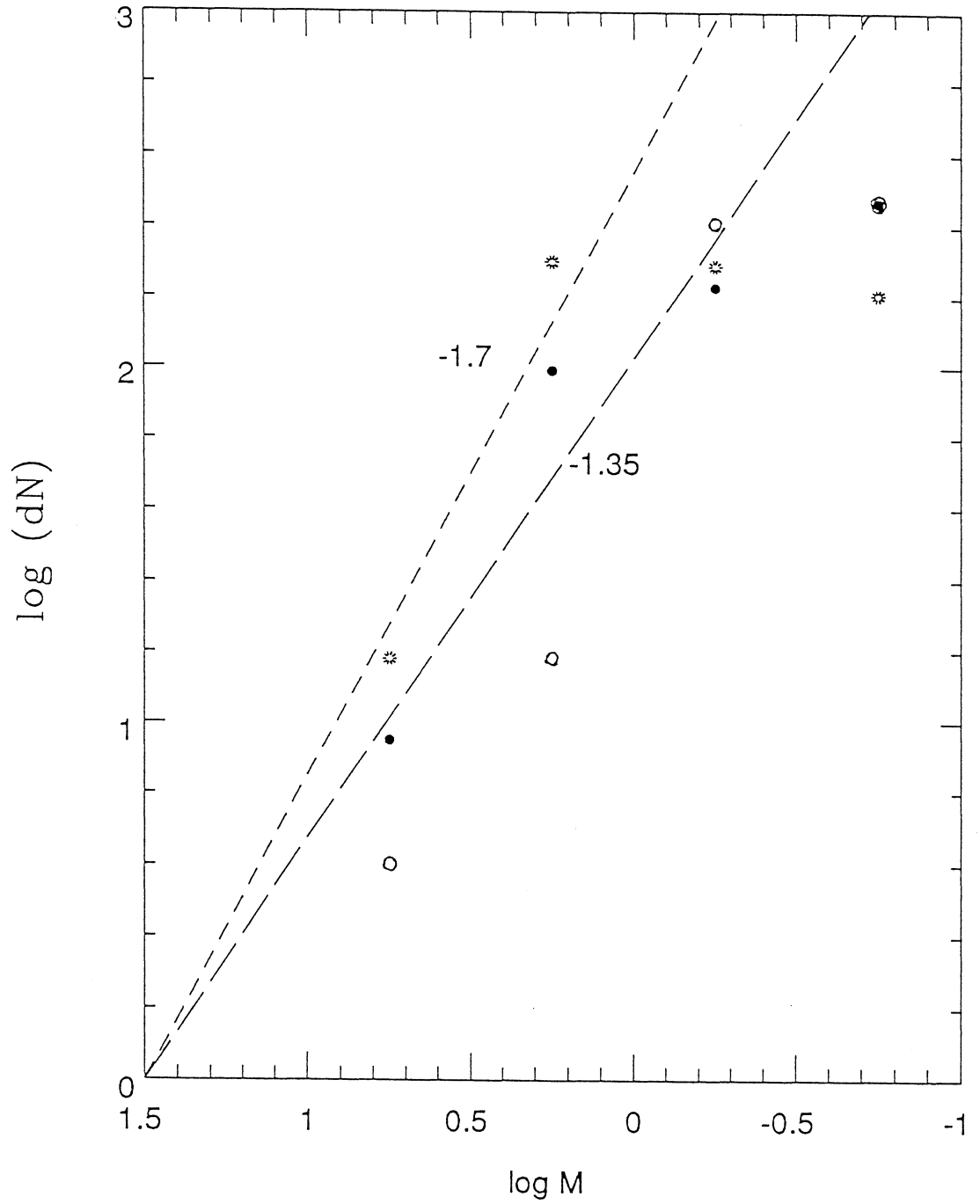


Figure 3.15: Initial mass function derived for infrared Trapezium Cluster for cluster ages of 10^6 yr (filled circles), 10^5 yr (open circles), and 5×10^6 yr (asterisks), compared with theoretically derived initial mass functions of Salpeter (1955; slope of -1.35, long-dashed line) and Scalo (1986; slope of -1.7, short-dashed line).

stellar evolution on neighbouring stars. It has been found that the incorporation of a mass function reduces the dynamical evolution time-scales. According to Chernoff & Weinberg (1990) the single-mass approximation used prolifically in the study of N -body systems is limited, essentially because multimass models all evolve faster than any single-mass model. Their work is based on systems which are many relaxation times old and have a significant spread in their intrinsic mass spectrum. Thus, stellar evolution effects are significant. Here, we make the assumption that the youth and relatively small range in mass of the low mass Trapezium Cluster stars ($\sim 0.1\text{--}3\text{ M}_\odot$, see Table 3.11) allow the use of a single-mass approximation to reasonable accuracy. The complexity involved in a complete analysis with stellar evolution considered is beyond the scope of the present investigation. We suggest that full numerical simulations taking account of such factors would be helpful in future studies of the dynamics of young embedded clusters.

In this discussion, the Θ^2 Ori stars are assumed to be foreground stars relative to the Θ^1 Ori OB subgroup (Balick et al. 1974; Becklin et al. 1976; Peimbert 1982; Cardelli & Clayton 1988). An additional simplification in our analysis is that the high mass Trapezium OB stars and the low mass cluster are considered as two separate systems of characteristic masses $\sim 21\text{ M}_\odot$ and $0.9\text{ M}_\odot$. We determine that the accelerative effects of one mass group on the other are insignificant compared with the self-interactions of each group, justifying this approach. Consider a two-mass system containing N stars of average mass M and mean radial extent r , and n stars with average mass m and mean radius r_h . In order for the two mass groups to have an insignificant effect on each other:

$$\frac{NM}{r^2} \gg \frac{nm}{r_h^2} \gg \frac{NM}{r_h^2} \quad (3.2)$$

In our calculations for the Trapezium Cluster we make the assumption that the cluster is that population of stars covered in radial extent by the survey of HAB (1992). Here, the maximum radius of any star from Θ^1 Ori C is $4.7'$ or 0.6 pc . The half-mass radius, r_h , is the radius containing half the mass of the system and is calculated directly from the mass distribution as described in § 3.4.3. We obtain a value of $101''$ (0.22 pc) for r_h . The number of stars, n , included in the HAB infrared cluster with a mean mass of $0.9\text{ M}_\odot$ is ~ 562 stars. Regarding the high mass Θ^1 Ori stars, there are four stars of mean mass is $\sim 21\text{ M}_\odot$, and separation $\sim 16''$ (0.03 pc). Therefore, equation 3.4 is evaluated approximately as: $93333 \gg 10450 \gg 1736$. Additionally, we calculate the number of encounters between high and low mass stars inside the volume containing the Trapezium OB stars. This number is given by:

$$N = \pi b^2 v t < n > \quad (3.3)$$

where $r = 1.1 \times 10^{17}$ cm ($\sim 16''$) is the radius of the high mass group, $v = 2.3 \times 10^5$ cms $^{-1}$ (Jones & Walker 1988) is the mean velocity of the low mass stars, $t = 10^6$ yr (present work) is the mean stellar age, and $\langle n \rangle = 2.1 \times 10^{-53}$ stars cm $^{-3}$ is the mean number density of the low mass cluster. Thus, $N = 6$, which is insignificant and indicates that encounters between the high mass OB stars and the low mass stars are not influencing the dynamics of either the high or low mass systems.

The first important time-scale to be evaluated is the relaxation time for the cluster. The relaxation time is formally defined as the time required for the velocities of all the particles to change by of order themselves. In this time a system approaches a state of kinetic equilibrium in which knowledge of initial conditions has been lost. Thus, the system should alter completely from its initial state in a few relaxation times. The standard equation for the relaxation time of a single-mass system is given by Spitzer & Hart (1971), in terms of the half-mass radius, r_h , the average stellar mass, $\bar{m}$, and the number of stars comprising the cluster, N :

$$t_{rh} = \frac{(Nr_h^3)^{\frac{1}{2}}}{8(G\bar{m})^{\frac{1}{2}} \ln N} \quad (3.4)$$

We determine the relaxation time for the low mass infrared Trapezium Cluster to be $\sim 0.8 \times 10^6$ yr. This is approximately equivalent to the derived mean age of the cluster. Thus, the system is still in the process of becoming totally relaxed. The cluster has probably not had time to attain kinetic equilibrium via dynamical evolution. Even if the modal mass of $0.3 M_{\odot}$ given by Zinnecker et al. (1992) is used instead of the mean mass obtained in our study, the relaxation time is $\sim 1.3 \times 10^6$ yr. Thus, the interpretation of the current dynamical state of the cluster remains essentially the same.

Our estimate of the *crossing* time gives further evidence of the present dynamical state of the Trapezium Cluster. The crossing time is the time taken for a single star to cross the system, or the radial extent of the cluster divided by the mean velocity dispersion (independent of mass). Using the JW measurement of σ as 2.3 kms $^{-1}$, the crossing time for the low mass stars is $\sim 3 \times 10^5$ yr. Thus, the relaxation time and the mean age of the cluster are equivalent to approximately three crossing times. An age of at least nine crossing times is generally required before a system can be considered to be approaching kinetic equilibrium (Binney & Tremaine 1987).

We continue our dynamical analysis by considering the high mass stars in isolation. The relevant half-mass radius in this case is $16''$ or 0.03 pc, and the average stellar mass is $21 M_{\odot}$. Consequently, the relaxation time for the eight high mass stars is estimated to be $\sim 3 \times 10^3$ yr. As discussed previously, the lower limit to the age of the stars is $\sim 6 \times 10^4$ yr (Iben 1965), ~ 20 times the relaxation time. We

determine the crossing time for the high mass system to be $\sim 10^3$ yr, making the stars greater than 60 crossing times old. Thus, our estimates are consistent with the long-held view that the Trapezium OB stars have had sufficient time to interact strongly with each other and lose information regarding their initial characteristics (for example, Ambartsumian 1954, Allen, Tapia, & Parrao 1977; Beichman, Becklin, & Wynn-Williams 1979).

A noteworthy feature of the low mass Trapezium Cluster is its isothermality. The most fundamental indication that the Trapezium Cluster is isothermal is the fact that the stellar velocity dispersions are found to be approximately constant out to at least $15'$ from Θ^1 Ori C (JW). Additionally, we compare the slope of the cluster number density distribution with that of an isothermal distribution function in Figure 3.16. (Note that the radial bin corresponding to $\sim 2.4''$ contains no member stars.) The cluster number density profile given here represents stars within $\sim 15'$ of Θ^1 Ori C, and is based on the measurements of Jones & Walker (1988). While these authors were unaware of the existence of the most heavily embedded near-infrared stars, $\sim 60\%$ of the $2\mu\text{m}$ selected objects are included in their data set. Additionally, the motions of the optical stars reflect the gravitational potential of the full cluster mass, justifying the use of these stars to probe the potential. The distribution observed follows an isothermal gradient for r between ~ 20 and $200''$. The relaxation timescale evaluated above strongly suggests that the system has not had time to reach isothermality via dynamical evolution. Therefore, the observed isothermality is more likely to reflect formation characteristics of the stars. The findings suggest that the clumps from which the stellar cluster formed themselves had an isothermal distribution.

Virial equilibrium of a system of particles is achieved in approximately one or two crossing times (JW). Therefore, it is reasonable to assume that the Trapezium Cluster stars are in virial equilibrium such that the total cluster potential energy is approximately constant. However, our estimate of the cluster relaxation time indicates that individual stellar energies are still being exchanged in this potential, driving the system gradually towards the state of 'two-body relaxation'. The extent to which a system has evolved towards two-body relaxation is measurable via various observational phenomena (Spitzer 1987), including evaporation and mass segregation. Stars evaporate from the cluster when their velocities are greater than the escape velocity. The lowest mass stars are given higher intrinsic velocities by the more massive members losing kinetic energy to them. The higher mass stars sink into the cluster center, while those of lower mass are boosted to the outer parts of the cluster. This effect is known as mass segregation. Evaporation of lower mass stars with high kinetic energies occurs over several relaxation times and is a signature of collapse. The proportion of cluster stars which acquire greater than escape velocity,

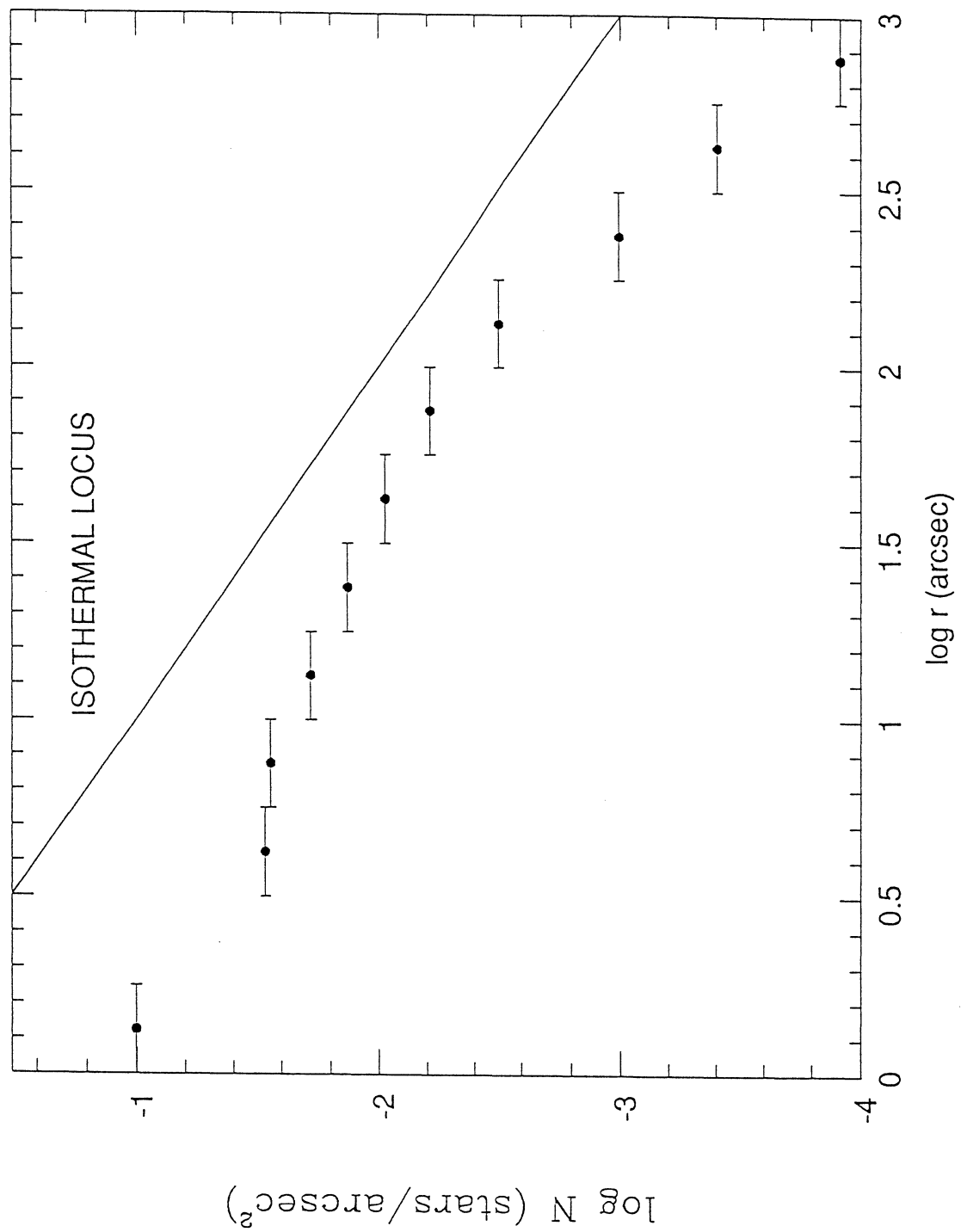


Figure 3.16: Number Density of Trapezium Cluster Stars as a function of distance from Θ^1 Ori C. Locus for isothermal distribution shown (solid line).

$\sim 3 \text{ kms}^{-1}$, over one relaxation time has been estimated to be $\sim 1 \%$ (Binney & Tremaine 1987), or six stars for the Trapezium Cluster, and therefore is negligible. As regards evidence for mass segregation, the projected location of the high mass Trapezium OB stars at the center of the cluster implies mass segregation at some level. However, the extinction estimates based on our small sample suggest that the low mass cluster stars are on average at least as embedded and probably more embedded in the molecular cloud than the Θ^1 Ori stars. The issue of the relative locations of the high mass and low mass Trapezium stars may be addressed by accurate determinations of the extinctions towards a large number of the low mass cluster stars, as may the question of mass segregation among the low mass cluster members. Considering the high mass stars, if these are in fact centrally placed, there are at least two explanations for their location. The first is that the OB stars have fallen in to their present positions from some larger radius, and the second that they were born where they are currently found. The parameter of interest concerning the first case is the dynamical friction time-scale. This is calculated for a model where a star of mass M moves through a group of stars of mass m (Binney & Tremaine 1987; Spitzer 1987). The time-scale is a function of the initial and final radius of star M , using the velocity of the star, σ , the mass, and the ratio of maximum-to-minimum impact parameters, $\frac{p_{max}}{p_{min}}$:

$$t_{df} = [r^2(0) - r^2(t_{df})] \frac{\sigma}{0.605GM \ln(\frac{p_{max}}{p_{min}})} \quad (3.5)$$

where

$$p_{min} = \frac{G(m + M)}{\sigma^2}$$

and p_{max} is just the diameter of the cluster. We obtain a value of $\sim 4 \times 10^6 \text{ yr}$ for the time that a single high mass star needs to travel from the outermost radius of the infrared cluster to the center. Given that at least six stars had to fall in to the center in this manner and given the ages of the cluster and the high mass stars, it seems unlikely that all six stars fell in from outside the cluster. Clearly, some proportion of them may have fallen in from differing radii. However, we suggest that the dynamical friction timescale calculated here implies that the high mass OB stars actually formed in their present locations.

The Bound Nature of the Trapezium Cluster

In order to understand how the Trapezium Cluster will evolve in the future, we now evaluate the stability of its components. Let us initially focus on the low mass cluster alone. The velocity dispersion of these stars is $\sigma \sim 2.3 \text{ km s}^{-1}$ (JW) in each coordinate. We use the virial theorem for an isothermal system to estimate the velocity dispersion required for the ~ 562 low mass stars with a half-mass radius of

$\sim 101''$ (0.22 pc) to be bound and virialized. The total mass of stars contained in the low mass infrared cluster is $491 M_{\odot}$. For a virialized isothermal system, the binding equation is:

$$\sigma = \sqrt{\left(\frac{GM}{2r_h}\right)} \quad (3.6)$$

Thus, σ calculated using this equation is 2.2 km s^{-1} . The excellent agreement with the observed value leads us to conclude that there is sufficient mass in stars in the low mass Trapezium Cluster for the system to be bound at present. The amount of gas remaining in the cluster based on the maximum A_K estimated here of 1.1 mag can be derived using the relationship (see Dickman 1978) given in Chapter 2 (Equation 2.8). Here, the gas mass obtained is $\sim 220 M_{\odot}$. Addition of this mass into the binding equation has the effect of making the system more bound. Furthermore, our refined estimates show that future removal of this gas will not be sufficient to unbind the low mass cluster. The difference between our results here and those of Chapter 2 emphasizes the importance of taking account of the entire infrared cluster. We note that the conclusion of both Jones & Walker (1988) and Genzel & Stutzki (1989) that the Trapezium Cluster is not bound is based on a severe underestimate of the stellar mass in the cluster.

The extremely high mass density of the cluster does could well be due to a high star formation efficiency (SFE) in the Trapezium Cluster vicinity. Additionally, *bound* stellar clusters are predicted to form in regions of high star formation efficiency (Mathieu 1983; Elmegreen 1983; Lada, Margulis & Dearborn 1984; Verschueren 1990). An order-of-magnitude estimate of the star formation efficiency in the Trapezium Cluster can be made using the present cluster gas mass calculated above of $\sim 220 M_{\odot}$. Clearly, this value is an approximation given the removal of gas from the region via ultraviolet radiation and stellar winds from the high mass stars since their birth. The total stellar mass in the cluster region estimated here is $\sim (491 + 84) M_{\odot}$. Using Equation 2.10 (Chapter 2), the star formation efficiency is then $\sim 72 \%$. Thus, this suggests that the Trapezium Cluster is the result of a continuous episode of highly efficient star formation beginning $\sim 10^6$ yr ago. Similarly high star formation efficiencies of 20–42 % are determined for the embedded clusters in NGC 2071, NGC 2068 and NGC 2024 (Lada 1990) in L1630. The clustered mode of star formation seems to be occurring under very similar conditions in a number of regions in the Orion complex.

The two central Trapezium OB stars, Θ^1 Ori A and B, are known binary systems. It is of interest in terms of the distribution of energy within the cluster to compare the binding energy locked up in these two binary pairs with the amount of energy available in the total low mass cluster. Characteristics of the binaries have been

published by various authors including Abt et al. (1991). We find that the Θ^1 Ori B system, also known as BM Ori, is approximately three times more bound than the Θ^1 Ori A binary. The calculated binding energy of BM Ori is $\sim 10^{48} \text{ gcm}^2 \text{ s}^{-2}$. Assuming virial equilibrium and using the estimate for the velocity dispersion of the low mass stars found by JW, the low mass cluster energy can be calculated. We determine a value of $\sim 2.6 \times 10^{46} \text{ gcm}^2 \text{ s}^{-2}$. Thus, the total cluster energy is less by a factor of ~ 40 than the binding energy of BM Ori alone ! We conclude that the binding energy in the binaries must be due to initial formation conditions of these systems, rather than due to dynamical interaction with the low mass cluster since this amount of energy would be more than sufficient to disperse the low mass cluster. Furthermore, the number of encounters between the two binaries and low or high mass stars in the region is determined to be insignificant (Equation 3.5). Our calculations show that the influence of the binaries is negligible with respect to both the low mass cluster and the other high mass stars.

Ambartsumian (1954), Allen & Poveda (1974), and Abt (1986), among others, have used numerical simulation methods to study Trapezium OB systems, and find that they are dynamically unstable. The models predict that the ejection of members of the original group increases the binding energy of the stars left behind, until all that remains of a Trapezium-type system is a tight binary. Allen & Poveda (1974) calculate a disintegration time of $\sim 10^6$ yr, while Mirzoyan & Salukvadze (1984) obtain a figure of 2×10^6 yr. The important point to note regarding these models is that they do not consider the influence of a closely-associated low mass stellar population. Clearly, the significant mass contained in the low mass population surrounding the OB stars *has* an influence on the evolution of the system. It is possible that the low mass cluster is able to slow down or even prevent the destruction of the central high mass Trapezium system.

3.5 Conclusions

The work undertaken here has provided the most accurate estimate for the age of the low mass Trapezium Cluster obtained thus far. We obtain a mean age of $\sim 10^6$ yr for our sample of 33 cluster stars. The improved accuracy of our results is due to the acquisition of stellar spectral-types, allowing estimates of the extinction towards each star. Hence, the stars may be dereddened in the color-magnitude diagram more appropriately than previously possible. The mean extinction obtained here of 0.3 mag at K is in good agreement with the value used by Herbig & Terndrup (1986). Our extinction data support a morphology whereby the high mass Trapezium OB stars and some proportion of the low mass cluster are at the near-face of the region, with a significant number of low mass cluster stars situated at greater depths into the

molecular cloud. We find that the low mass stars constituting the central Trapezium Cluster have a mean spectral class of K3, representative in spectral type of the whole low mass PMS Orion population (Cohen & Kuhi 1979; Parsamian & Chavira 1982; Walker 1983). The mean stellar mass of the low mass population is $\sim 0.9 M_{\odot}$, derived from the K luminosity function of HAB (1993) and Zinnecker et al. (1992) for the infrared cluster population. Translation of this luminosity function to a mass function reveals that the slope of the initial mass function is fit by both the traditional Salpeter (1955) function and the more recent determination of Scalo (1986), within the errors of such a transformation. We estimate the mass density of the Trapezium Cluster and high mass stars to be $\sim 4690 M_{\odot} \text{pc}^{-3}$. This is $\sim 1.5 \times$ the estimate of Herbig & Terndrup (1986), a reflection of the large cluster population revealed at infrared wavelengths compared with optical. Comparison with the results of Cohen & Kuhi (1979) for the Orion Nebula Cluster indicates that there is no major difference between the low mass PMS populations of the central Trapezium Cluster and the outer Orion Nebula Cluster as regards spectral type, mass or age. We determine an order-of-magnitude estimate for the star formation efficiency of the Trapezium Cluster based on the stellar mass and extinction estimates derived here. We obtain a value of $\sim 72 \%$ in this extremely populous young cluster.

We find that the low mass Trapezium Cluster is at an early stage in its dynamical evolution. The low mass cluster has attained virial equilibrium and is at present bound by the stellar mass contained within it. The system of low mass stars is only $\sim$ one relaxation time old, and therefore too young for significant mass segregation to have occurred. The high mass stars are calculated to have had more than sufficient time to interact among themselves and to have relaxed as a system. The binding energies of the two binaries among the high mass stars, Θ^1 Ori A and B, are here calculated to be almost forty times the energy of the low mass cluster itself. The negligibly small probability of an encounter between either binary and any low or high mass star leads us to conclude that the binaries have little influence on the rest of the system. We suggest that the observed isothermality of the cluster is caused by initial conditions rather than dynamical evolution, as is the observed location of the high mass Trapezium OB stars in the core region, and the binding energies of the two central binary stars. Thus, we conclude that present characteristics of the Trapezium Cluster stars reflect the initial conditions of the clumps from which the stars have formed, rather than being a function of interactions between the PMS stars themselves. The implication is that stellar parameters, such as those derived here for the Trapezium Cluster, are of fundamental importance in understanding the mechanisms by which clumps in molecular clouds form stars.

The discoveries of embedded clusters using infrared arrays have included the identification of a number of Trapezium-type systems where a low mass population

surrounds central high mass, high luminosity stars (Lada et al. 1991; Gatley et al. 1991; McCaughrean et al. 1991; Greene & Young 1992; among others). Evaluation of the nature of these similar star-forming regions will help place the Trapezium Cluster in context with respect to the clustered mode of high- and low-mass star formation. There are also numerous observations of ultra-compact H II regions, the birthplaces of OB clusters (Mezger et al. 1967; Habing & Israel 1979; Churchwell 1991). The existence of lower mass stars in association with the OB stars in ultra-compact H II regions has been hypothesized (for example, Wood & Churchwell 1990). Evolutionary models of ultra-compact H II regions are likely to be of significance to our understanding of star formation in the Trapezium Cluster.

The extremely dense low mass Trapezium Cluster has evolved on a similar time-scale to and surrounding the high mass OB stars in a dense core of the Orion Molecular Cloud. The cluster is itself surrounded by the Orion Nebula Cluster, a similar population in both mass and age. We find that the Trapezium Cluster has sufficient mass to maintain its configuration at present. However, as time goes on, more lower mass stars will acquire sufficient kinetic energy to escape the cluster. This process will lower the total kinetic energy of the system, leading to contraction of the remaining cluster. In time, the low mass cluster may become lost to the central core, the high mass stars may also be successively ejected, and finally all that remains of the cluster may be a single tight binary system (Allen & Poveda 1974; Abt 1986).

Chapter 4

Ca II Infrared Triplet Emission in Pre-Main-Sequence Stars

4.1 Introduction

The optical spectroscopy study of the low mass pre-main-sequence (PMS) Trapezium Cluster population described in Chapter 3 has revealed that four of the 46 stars in the sample exhibit Ca II infrared (IR) triplet emission. In this chapter we present optical spectra of PMS stars in the Chamaeleon I dark cloud in order to compare the frequency of triplet emitters in the two PMS populations. Hence we hope to better elucidate the nature of the Trapezium Cluster population. The occurrence of triplet emission in young stellar objects has been studied by a number of groups such as Herbig & Soderblom (1980, hereafter HS), McGregor, Persson & Cohen (1984, hereafter MPC), Basri (1987), Persson, McGregor, & Campbell (1988), and Hamann & Persson (1992a, 1992b, 1992c, hereafter HPa, HPb, and HPc). At least two theories for the origin of the emission have been proposed. One of these is that the lines either arise in or derive from circumstellar disk regions in T Tauri stars (MPC; Persson et al. 1988; Hamann & Persson 1989; HPa). This proposal is based primarily on the observed correlation between triplet emission and infrared excess in these stars. An alternative explanation is that the triplet lines originate in PMS stellar chromospheres (HS; Basri 1987; Basri, Marcy & Valenti 1992; HPa). Knowledge of the region giving rise to the emission is fundamental to an understanding of the significance of calcium triplet emission in the star formation process.

The Ca II IR triplet lines occur at 8498 Å, 8542 Å, and 8662 Å. They arise from transitions between the 4^2P and 3^2D levels in singly-ionized calcium (see Figure 4.1). For the low mass PMS stars of K–M spectral types considered in the current work, the upper 4^2P level is predominantly populated by absorption of calcium H and K photons from the 4^2S level. The lower 3^2D level is metastable, such that electrons

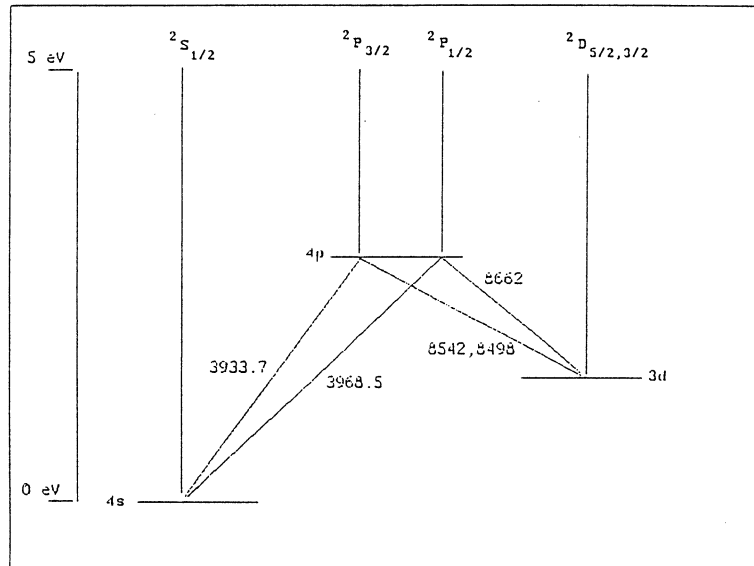


Figure 4.1: Energy level diagram of Ca^+ .

decay from here to ground level via forbidden transitions. The observation of these forbidden lines at $\lambda\lambda 7291$ and 7324 imply that some parts of the triplet-emitting regions have densities of $< 10^7 \text{ cm}^{-3}$ (MPC). Calculated strengths (gf -values) of the triplet lines (8498:8542:8662) for optically thin emission are in the ratio 1:9:5 (Shine & Linsky 1974).

The first observations of calcium triplet emission in T Tauri stars were obtained by Joy (1945), followed by Herbig (1962). Detailed analyses of triplet emission in young stars began with the work of HS. These authors first noted that the peak intensities of the triplet lines in most T Tauri stars do not follow the predicted optically thin 1:9:5 ratio. Instead, the three lines have approximately equal intensities. This observation strongly supports an optically *thick* interpretation for the emission (HS; Polidan 1980; MPC; Finkenzeller & Basri 1987; Persson et al. 1988). MPC point out that the metastability of the lower triplet transition levels allows high optical depths in the lines. In addition, optically thick emission in the triplet lines implies a high column density of Ca II ions. HS make comparisons with solar activity where optically thick emission in these lines is also found. Hence, they propose that the calcium emission occurs in hot regions in the stellar chromosphere.

More recent observations have led to other interpretations for the source of triplet emission in PMS stars. As mentioned above, the observed strong correlation between

Ca II IR triplet emission and infrared excess supports a circumstellar disk origin for the triplet lines (MPC, HPa, among others). Two general types of Ca II triplet line profile are observed by HPa and in the work of Basri et al. (1992). Where the profiles are narrow ($\leq 40 \text{ kms}^{-1}$ or $\sim 1.2 \text{ \AA}$, HPa), the lines are proposed to originate in the stellar chromosphere. The broad line profiles ($\geq 100 \text{ kms}^{-1}$ or $3 \text{ \AA}$, HPa) are attributed to the inner parts of active accretion disks. The estimated densities of the disk regions based on these broad lines are $> 10^{11} \text{ cm}^{-3}$ (HPa). The sizes of the emitting regions are determined to be several times those of the central stars themselves. These findings support the work of Persson et al. (1988), who proposed that Ca II triplet emission in S106/IRS 3 arises in inner disk regions close to the central star for which the gas density is evaluated to be $\sim 10^{13} \text{ cm}^{-3}$. The observed breadth of the triplet lines is modelled as due to high velocity random gas motion involved in the accretion process. The derived electron densities for the Ca II zone in V645 Cyg are between 10^9 and 10^{15} cm^{-3} , using an electron temperature of 5000 K. Thus, the current consensus regarding the origin of Ca II IR triplet emission in young stellar objects is that neither chromospheric nor disk models constitutes a unique explanation (HPa, HPb, HPC, among others).

In this chapter, we discuss observations of calcium triplet emission in PMS stars in the Chamaeleon I dark cloud. These were obtained to determine the frequency of the emission in this PMS population. The results are compared with the frequency found in the Trapezium Cluster, and combined with published data in an attempt to understand why these proportions of triplet emitters are found in the two different star forming regions.

4.2 Observations

Spectra of the 33 Chamaeleon PMS stars observed here were acquired using the Reynolds spectrograph and Thomson CCD on the ANU 1.9m telescope at Mount Stromlo Observatory in March 1991. A 300-l grating was used in combination with the 13.5cm camera, providing a nominal dispersion of $219 \text{ \AA/mm}$. The slit width was set to $350 \text{ }\mu\text{m}$, giving a resolution of $\sim 4.8 \text{ \AA}$ (192 kms^{-1}) at the detector. The observations were made over the wavelength range 6000–8750 $\text{\AA}$. The 33 Chamaeleon stars observed in the current program were selected from the 45 H α stars surveyed by Schwartz (1977). The 33 stars are listed in Table 4.1. The data were reduced using the IRAF data reduction packages.

Table 4.1: Flux Measurements (ergs s⁻¹ cm⁻²) for Chamaeleon Sample

Name (1)	F(H α) (2)	F(Ca λ 8498) (3)	F(Ca λ 8542) (4)	F(Ca λ 8662) (5)	F(O λ 8446) (6)	Sp.T (7)	Lum ⁽⁴⁾ (8)	Comment ⁽⁵⁾ (9)
SZ 4	$(3.2 \pm 0.3) \times 10^{-13}$	$< 1.0 \times 10^{-14}$	$< 1.0 \times 10^{-14}$	$< 1.0 \times 10^{-14}$	$< 1.0 \times 10^{-14}$		0.25	
SZ 7	$(1.1 \pm 0.1) \times 10^{-13}$	$< 3.4 \times 10^{-14}$	$< 3.4 \times 10^{-14}$	$< 3.4 \times 10^{-14}$	$< 3.4 \times 10^{-14}$		0.84	
SZ 9	$(1.6 \pm 0.1) \times 10^{-12}$	$< 1.7 \times 10^{-14}$	$< 1.7 \times 10^{-14}$	$< 1.7 \times 10^{-14}$	$< 1.7 \times 10^{-14}$	K5: ⁽²⁾ , M0 ⁽¹⁾	1.17	
SZ 11	$(1.6 \pm 0.1) \times 10^{-12}$	$(5.3 \pm 0.5) \times 10^{-13}$	$(5.6 \pm 1.2) \times 10^{-13}$	$(5.2 \pm 0.6) \times 10^{-13}$	$(1.6 \pm 0.1) \times 10^{-13}$	K7 ⁽¹⁾	0.92	
SZ 14	$(3.8 \pm 0.1) \times 10^{-12}$	$< 2.5 \times 10^{-12}$	$< 2.5 \times 10^{-12}$	$< 2.5 \times 10^{-12}$	$< 2.5 \times 10^{-12}$			
SZ 18	$(4.7 \pm 2.6) \times 10^{-14}$	$< 7.6 \times 10^{-15}$	$< 7.6 \times 10^{-15}$	$< 7.6 \times 10^{-15}$	$< 7.6 \times 10^{-15}$	M2 ⁽²⁾ , M3 ⁽¹⁾	0.16	
SZ 21	$(2.0 \pm 0.1) \times 10^{-13}$	$< 3.3 \times 10^{-15}$	$< 3.3 \times 10^{-15}$	$< 3.3 \times 10^{-15}$	$< 3.3 \times 10^{-15}$	M0.5 ⁽³⁾	0.57	
SZ 22	$(3.2 \pm 0.3) \times 10^{-13}$	$(9.6 \pm 0.01) \times 10^{-14}$	$(8.7 \pm 0.1) \times 10^{-14}$	$(9.8 \pm 0.2) \times 10^{-14}$	$(4.9 \pm 0.6) \times 10^{-14}$		2.50	
SZ 23	$(3.3 \pm 0.03) \times 10^{-12}$	$(4.0 \pm 0.2) \times 10^{-13}$	$(3.9 \pm 0.01) \times 10^{-13}$	$(4.3 \pm 1.0) \times 10^{-13}$	$(1.1 \pm 0.1) \times 10^{-13}$		0.15	
SZ 26	$(4.7 \pm 1.0) \times 10^{-15}$	$< 8.7 \times 10^{-15}$	$< 8.7 \times 10^{-15}$	$< 8.7 \times 10^{-15}$	$< 8.7 \times 10^{-15}$			
SZ 27	$(3.4 \pm 0.2) \times 10^{-13}$	$< 1.1 \times 10^{-15}$	$< 1.1 \times 10^{-15}$	$< 1.1 \times 10^{-15}$	$< 1.1 \times 10^{-15}$			
SZ 30	$(3.0 \pm 0.02) \times 10^{-11}$	$< 2.7 \times 10^{-12}$	$< 2.7 \times 10^{-12}$	$< 2.7 \times 10^{-12}$	$< 2.7 \times 10^{-12}$			
SZ 33	$(3.2 \pm 0.04) \times 10^{-14}$	$< 3.6 \times 10^{-15}$	$< 3.6 \times 10^{-15}$	$< 3.6 \times 10^{-15}$	$< 3.6 \times 10^{-15}$			
SZ 37	$(3.7 \pm 0.3) \times 10^{-13}$	$(1.8 \pm 0.04) \times 10^{-13}$	$(1.9 \pm 0.03) \times 10^{-13}$	$(1.7 \pm 0.1) \times 10^{-13}$	$(1.1 \pm 0.2) \times 10^{-14}$	K7: ⁽²⁾		
SZ 40	$(2.0 \pm 0.04) \times 10^{-11}$	$< 1.5 \times 10^{-12}$	$< 1.5 \times 10^{-12}$	$< 1.5 \times 10^{-12}$	$< 1.5 \times 10^{-12}$	K7 ⁽²⁾		
SZ 43	$(7.9 \pm 0.9) \times 10^{-13}$	$(1.1 \pm 0.1) \times 10^{-13}$	$(1.1 \pm 0.02) \times 10^{-13}$	$(0.9 \pm 0.1) \times 10^{-13}$	$(0.7 \pm 0.6) \times 10^{-14}$	G: ⁽²⁾	0.32	
SZ 44	$(1.2 \pm 0.1) \times 10^{-14}$	$< 1.8 \times 10^{-15}$	$< 1.8 \times 10^{-15}$	$< 1.8 \times 10^{-15}$	$< 1.8 \times 10^{-15}$			

Table 4.1: (continued) Flux (ergs s⁻¹ cm⁻²) Measurements for Chamaeleon Sample

Name (1)	F(H α) (2)	F(Ca λ 8498) (3)	F(Ca λ 8542) (4)	F(Ca λ 8662) (5)	F(O λ 8446) (6)	Sp.T (7)	Lum ⁽⁴⁾ (8)	Comment ⁽⁵⁾ (9)
SZ 45	$(7.7 \pm 0.4) \times 10^{-13}$	$< 5.5 \times 10^{-15}$	$< 5.5 \times 10^{-15}$	$< 5.5 \times 10^{-15}$	$< 5.5 \times 10^{-15}$	M0.5 ⁽¹⁾	0.34	YY Ori star
SX Cha	$(3.5 \pm 0.4) \times 10^{-13}$	$< 8.9 \times 10^{-14}$	$< 8.9 \times 10^{-14}$	$< 8.9 \times 10^{-14}$	$< 8.9 \times 10^{-14}$	M0.5 ⁽¹⁾	0.55	
SY Cha	$(2.1 \pm 0.1) \times 10^{-13}$	$< 2.1 \times 10^{-14}$	$< 2.1 \times 10^{-14}$	$< 2.1 \times 10^{-14}$	$< 2.1 \times 10^{-14}$	M0 ⁽¹⁾	0.47	YY Ori star
SZ Cha	$(1.1 \pm 0.1) \times 10^{-12}$	$< 2.5 \times 10^{-13}$	$< 2.5 \times 10^{-13}$	$< 2.5 \times 10^{-13}$	$< 2.5 \times 10^{-13}$	K0 ⁽¹⁾	1.27	
TW Cha	$(4.4 \pm 0.2) \times 10^{-13}$	$< 2.8 \times 10^{-14}$	$< 2.8 \times 10^{-14}$	$< 2.8 \times 10^{-14}$	$< 2.8 \times 10^{-14}$	M0 ⁽¹⁾	0.45	YY Ori star
UY Cha	$(1.3 \pm 0.1) \times 10^{-10}$	$(3.3 \pm 1.0) \times 10^{-11}$	$(3.7 \pm 0.6) \times 10^{-11}$	$(3.2 \pm 0.1) \times 10^{-11}$	$< 2.4 \times 10^{-12}$		0.14	
UZ Cha	$(1.1 \pm 0.1) \times 10^{-10}$	$< 1.4 \times 10^{-12}$	$< 1.4 \times 10^{-12}$	$< 1.4 \times 10^{-12}$	$< 1.4 \times 10^{-12}$		0.21	
VV Cha	$(3.9 \pm 0.2) \times 10^{-13}$	$< 3.2 \times 10^{-15}$	$< 3.2 \times 10^{-15}$	$< 3.2 \times 10^{-15}$	$< 3.2 \times 10^{-15}$	M1.5 ⁽¹⁾	0.23	YY Ori star
VW Cha	$(3.2 \pm 0.004) \times 10^{-12}$	$(2.9 \pm 0.1) \times 10^{-13}$	$(3.4 \pm 0.5) \times 10^{-13}$	$(3.0 \pm 0.7) \times 10^{-13}$	$(1.3 \pm 0.3) \times 10^{-13}$	K2 ⁽¹⁾	2.27	YY Ori star
VY Cha	$(2.9 \pm 0.3) \times 10^{-14}$	$< 2.4 \times 10^{-15}$	$< 2.4 \times 10^{-15}$	$< 2.4 \times 10^{-15}$	$< 2.4 \times 10^{-15}$	M0.5 ⁽¹⁾	0.13	
VZ Cha	$(3.7 \pm 0.5) \times 10^{-10}$	$< 3.9 \times 10^{-11}$	$< 3.9 \times 10^{-11}$	$< 3.9 \times 10^{-11}$	$< 3.9 \times 10^{-11}$	K6 ⁽¹⁾	0.56	YY Ori star
WW Cha	$(7.7 \pm 0.002) \times 10^{-13}$	$(5.3 \pm 0.3) \times 10^{-13}$	$(5.8 \pm 0.04) \times 10^{-13}$	$(4.8 \pm 0.1) \times 10^{-13}$	$(1.0 \pm 0.1) \times 10^{-13}$	K5: ⁽²⁾		
WX Cha	$(8.6 \pm 0.4) \times 10^{-13}$	$(2.8 \pm 0.3) \times 10^{-13}$	$(2.5 \pm 0.03) \times 10^{-13}$	$(2.2 \pm 0.03) \times 10^{-13}$	$(4.0 \pm 0.2) \times 10^{-14}$	K7-M0 ⁽¹⁾	0.76	
WY Cha	$(7.8 \pm 1.0) \times 10^{-11}$	$< 1.0 \times 10^{-12}$	$< 1.0 \times 10^{-12}$	$< 1.0 \times 10^{-12}$	$< 1.0 \times 10^{-12}$	K7 ⁽²⁾ , M0 ⁽¹⁾	0.51	
WZ Cha	$(1.8 \pm 0.1) \times 10^{-13}$	$(1.4 \pm 0.1) \times 10^{-14}$	$(1.4 \pm 0.1) \times 10^{-14}$	$(1.6 \pm 0.1) \times 10^{-14}$	$(3.6 \pm 0.9) \times 10^{-15}$	M1 ⁽¹⁾	0.11	YY Ori star
XX Cha	$(4.1 \pm 0.2) \times 10^{-13}$	$< 5.5 \times 10^{-15}$	$< 5.5 \times 10^{-15}$	$< 5.5 \times 10^{-15}$	$< 5.5 \times 10^{-15}$	M2 ⁽¹⁾	0.37	YY Ori star

1: Appenzeller et al. 1977; 2: Appenzeller et al. 1983; 3: Rydgren 1980; 4: Prusti 1992; 5: Appenzeller et al. 1977, 1979

4.3 Results

The survey conducted here of $H\alpha$ PMS stars in the Chamaeleon I dark cloud has revealed that $\sim 30\%$ of our sample have detectable Ca II IR triplet emission. Spectra of the ten triplet stars found are given in Figure 4.2, over the wavelength range of the triplet lines. Table 4.1 lists the measured fluxes of $H\alpha$, the Ca II IR triplet, and O I $\lambda 8446$ features for our entire Chamaeleon sample of 33 stars. These measurements have been made by defining a continuum adjacent to each side of a line and fitting a Gaussian profile to the line above this continuum. Published spectral types and bolometric luminosities are also listed in Table 4.1 where available. Overall, the sample have typical T Tauri spectral types of K–M.

TiO Absorption Measurements

The 7100 Å TiO absorption band is used here to confirm the M spectral types of Appenzeller et al. (1977, 1983) and Rydgren (1980). Table 4.2 gives TiO equivalent widths for the M stars in our sample. Because we have not observed standard M-type stars here, we use the relationship found between 7100 Å TiO absorption and spectral type for standard stars in Chapter 3 (Figure 3.2) in order to classify our Chamaeleon stars. Of the 13 stars classified in earlier studies as M-type, six are observed here with TiO bands. In addition, we find five stars with TiO absorption which have not previously been classified as M stars. Clearly, our observations indicate significant variation in the photospheric absorption spectra of these stars since their previous classifications, by up to six spectral sub-classes in the case of Sz 40.

The $H\alpha$, O I $\lambda 8446$, and Ca II triplet lines are generally the only emission features of significance in our observed spectra. Weaker lines such as O I $\lambda 7773$, the forbidden Ca II lines at 7291 and 7324 Å, and several Fe I and II lines which have been observed in this wavelength range in PMS stars by other workers (e.g., HPa) are not detectable here due to the resolution of our data.

Ca Triplet Emission Measurements

Table 4.3 presents measured equivalent widths for the Ca II IR triplet lines and the O I $\lambda 8446$ feature from our observations. The measurements obtained by HPa are included for the stars in common. Comparison of the two data sets shows satisfactory agreement. Two stars, TW Cha and VZ Cha, are observed by HPa to exhibit very weak Ca II triplet emission, which is *not* observed in our data of these objects. No measured equivalent widths are given for the triplet lines in these objects. Clearly, the much lower resolution of the current work provides a sufficient explanation for

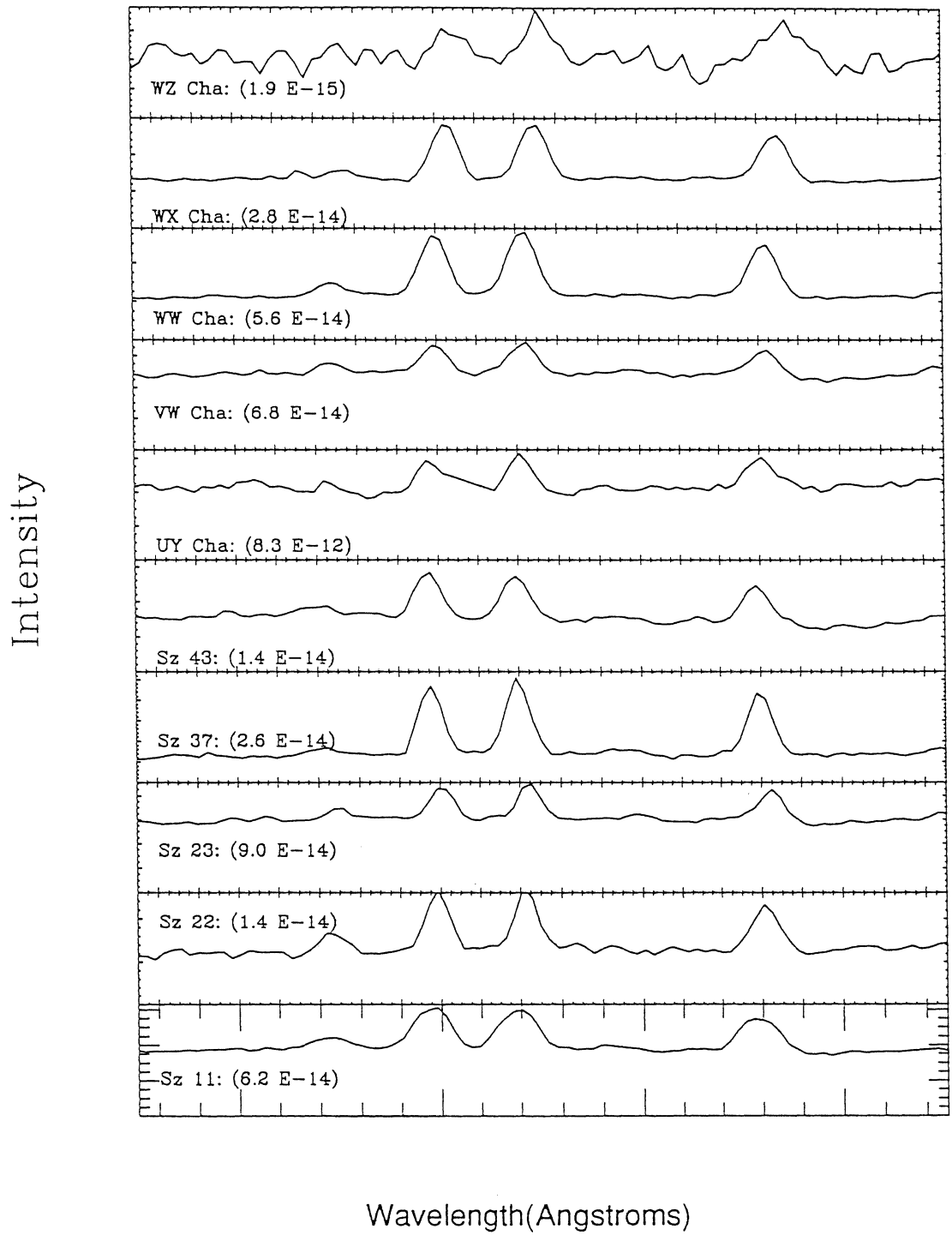


Figure 4.2: Ten Chamaeleon stars with Ca II IR triplet emission. The peak heights above zero are denoted (ergs s⁻¹ cm⁻² Å).

Table 4.2: TiO Absorption in the Chamaeleon Sample

Name (1)	EW(TiO) (2)	SpT (3)	SpT ⁽⁴⁾ (4)
Sz 4	114.0		M4
Sz 9		K5: ⁽²⁾ , M0 ⁽¹⁾	
Sz 18	96.4	M2 ⁽²⁾ , M3 ⁽¹⁾	M3
Sz 21		M0.5 ⁽³⁾	
Sz 26	133.2		M4
Sz 40	186.8	K7 ⁽²⁾	M6
Sz 44	171.5		M6
Sz 45		M0.5 ⁽¹⁾	
SX Cha	86.9	M0.5 ⁽¹⁾	M2.5
SY Cha	46.3	M0 ⁽¹⁾	M0.5
TW Cha		M0 ⁽¹⁾	
UY Cha	125.2		M4
VV Cha	103.1	M1.5 ⁽¹⁾	M3
VY Cha	91.7	M0.5 ⁽¹⁾	M2.5
WX Cha		K7--M0 ⁽¹⁾	
WY Cha		K7 ⁽²⁾ , M0 ⁽¹⁾	
WZ Cha		M1 ⁽¹⁾	
XX Cha	96.5	M2 ⁽¹⁾	M3

1: Appenzeller et al. 1977; 2: Appenzeller et al. 1983; 3: Rydgren 1980; 4: Present Work

the non-detection of this very weak triplet emission in the present observations of TW Cha and VZ Cha.

Details of our observations of Trapezium Cluster stars are presented in Chapter 3, §3.2. The stars were selected on the basis of several factors: they belong to the Orion Nebula region (Jones & Walker 1988), brighter than $I \sim 16$ magnitudes, and are as close as possible to the central core region of the Trapezium Cluster. Our optical spectroscopy program (Chapter 3) showed that $\sim 9\%$ (4 out of 44) of the Trapezium Cluster stars observed had calcium triplet emission. The influence of selection effects on this proportion is considered in detail below. Table 4.4 gives Ca II IR triplet and O I $\lambda 8446$ fluxes for these four stars. Also included in the table are the spectral types obtained from our optical spectroscopy program, where available. The spectra corresponding to this sample are provided in Figure 4.3.

The measured fluxes and equivalent widths of the three Ca lines in all members of both Chamaeleon and Trapezium Cluster samples clearly show that the triplet lines have an approximate 1:1:1 ratio. This corroborates the trend observed by HS, MPC, Persson et al. (1988), Finkenzeller & Basri (1987), and HPa, among others; the ratio observed implies optically thick emission. The implication is that the densities of the triplet emitting regions in our stars are at least those calculated by, for example, HPa of $\sim 10^{11} \text{ cm}^{-3}$.

H α Emission Measurements

H α equivalent widths have been measured for a subset of our sample by Appenzeller et al. (1977), Rydgren (1980), Appenzeller et al. (1983), and HPa. These values are provided in Table 4.5 for comparison purposes. Differences are apparent in the H α measurements for three stars (SX Cha, SY Cha and VW Cha) of the eleven common to the Chamaeleon sample here and Appenzeller et al. (1977). These are readily explained as due to intrinsic variability in the young stars, considering the good agreement between our results and those of HPa which were obtained only a year apart. This interpretation is supported by the fact that both SY Cha and VW Cha are classified as YY Ori stars which typically show greater variability than other T Tauri stars (Appenzeller 1977, 1979; Walker 1972). VW Cha in particular has been reported to exhibit large variations in several line profiles (HPa). The differences between five of the stars measured by Appenzeller et al. (1983) (Sz 9, Sz 37, SX Cha, SY Cha, and WX Cha) and our results can also be attributed to variability of the sources. Of these five stars, Sz 37 and WX Cha are among the ten triplet emitters identified here. Sz 37 in particular has the strongest measured calcium triplet features. The H α equivalent width measurement of Appenzeller et al. (1983) is more than twice our value for this star.

Table 4.3: Ca II Triplet and O I Equivalent Width (Å) Measurements for Chamaeleon Sample

Name (1)	EW(Ca λ 8498) (2)	EW(Ca λ 8542) (3)	EW(Ca λ 8662) (4)	EW(Ca λ 8498) ⁽¹⁾ (5)	EW(Ca λ 8542) ⁽¹⁾ (6)	EW(Ca λ 8662) ⁽¹⁾ (7)	EW(O λ 8446) (8)	EW(O λ 8446) ⁽¹⁾ (9)
SZ 11	14.2±1.7	15.2±3.9	14.8±1.9	14.2	13.3	11.1	4.2±0.4	4.87
SZ 22	15.0±0.03	12.9±0.2	16.4±0.5				8.7±1.3	
SZ 23	6.7±0.4	6.3±0.1	7.3±2.0				1.8±0.2	
SZ 37	33.6±1.1	36.3±1.1	33.3±3.8				1.9±0.4	
SZ 42				26.1	25.4	20.3		5.33
SZ 43	15.2±1.7	14.8±0.4	13.0±2.6				0.9±0.8	
SZ 59				4.72	4.33	3.70		1.95
UY Cha	8.6±2.7	9.8±1.9	7.7±0.4					
VW Cha	6.0±0.3	7.1±1.2	6.3±1.7	4.32	4.42	3.17	2.6±0.6	1.86
WW Cha	22.7±1.9	24.7±0.3	21.6±0.8	11.5	11.8	9.06	4.5±0.6	3.38
WX Cha	22.9±3.8	19.1±0.3	17.3±0.3				3.0±0.1	
WZ Cha	16.5±0.8	15.0±0.7	18.9±2.7	19.3	21.1	13.6	3.8±1.2	3.27

1: Hamann & Persson 1992 (HIPa)

Table 4.4: Flux ($\text{ergs s}^{-1} \text{ cm}^{-2}$) Measurements for Trapezium Cluster Sample

Name (1)	F(Ca λ 8498) (2)	F(Ca λ 8542) (3)	F(Ca λ 8662) (4)	F(O λ 8446) (5)	Sp.T ⁽¹⁾ (6)
JW273	$(4.2 \pm 0.02) \times 10^{-10}$	$(3.9 \pm 0.5) \times 10^{-10}$	$(3.6 \pm 0.5) \times 10^{-10}$	$(7.2 \pm 0.1) \times 10^{-11}$	
JW401	$(1.5 \pm 0.03) \times 10^{-10}$	$(1.7 \pm 0.02) \times 10^{-10}$	$(1.4 \pm 0.04) \times 10^{-10}$	$(3.4 \pm 0.3) \times 10^{-11}$	
JW482	$(2.6 \pm 0.3) \times 10^{-12}$	$(1.6 \pm 0.1) \times 10^{-11}$	$(1.2 \pm 0.02) \times 10^{-11}$	$(2.6 \pm 0.3) \times 10^{-12}$	M3
JW622	$(8.4 \pm 0.4) \times 10^{-12}$	$(9.7 \pm 1.1) \times 10^{-12}$	$(9.2 \pm 2.0) \times 10^{-12}$	$< 1.7 \times 10^{-12}$	K7

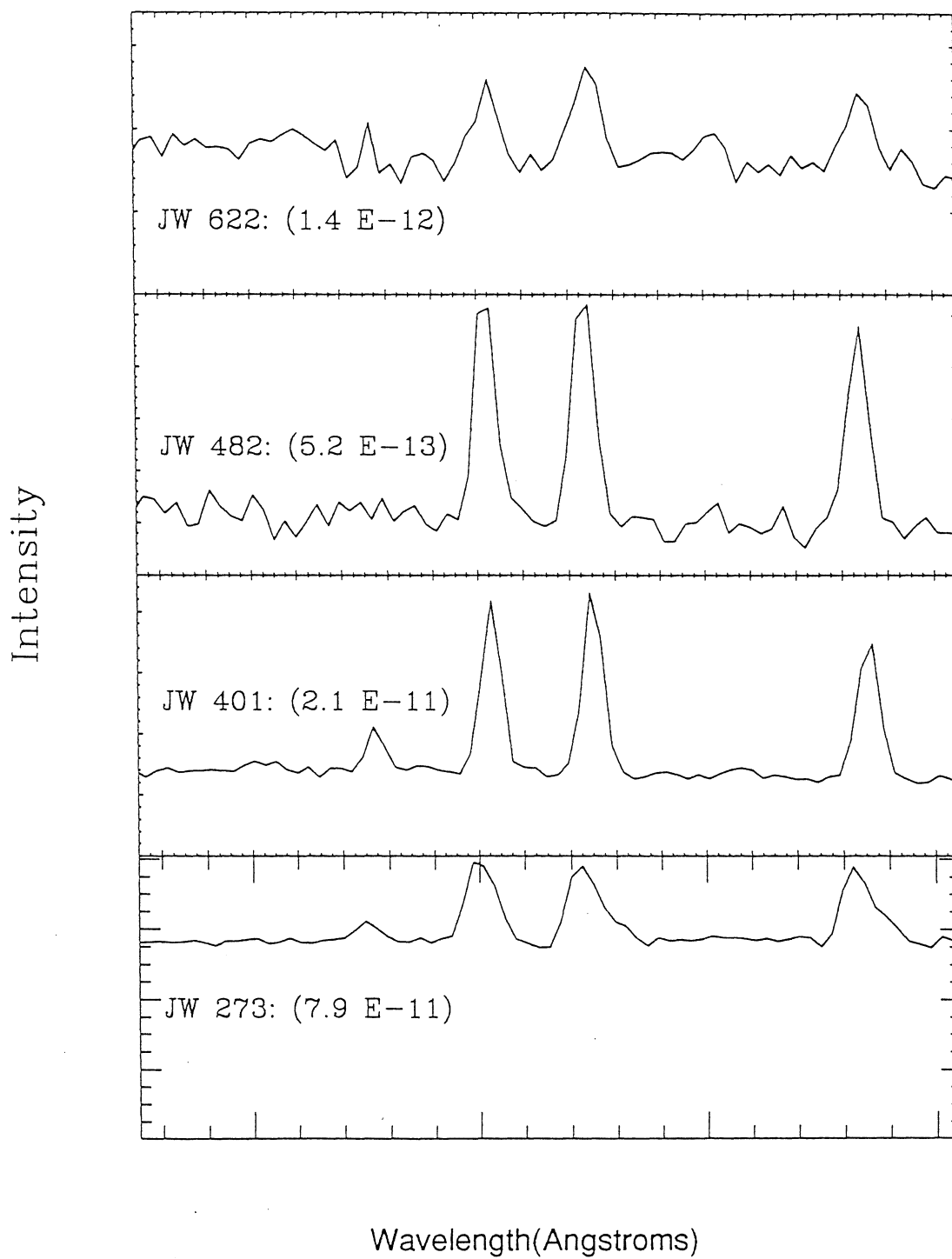


Figure 4.3: Four Trapezium Cluster stars with Ca II IR triplet emission. Peak heights above zero are denoted ($\text{ergs s}^{-1} \text{cm}^{-2} \text{\AA}$).

Table 4.5: H α Equivalent Width (Å) Measurements for Chamaeleon Sample

Name (1)	EW(H α) ⁽¹⁾ (2)	EW(H α) ⁽²⁾ (3)	EW(H α) ⁽³⁾ (4)	EW(H α) (5)
SZ 4	41.0 $\pm$ 7.6			
SZ 7	7.6 $\pm$ 0.7			
SZ 9	47.7 $\pm$ 4.7			13 ⁽⁴⁾
SZ 11	49.6 $\pm$ 5.1		52.5	56 ⁽⁴⁾
SZ 14	7.2 $\pm$ 0.3			
SZ 18	7.6 $\pm$ 4.2			12v ⁽⁴⁾
SZ 21	54.9 $\pm$ 3.4			94 ⁽⁵⁾
SZ 22	71.9 $\pm$ 20.9			
SZ 23	73.9 $\pm$ 1.4			
SZ 26	3.0 $\pm$ 0.5			
SZ 27	109.2 $\pm$ 5.4			
SZ 30	219.5 $\pm$ 28.9			
SZ 33	58.3 $\pm$ 3.6			
SZ 37	84.4 $\pm$ 19.3			200 ⁽⁴⁾
SZ 40	18.0 $\pm$ 0.2			
SZ 42			82.7	58 ⁽⁴⁾
SZ 43	56.7 $\pm$ 15.7			
SZ 44	8.3 $\pm$ 0.2			
SZ 45	43.7 $\pm$ 6.7			32 ⁽⁴⁾
SZ 59			48.5	
SX Cha	51.2 $\pm$ 11.7	26.7		21 ⁽⁴⁾
SY Cha	13.8 $\pm$ 1.3	63.6		49 ⁽⁴⁾
SZ Cha	11.7 $\pm$ 1.5			7 ⁽⁵⁾
TW Cha	27.6 $\pm$ 1.7	26.1		
UY Cha	74.5 $\pm$ 15.6			
UZ Cha	20.8 $\pm$ 1.1			
VV Cha	60.4 $\pm$ 7.2	74.9		88v ⁽⁴⁾
VW Cha	79.6 $\pm$ 3.6	146.9	65.2	116 ⁽⁴⁾
VY Cha	38.4 $\pm$ 6.1	55.1		55 ⁽⁴⁾
VZ Cha	46.0 $\pm$ 11.5	71.4		71 ⁽⁴⁾
WW Cha	57.7 $\pm$ 1.0		67.6	54v ⁽⁴⁾
WX Cha	83.5 $\pm$ 9.3	65.5		51v ⁽⁴⁾
WY Cha	46.2 $\pm$ 12.8	56.3		52 ⁽⁴⁾
WZ Cha	339.4 $\pm$ 58.7	388.2	269.0	313 ⁽⁴⁾
XX Cha	83.8 $\pm$ 19.1	133.5		87v ⁽⁴⁾

1: Present work; 2: Appenzeller et al. 1977; 3: Hamann & Persson 1992 (HPa);
4: Appenzeller et al. 1983; 5: Rydgren 1980

4.4 Discussion

4.4.1 Frequency of Calcium Triplet Emitters in PMS Populations

The actual percentage of calcium triplet emitters is uncertain due to the small numbers of detected emitters in each sample. The uncertainties are estimated here using Poisson statistics. We then find that $\sim 30 \pm 10\%$ (1σ) of a sample of $H\alpha$ stars from the Chamaeleon I dark cloud are Ca II IR triplet emitters. This compares with only $\sim 9 \pm 5\%$ from a sample of Trapezium Cluster PMS stars which may or may not exhibit $H\alpha$ emission. Thus, there appears to be a significant difference in the proportion of stars with Ca II IR triplet emission in the two PMS populations. In the following, we examine the extent to which selection effects have contributed to this result. We probe the nature of the differences and consider the factors involved in the star formation process in each region that could give rise to these differences. HPA determine that triplet lines with fluxes smaller than $\sim 5 \times 10^{-15}$ ergs s $^{-1}$ cm $^{-2}$ originate in stellar chromospheres, while larger fluxes are of disk origin. This flux is estimated for the distance to Chamaeleon of ~ 170 pc (Henize & Mendoza 1977), and corresponds to an intrinsic luminosity of $\sim 2 \times 10^{28}$ ergs s $^{-1}$. The triplet fluxes detected for our data are all greater than this limit. Thus, the following discussion assumes a disk origin for the triplet features observed here.

Calcium Triplet vs $H\alpha$ Emission

While the Chamaeleon sample observed here are known $H\alpha$ emission stars (Schwartz 1977), the Trapezium Cluster stars are only those members of the cluster which are bright enough to be distinguished from the nebula background. We do not know if the Trapezium Cluster stars observed here are $H\alpha$ stars, due to the extreme difficulty in discriminating between nebula and stellar $H\alpha$ emission in our sample.

It is necessary to test the correlation between $H\alpha$ emission and calcium triplet emission in order to gauge the importance of this selection effect on the result obtained here. In Figure 4.4 we plot the flux in $H\alpha$ against Ca II emission, using the Ca II $\lambda 8498$ feature to represent the three triplet lines. The figure does show that for stars which exhibit calcium triplet emission there is a correspondence between the measured flux in the $H\alpha$ line and that in the Ca II IR triplet feature. We find that $F(H\alpha) = 0.13F(CaII)^{0.88}$. (Note that this corresponds to $F(H\alpha) > F(CaII)$ in the range considered.) It is important to note that very strong-line $H\alpha$ sources such as Sz 30, Sz 40, UZ Cha, VZ Cha and WY Cha do *not* have detectable triplet emission in our data. This demonstrates that $H\alpha$ emission is not a function of calcium triplet emission, but that the strength of the Ca II IR triplet emission, if present, is related in some way to the strength of $H\alpha$ emission. In terms of the origins of the emission, the inner disk regions which produce the triplet features are likely to be

dependent on the strengths of the Balmer lines originating in the boundary layers (Basri & Bertout 1989).

The implication of this observed dependence between calcium triplet emission and $H\alpha$ strength is that the $H\alpha$ emission stars which constitute our Chamaeleon sample are more likely to include Ca II IR triplet stars. By choosing a random (with respect to $H\alpha$ emission) sample of Trapezium Cluster stars the probability of including triplet emitters is potentially smaller.

The K_o , $J-K_o$ Diagram

Another possible selection effect arises from the choice of visibly brighter members of the Trapezium Cluster. We have plotted the Chamaeleon stars observed here in the K_o , $J-K_o$ color-magnitude diagram derived for the Trapezium Cluster (see Chapter 2) in order to compare the two populations in luminosity, mass and age. The data presented correspond to the distance of the Trapezium Cluster (~ 440 pc). The resultant diagram is shown in Figure 4.5(a) and (b). We do not have spectral types for five Chamaeleon triplet stars as well as the four Trapezium Cluster calcium triplet stars. These have been dereddened solely on the basis of their JHK colors.

Initially, we compare positions of the two samples with respect to luminosity. The figure shows that almost all of the Chamaeleon stars would appear fainter than $K \sim 10$ mag at the distance of Orion with the faintest being ~ 13 mag. The Trapezium Cluster stars are overall a brighter population, spread in K_o luminosity from fourth to eleventh mag. However, consideration of the positions of the triplet emitters among the Chamaeleon sample reveals that seven of the ten have relatively high luminosities brighter than $K_o \sim 11$ mag. These seven are located in the overlap region of the luminosity range for the two samples. We conclude that the selection of brighter Trapezium Cluster objects is not a major reason for the smaller proportion of triplet stars found in our Trapezium Cluster sample. The luminosity difference noted translates into a mass difference between the two samples. The Chamaeleon sample have derived masses of $\leq 1.5 M_\odot$ with the majority being $\sim 0.2-0.6 M_\odot$. The Trapezium Cluster stellar masses are largely between 0.6 and $3 M_\odot$. As is expected (Cohen & Kuhl 1979; Herbig 1977; Appenzeller, Jankovics & Krautter 1983; Larson 1991), the Chamaeleon stars observed here represent a *lower* mass PMS population than the Trapezium Cluster sample. However, many authors (MPC; HPb among others) have shown that high mass PMS stars are also found with triplet emission. It is not likely that fewer triplet emitters are present in the Trapezium Cluster sample solely due to the higher mass of this group. The average ages of the two complete samples are comparable at $\sim 10^6$ yr. Seven of the ten Chamaeleon calcium triplet stars are situated high on their Hayashi tracks. This suggests that Ca II IR triplet emitters are among the younger members of the population, consistent with the

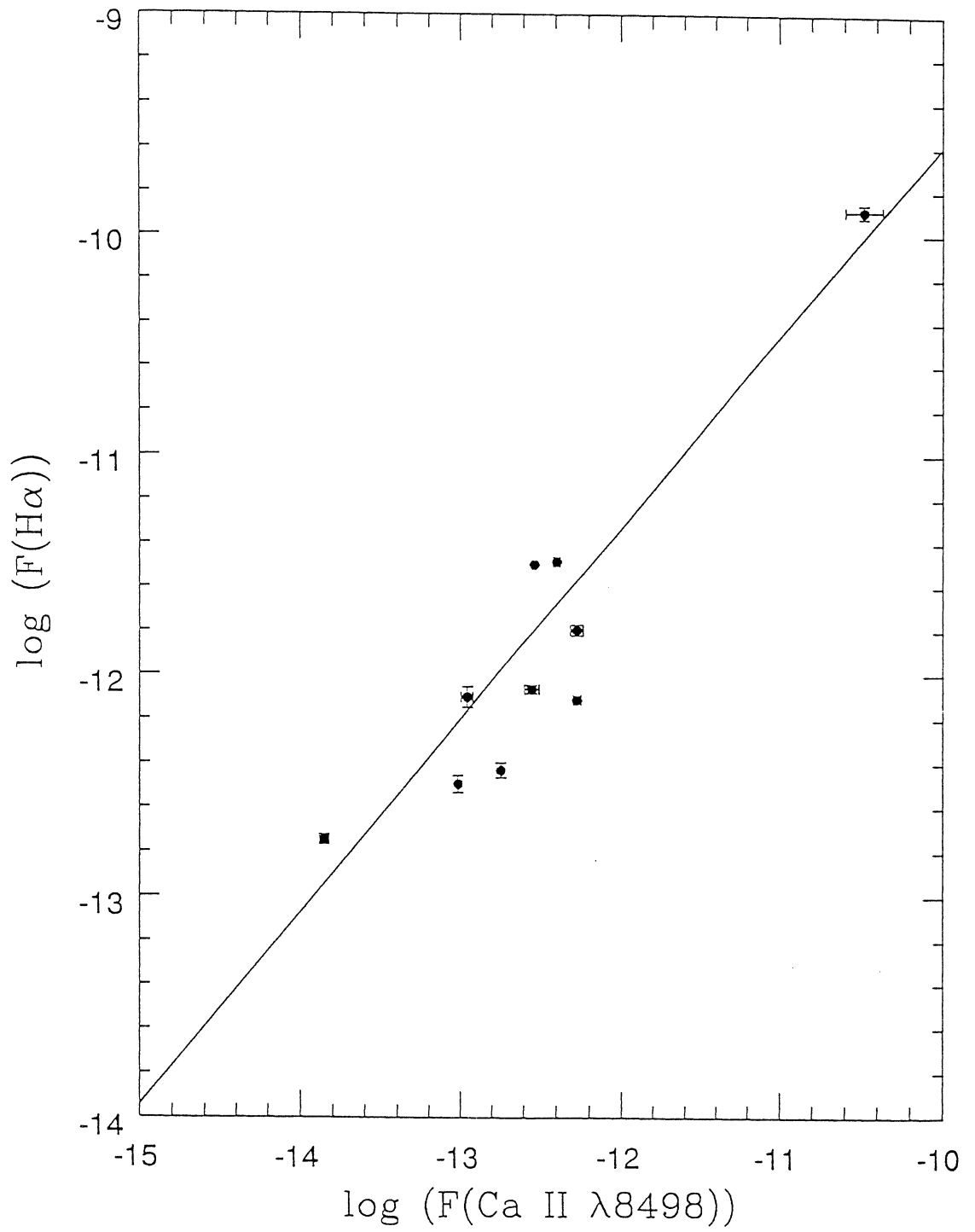


Figure 4.4: H α flux vs Ca II triplet flux (8498 Å feature) in log-log plane.

Figure 4.5: (a) and (b): K_o , $(J-K)_o$ diagrams, on following pages. (a) shows the positions of the Trapezium Cluster sample of Chapter 3. Filled circles represent stars for which a unique spectral class has been derived. Those stars whose spectral types were not so well constrained are shown as open circles connected by a dashed line, corresponding to the two extremes in spectral class determined for each star. The four Trapezium Cluster stars with triplet emission which have no spectral type data are shown as open circles with attached arrows. The main-sequence locus is indicated by the solid line in the left of the diagram. Dashed lines give PMS evolutionary tracks from 0.12 to 3 $M_\odot$ (VandenBerg 1991; see Chapter 2, §2.3.4) and for a 5 $M_\odot$ star (Iben & Talbot 1966). Solid lines marked V to Z correspond to isochrones such that V: 10^5 yr; W: 5×10^5 yr; X: 10^6 yr; Y: 5×10^6 yr; Z: 10^7 yr. The figure includes lines marking the observed $J-K_o$ colors for A- to M-type dwarfs (Bessell & Brett 1988), along the top axis.

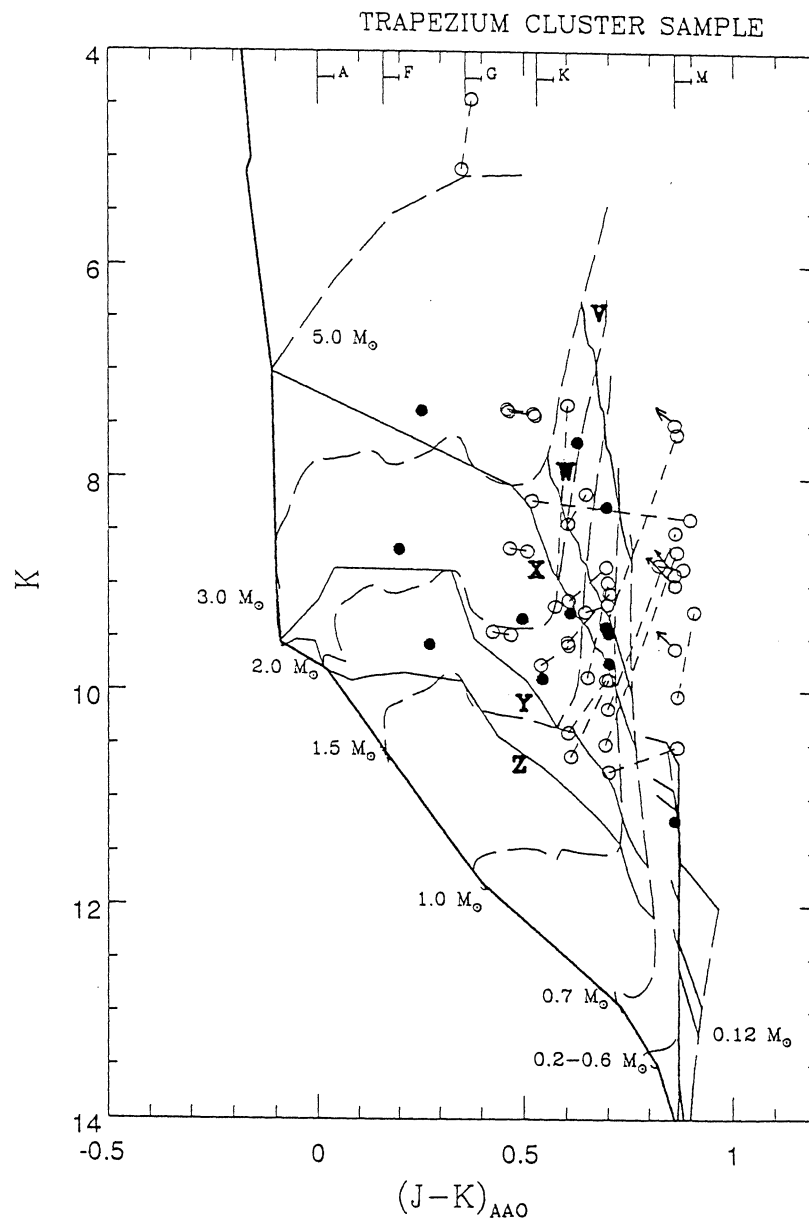


Figure 4.5: *cont.*

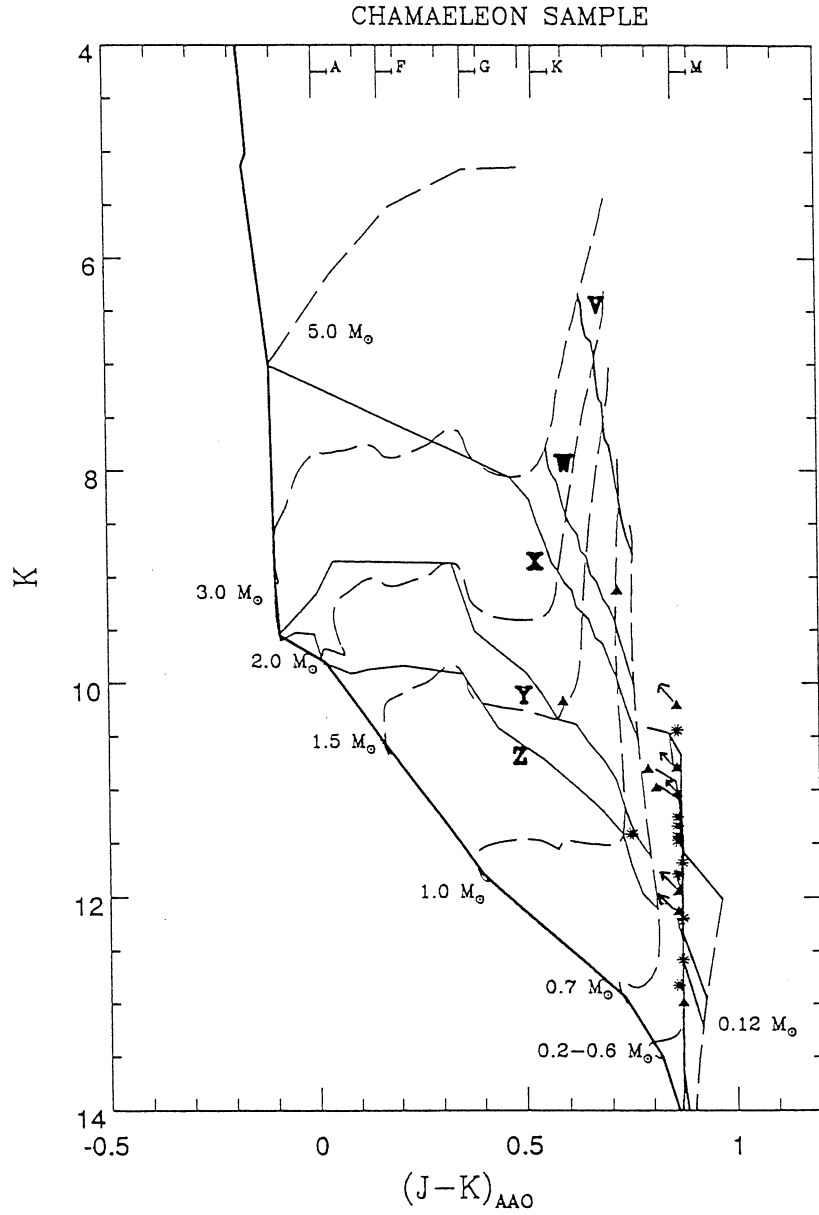


Figure 4.5: (b) As for (a), with the locations of the Chamaeleon sample shown for comparison. The non-triplet emitters are indicated by asterisks, stars with detected triplet emission as closed triangles, and those with triplet emission but no spectral type data are shown as closed triangles with attached arrows.

presence of circumstellar disks. However, the fact that the Trapezium Cluster stars and the Chamaeleon sample have similar ages implies that the smaller number of triplet emitters in the Trapezium Cluster sample is not a function of the ages of the stars we have observed.

In summary, the significant difference in the proportion of calcium triplet stars in the two PMS populations may be attributable to a paucity of $H\alpha$ stars in the Trapezium Cluster sample. We are sampling a more luminous, higher mass population in our Trapezium Cluster stars compared with the Chamaeleon members observed. However, these factors do not appear to be influential in determining the number of triplet emitters in each group.

Calcium Triplet Emission vs. Infrared Excess

As mentioned previously, HPA find that the observed triplet fluxes arising from chromospheric regions are less than $\sim 5 \times 10^{-15}$ ergs s $^{-1}$ cm $^{-2}$ (at ~ 170 pc), below the detection limit of our observations. Only the triplet flux measured in WZ Cha is close to this limit. Stronger triplet features, as observed in our sample of Chamaeleon stars (Table 4.1), are suggested by HPA to originate in inner disk regions. In this case, there should be a strong correlation between the proportion of stars with circumstellar disks and the proportion of triplet emitters.

Our previous work (see Chapter 3) on the spectral classification of Trapezium Cluster stars included a determination of the amount of circumstellar disk emission associated with the stars observed. We found that around one-third of our Trapezium Cluster sample have little or no dust excess. In comparison, ~ 20 – 50% of the PMS stars in the Taurus-Auriga and Ophiuchus clouds are found to belong to the naked T Tauri star class (without dust excesses; Walter 1986; Walter et al. 1988). Thus, it appears that our finding for the Trapezium Cluster is reasonably typical of star-forming regions. We compare this result with the Chamaeleon PMS sample.

Figure 4.6 shows the $J-H$ vs $H-K$ diagram for the 33 Chamaeleon stars observed here. The reddened $J-H$ and $H-K$ colors of the Chamaeleon stars have been obtained by Prusti (1992). Comparison of the reddened locations of our Chamaeleon sample with their intrinsic spectral types given in Table 4.1 clearly shows that most of the stars cannot be simply dereddened back to main sequence positions. Consequently, almost all of our Chamaeleon sample have associated infrared excesses at near-infrared wavelengths. This includes all the triplet stars, as would be expected.

Unfortunately, the four Trapezium Cluster stars in which Ca II IR triplet emission features have been observed were not dereddened. However, our infrared photometry work (Chapter 2) shows that, given late spectral types for the four, each has a large amount of associated infrared excess. The proportion of triplet stars observed compared with the total number of stars with infrared excesses in the Trapezium

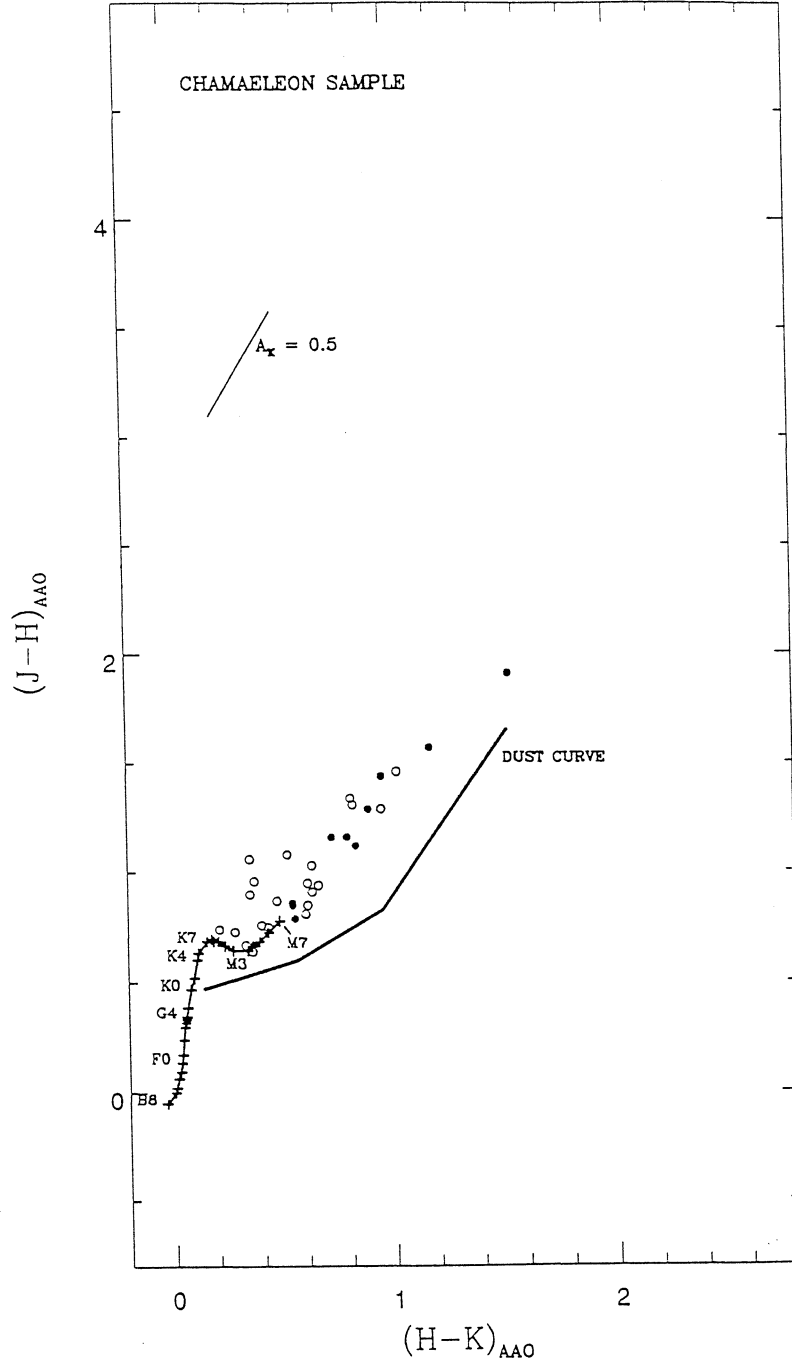


Figure 4.6: $(J-H)$ vs $(H-K)$ diagram for the Chamaeleon sample (open circles). The triplet stars are represented by the filled circles. Heavy solid curve in lower left represents main-sequence locus with spectral types marked (Bessell & Brett 1988; Bessell 1991). Colors for a typical late-type star with circumstellar dust have been taken from Hyland, Jones & Mitchell (1982); the corresponding locus is indicated as the 'dust curve'. We have used the model given by Hyland et al. corresponding to a 5400 K star with a maximum shell radius of $10^3 R_*$ ($R_{min}/R_* = 50$). Also given is the extinction vector representing $A_K = 0.5$ mag ($A_V \approx 4.5$ mag), assuming a normal reddening law (Rieke & Lebofsky 1985).

Cluster is $\sim 20 \pm 10$ %. We found 30 ± 10 % of stars in Chamaeleon exhibit triplet emission, from a sample in which 100% have infrared excesses. Hence we conclude that, within the errors, there are in fact a comparable number of triplet emitters in the two classical T Tauri star samples.

Therefore, the Trapezium Cluster stars appear to be a normal PMS population in both their Ca II triplet and H α emission properties and their ratio of classical (dust excess) to naked (non-dust excess) T Tauri stars, assuming that their near-infrared dust excess statistics directly reflect the relative numbers of classical and naked T Tauri stars. Hartigan (1993) finds that the number of weak-lined (comparable to naked) T Tauri stars in the PMS population of Chamaeleon is ~ 44 %. This indicates that overall the Chamaeleon population is also typical of star-forming regions in this sense, although *our* sample is exclusively composed of the classical T Tauri star members.

4.5 Conclusions

We find that between 20 and 30 % of classical T Tauri stars in samples taken from two PMS populations exhibit calcium triplet emission. Our samples are from the Trapezium Cluster in the Orion Nebula (20 %) and the Chamaeleon I dark cloud (30 %). The proportion of dust-excess stars in the Trapezium Cluster *with* detectable triplet emission is of the same order as found in Chamaeleon. Thus, our results suggest that classical T Tauri stars in the Trapezium Cluster seem typical of young stellar populations in their triplet emission characteristics. It remains to be resolved why calcium triplet emitters are found in such proportions in classical T Tauri star populations. Our results for the Trapezium Cluster show that it is less likely that triplet emitters will be observed in a random sample of PMS stars (9 %) compared with a sample of CTTS (20 %).

We judge that the resolution of our data allows us to detect only the strong *disk* triplet emission component in our stars, based on the work of Hamann & Persson (1989a). The ratios of peak heights of the Ca II triplet features observed here are in all cases $\sim 1:1:1$, indicative of optically thick emission. This supports the widely-held view that the peak heights of the triplet features in T Tauri stars are approximately equal (for example, Herbig & Soderblom 1980; McGregor, Persson & Cohen 1984; Persson et al. (1988); Finkenzeller & Basri (1987); and Hamann & Persson 1992, HPa). The analysis undertaken here confirms that the presence of triplet emission in PMS stars relates to the strength of H α emission and infrared excess. We do not find any correlation of calcium triplet emission with stellar luminosity or age.

Chapter 5

Conclusions

We have conducted an indepth investigation of the Trapezium Cluster star formation region using optical and near-infrared techniques. Additionally, we have acquired considerable stellar spectral type information of a large number of Trapezium Cluster stars for the first time, allowing greater accuracy in the placement of these stars in the HR diagram. Thus, the spectral types, masses, ages, extinction properties, and dynamical state of the cluster are estimated to a higher degree of reliability in this dissertation than has been possible previously using optical photometry alone (Herbig & Terndrup 1986). The results presented here are of importance in understanding star formation in populous embedded clusters containing both low and high mass stars. They provide a useful reference point for the elucidation of similar populations recently revealed via infrared array imaging (Gatley et al. 1991; McCaughrean et al. 1991; Lada et al. 1991; Greene & Young 1992; among others).

The infrared analysis presented in the thesis has provided an initial exploration of the nature of the Trapezium Cluster with respect to parameters such as stellar age, mass and associated dust excesses and extinctions. The combination of both I - J , J - K and J - H , H - K color-color diagrams is used for the first time in a self-consistent manner in order to deredden stars in the K , J - K color-magnitude plane. We have then applied the more accurate means of using stellar spectral type information to improve our dereddening estimates and refine the findings of our infrared work. The results from both programs are presented.

5.1 Major Findings of the Current Work

The low mass Trapezium Cluster ($\sim 5'$ in radius or ~ 0.6 pc; Hyland, Allen & Bailey 1993) is estimated here to have a mean age of $\sim 10^6$ yr, with the large majority of surveyed members having ages of $< 5 \times 10^6$ yr. Star formation in the cluster is estimated to have continued from around a few $\times 10^6$ yr to the present. These

results confirm the pre-main-sequence (PMS) nature of the low mass cluster and are in good agreement with those found by Herbig & Terndrup (1986) in the most recent extensive examination of the properties of the Trapezium Cluster population. The Trapezium OB stars ($\sim 16''$ radially or 0.03 pc) are estimated to be approximately zero-age-main-sequence objects (Warren & Hesser 1978). Therefore, a lower age limit for these stars is $\sim 4 \times 10^4$ yr (Iben 1965), the PMS lifetime for high mass stars. If the massive stars have in fact recently arrived on the main sequence, then this lower age limit is roughly appropriate, making them among the youngest stars in the region. However, if the OB stars have been on the main sequence for some time, our findings of low mass stars with ages younger than 10^5 yr imply that the formation of these high mass stars has not inhibited low mass star formation in this region (Herbig 1962; Elmegreen & Lada 1977; Silk 1977; Larson 1985; Stahler 1985). Clarification of this point and its universality awaits better determinations for the ages of the OB stars, and observations of more clusters in which low and high mass star formation is occurring.

Cohen & Kuhi (1979) have investigated the nature of the surrounding Orion Nebula Cluster of low mass stars ($\sim 0.3 \times 0.6$ deg² or 2.5×4.5 pc²), finding a range in age for this population from 3×10^4 yr to 6×10^6 yr, similar to that found here for the Trapezium Cluster. Thus, overall, star formation has been reasonably uniform in duration over a radius from the central Trapezium OB stars out to the extent of the Orion Nebula Cluster ($\sim 18'$, or ~ 2.3 pc, in radius). On the basis of the ages of the stars, it is possible that a single triggering mechanism has been responsible for the creation of both high and low mass stars. A more recent burst of at least high mass star formation is occurring interior to the molecular cloud. The BN-KL region, 1–1.5' from the Trapezium stars and deeply embedded in the cloud, includes the high mass BN and IRC2 sources. These are thought to have ages of $\leq 10^4$ yr (for example, Scoville et al. 1983; Mundy et al. 1986). They represent the youngest OB subgroup detected in the Orion Molecular Cloud.

The mean reddening for our Trapezium Cluster sample is found to be $A_K \sim 0.3$ mag, with a range from $A_K \sim 0.0$ to 1.1 mag. The large scatter in reddening for our sample highlights the importance of evaluating the extinction on an individual basis as done here. Only in this way can we satisfactorily account for the highly variable amounts of line-of-sight dust associated with each star in this extremely nebular environment. The mean value found in this work agrees well with the average used by Herbig & Terndrup ($A_K \sim 0.26$ mag; 1986) for their sample of optically-selected Trapezium Cluster stars. The Trapezium OB stars are estimated to be extinguished by A_K between 0.1–0.3 mag, both from our near-infrared data and previous work (Warren & Hesser 1978; Garay, Moran & Reid 1987); the extinction towards the Orion Nebula H II region is determined to be $A_K \sim 0.2$ mag (Greve et al.

1989). The extended Orion Nebula Cluster surveyed by Cohen & Kuhl (1979) has an average extinction of $A_K \sim 0.02$ mag. The morphology revealed by the combination of all of these results is of the high mass Trapezium OB stars being located at the near-face of the Orion A molecular cloud together with some proportion of the low mass surrounding cluster. The remainder of the low mass Trapezium Cluster stars are embedded to varying degrees in the cloud to $A_K \geq 1.1$ mag. We have used the K luminosity function for the infrared cluster (Hyland et al. 1993) in order to determine the spatial extent of the cluster with respect to the molecular cloud. Our findings support the picture proposed by Herbig & Terndrup (1986) in which the distribution of low mass Trapezium Cluster stars is enhanced at the near-face of the cloud, rather than being uniformly spread through it. The amount of extinction associated with the region is considerably reduced in the Orion Nebula Cluster vicinity. This decrease in reddening with greater radial distance from the core is corroborated by the work of Ito & Sasaki (1982). They find that stars in the extended Orion Nebula region (up to $30'$, or 3.8 pc, in radius) are extinguished by $A_K < 0.02$ mag. The low mass Trapezium Cluster stars observed in this work are considerably less embedded than the BN-KL nebula, which is estimated to have an associated extinction of $A_K \sim 2-5$ mag (Gillett et al. 1975; Joyce, Simon & Simon 1978; Scoville et al. 1983; Beckwith 1982; Hyland et al. 1984; Minchin et al. 1991). It is of considerable interest to determine whether any of the low mass population identified as members of the Trapezium Cluster are in fact associated with the BN-KL star-forming region. The difficulties involved in accurately dereddening cluster stars are clearly outlined in the current work. However, a complete census of the cluster in terms of extinction is required to settle this issue of membership. Whether a significant population of low mass stars is also associated with the BN-KL high mass group remains one of the outstanding questions concerning this environment (Lonsdale et al. 1982).

The results obtained in this investigation reveal that approximately one-third of our sample of low mass PMS Trapezium Cluster stars have dust excesses commonly attributed to circumstellar disks. If these excess stars are equated to the classical T Tauri star (CTTS) class and those without significant excess are similarly equated to the naked T Tauri star (NTTS; Walter 1992 and references therein) class, then the proportions of each class found in our survey are comparable with the ratios observed in a number of other PMS populations (e.g., ρ Oph, Taurus-Auriga: Walter 1986; Walter et al. 1988; Chamaeleon: Hartigan 1993). The fact that the proportions of NTTS/CTTS found in our survey of the Trapezium Cluster is comparable with PMS populations of lower stellar densities suggests that disk-disk interactions in this populous environment have not caused the removal of *inner*-disk material around a significant number of cluster members. Interactions of this kind (Herbig & Terndrup

1986) may have affected the distribution of material in *outer-disk* regions of the stars; this is best estimated at millimeter wavelengths where these extended circumstellar regions may be probed.

Additional evidence that the circumstellar environments of the low mass Trapezium Cluster stars are similar to those of other young low mass stellar groups is provided by our survey of Ca II IR triplet emitters. Strong calcium II IR triplet emission features, as observed in our study, have been modelled as originating in inner-disk regions of PMS stars (Hamann & Persson 1992, HPa). We have surveyed the frequency of triplet emitters in both the Trapezium Cluster and Chamaeleon I star-forming regions. We find a comparable number, between 20–30 %, taking account of only the CTTS in both regions. The correlation found in our Ca II IR triplet survey between triplet emission and H α emission strength supports the idea that calcium triplet emission is a feature of the CTTS class.

The Trapezium Cluster stars examined to greater accuracy with optical spectroscopic methods in the present work are predominantly of mid-K spectral type. The fact that studies of low mass stars in the vicinity of, but external to, the Trapezium Cluster (e.g., Cohen & Kuhl 1979; Parsamian & Chavira 1982; Walker 1983) determine the same mean spectral type shows that, in this sense, the central low mass cluster is typical of the Orion A PMS population. In comparison, while a mean K spectral type is also found in NGC 2264, the PMS populations of NGC 7000/IC5070, Taurus-Auriga, Chamaeleon and Lupus all have an average spectral type of $\sim$ M0 (Herbig 1977; Cohen & Kuhl 1979; Appenzeller, Jankovics and Krautter 1983). As discussed in this work, given an age for the PMS population, a mean spectral type translates into a mean stellar mass due to the nature of PMS isochrones. Thus, the variations in mean spectral type noted here in the different star-forming regions indicate variations in the average mass of stars in each region. We demonstrate this further through the explicit derivation of the mean stellar mass of the low mass Trapezium Cluster.

The improved accuracy in the age of the low mass Trapezium Cluster determined here has been used to transform the near-infrared *K* luminosity function (Zinnecker et al. 1992; Hyland et al. 1993) for the entire cluster into the corresponding mass function. We obtain a mean stellar mass of $0.9 M_{\odot}$. The total mass of the low mass Trapezium Cluster as defined in our investigation is $\sim 491 M_{\odot}$. The mean stellar mass found here agrees well with the range in mass obtained by Herbig & Terndrup (1986) for their sample of 68 Trapezium Cluster stars of < 0.7 to $3 M_{\odot}$. It is quite different from the mass of $\sim 0.3 M_{\odot}$ determined by Zinnecker et al. (1992) to correspond to the peak in the *K* luminosity function. These authors emphasize that direct transformation from a peak *K* magnitude to a mean stellar mass is subject to a number of uncertainties due to the processes involved in PMS evolution, and caution

against such an approach. While a large number of very low mass stars are certainly present in the Trapezium Cluster, we demonstrate that, for the cluster age of 10^6 yr derived here, the total mass in these stars is too low to significantly skew the mass distribution towards lower masses. We have instead calculated a mean mass based on the cumulative mass distribution of the cluster. The value obtained of $0.9 M_{\odot}$ is approximately the same as the average mass estimated by Cohen & Kuhl (1979) for the outer Orion Nebula Cluster of $1 M_{\odot}$. Hence, the results obtained in the present work demonstrate that the low mass population in the Trapezium Cluster/Orion Nebula Cluster have a mean stellar mass comparable to that in star-forming regions such as NGC 2264, but higher than that found in, for example, the Taurus-Auriga, Lupus, and Chamaeleon dark clouds ($\sim 0.5 M_{\odot}$: Cohen & Kuhl 1979; Herbig 1977; Appenzeller, Jankovics & Krautter 1983). Our work supports the notion that low mass stars of higher mean mass are forming in massive giant molecular clouds while low mass stars of smaller mean mass are created in the less dense dark cloud regions. Clearly, it is of importance to ascertain what factors are responsible for the mean stellar mass of a PMS population. Two factors which appear significant are the mass of the natal cloud and its initial gas density (Silk 1982; Larson 1991).

The initial mass function (IMF) presented in this work is a first approximation, derived from the K luminosity function of Hyland et al. (1993). The errors in the transformation are such that the slope of the distribution can be fit by both the Salpeter (1955) and the more recent Scalo (1986) slopes. The reality of the turnover in the observed IMF remains uncertain. More detailed calculations of the relationship between luminosity and mass in PMS stars are required before an accurate IMF can be obtained (Zinnecker et al. 1992). Theoretical studies of this kind are of great importance, given that the nature of the IMF is crucial to an understanding of the earliest stages of star formation via fragmentation of the molecular cloud.

We use our derived stellar masses to determine the mass density of the low mass Trapezium Cluster. The density obtained of $\sim 4690 M_{\odot} \text{ pc}^{-3}$, including the Θ^1 Ori stars, is $\sim 1.5 \times$ that of Herbig & Terndrup ($3000 M_{\odot} \text{ pc}^{-3}$; 1986). The difference is attributable to the fact that Herbig & Terndrup were only able to probe the optical members of the cluster whereas the entire embedded infrared cluster (Hyland et al. 1993) is taken account of here, using a mean stellar mass of $0.9 M_{\odot}$ and the same volume considered by Herbig & Terndrup. The density of gas that would be required to obtain this mass density, given 100 % star formation efficiency (SFE) and a closed system, is calculated to be $\sim 10^5 \text{ H}_2 \text{ molecules cm}^{-3}$, comparable to densities found in cores of the Orion Molecular Cloud (Snell et al. 1984; Mezger, Wink & Zylka 1990). An approximate star formation efficiency in the Trapezium Cluster region is also estimated from the cluster mass obtained here and taking account of the mass

in high mass stars. We determine the mass of gas presently in the cluster from our extinction measurements. Thus, a first-order estimate of the star formation efficiency is calculated to be $\sim 72\%$. High star formation efficiencies (20–42 %) are also found for embedded clusters in L1630 (Lada 1990) and ρ Oph (Wilking, Lada & Young 1989), while less dense populations such as Taurus have estimated star formation efficiencies of $< 5\%$ (Myers 1982). However, we note that *clusters* are also found with low measured star formation efficiencies, such as NGC 2023 in L1630 (SFE $\sim 7\%$: Lada 1990). Observations of more regions of clustered and dispersed star formation will help constrain the nature of any correlation between the parameters of star formation efficiency and stellar density, leading to a greater understanding of both modes of star formation.

High star formation efficiencies are required to form bound clusters with high mass stars, given a rapid rate of gas removal (Mathieu 1983; Lada, Margulis & Dearborn 1984; Verschueren 1990). The question of whether the Trapezium Cluster is bound or not has been hotly argued for some time. Using the velocity dispersion for the low mass stars found by Jones & Walker (1988) of 2.3 km s^{-1} , we find that the cluster has attained virial equilibrium. This taken together with a consideration of the entire infrared (HAB) cluster with mean stellar mass as derived here leads to the conclusion that there *is* sufficient mass in low mass cluster stars to bind it at present. The addition of the calculated gas mass contained in the cluster volume has the effect of making the cluster even more bound, while the removal of gas from the region in the future will not affect the bound nature of the cluster.

Determination of the parameters of the low mass Trapezium Cluster, as undertaken here, is fundamental to an understanding of the dynamical nature of the cluster. We have presented an approximate analysis of the dynamics of the Trapezium Cluster in order to form a basis for further, more detailed modelling. Treating the low mass and high mass stellar groups separately, the relaxation time-scale for the low mass cluster is found to be equivalent to the mean age of the cluster, $\sim 10^6$ yr. This suggests that the low mass system has not yet lost knowledge of its initial characteristics. We find that the relaxation time calculated here corresponds to approximately three crossing times, whereas at least nine are estimated to be necessary for a system to be nearing kinetic equilibrium (Binney & Tremaine 1987). The relaxation time determined for the high mass Trapezium system is $\sim 3 \times 10^3$ yr, or around twenty times less than the lower limit to the age of the stars of $\sim 6 \times 10^4$ yr. The minimum age of the OB stars is equivalent to around sixty crossing times. Therefore, our results support the long-held view that the central Trapezium OB stars have had sufficient time to interact strongly with each other by the present epoch. The observed isothermality of the low mass cluster, derived from the work of Jones & Walker (1988), is proposed here to be a result of initial isothermality of the

gaseous clumps from which the cluster stars formed, since the system has not had time to reach an isothermal state dynamically. Based on dynamical arguments, we also propose that if the high mass Trapezium OB stars are at the center of the low mass cluster, then their location is a function of initial conditions and corresponds to their birthplace in the cloud, rather than being due to dynamical evolution. Thus, the central location of the Θ^1 Ori stars is not seen here as evidence of mass segregation in an isothermal, relaxed system. It remains to be ascertained whether there is any evidence for mass segregation within the total low mass system; we do not expect any significant segregation at this early stage in the evolution of the cluster.

The calculated binding energy of the cluster is compared with that of the two known binaries of the Trapezium OB system. The binding energy of BM Ori (Θ^1 Ori B) alone is almost forty times that of the entire low mass cluster. We conclude that the two binary systems acquired their present energies via the circumstances of their birth, rather than through interactions with the low mass cluster. The binding energies calculated for the binaries are so high that any such interactions would have long since dispersed the cluster. Theoretical models of high mass Trapezium systems predict that members of such systems are ejected over time leading to a more and more tightly bound system, until finally all that remains is a single extremely tight binary (Ambartsumian 1954; Allen & Poveda 1974; Mirzoyan & Salukvadze 1984; Abt 1986). However, the influence of a surrounding, dense, low mass stellar cluster needs to be accounted for in these models if a satisfactory picture of the dynamical evolution of Trapezium Cluster-type regions is to be obtained. It is likely that the presence of the low mass stars retards the rate at which the system evolves. One possible scenario is that when more and more low mass stars eventually acquire enough kinetic energy to escape, the cluster starts contracting. The high mass stars also gain kinetic energy and are successively lost to the system, leaving a single tight binary.

5.2 Star Formation in the Orion Molecular Cloud

The low mass Trapezium Cluster is, on average, significantly younger than its natal environment, given an age of more than a few $\times 10^7$ yr for the Orion Molecular Cloud (Blitz & Shu 1980). An important observational question that remains unanswered is the spatial relationship between the Trapezium Cluster, and the even more youthful BN-KL stars. Only through the determination of the amount of extinction associated with deeply embedded faint stars can this issue be resolved. The details provided in this work illustrate the extreme difficulty involved in such a determination. The summary given above clearly demonstrates that both the Trapezium Cluster and Orion Nebula Cluster PMS stellar populations are similar in mass, age and spectral

type of members. The only major differences are in the smaller amount of extinction associated with the surrounding Orion Nebula Cluster, and the greatly reduced mass density in this more extended cluster. Thus, the formation of the entire stellar population may have been triggered by the same event, but evidently a greater gas mass and density and/or higher star formation efficiency in the Trapezium core region are responsible for the enormous number of stars created here compared with the surroundings. Embedded clusters have also been identified in the other regions of L1641 (Strom et al. 1989) and in the neighbouring Orion B or L1630 molecular cloud, in the NGC 2024, NGC 2023, NGC 2071, and NGC 2068 regions of star formation. Details of these clusters are in the process of being obtained (for example, Lada & Lada 1991). Comparisons with the Trapezium Cluster population are of great interest in addressing questions regarding the triggering of stellar clusters in the Orion Molecular Cloud complex.

5.3 Future work, with particular reference to recent IR-array work

The dissertation presented here has successfully provided a detailed observational understanding of the Trapezium Cluster star-forming environment. Studies of the young embedded clusters being revealed by infrared-array imaging over the last few years will also benefit from analyses in different wavelength regimes as undertaken here. It is only on the basis of sufficient observational information that models of these dense high mass/low mass star-forming environments will be successfully built. In addition, comparisons with the Trapezium Cluster can be made, and its suitability as the prototype of this mode of star formation ascertained. It is noteworthy that ultracompact H II regions are commonly described as the birthplaces of OB-stellar groups; it remains to be seen whether they have associated low mass clusters (Wood & Churchwell 1990). Investigations of these regions may be of significance to the further elucidation of Trapezium Cluster environments.

As highlighted in the above summary, there is now a strong need for more accurate means of transforming from PMS stellar luminosities to corresponding stellar masses (Zinnecker et al. 1992). The means are achievable with detailed knowledge of the mechanisms involved in PMS evolution in a variety of environments. Observations, such as those presented here, of PMS populations in different environments provide an important step in this process. Many of the recent papers studying embedded infrared clusters have presented their K luminosity functions. The corresponding mass distributions provide much information on the processes by which clusters are created in molecular clouds. The numbers of stars present in different mass ranges is clearly dependent on how clumps of material initially formed and pro-

duced stars. Hence, knowledge of the cluster IMF also helps solve another problem, concerning the factors which determine the mean stellar mass of a PMS population. Importantly, an understanding of the mechanisms responsible for converting molecular cloud material into a dense stellar cluster also addresses the question of what initial mass of gas produced the cluster. This leads to the determination of the star-formation efficiency (SFE) in these embedded cluster regions. Following on from these issues is the resolution of why such extremely populous clusters are created, that is, what is causing these high SFEs.

Modelling of multi-mass PMS N-body systems is a very involved problem. While assumptions need to be made in order to simplify it, observational studies such as that presented here provide a crucial database from which to compute these models. The examination of many similar star-forming environments will help to further constrain the theories from which to predict the future dynamical evolution of these systems.

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