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STELLAR POPULATIONS IN DEEPLY EMBEDDED YOUNG CLUSTERS:
NEAR-INFRARED SPECTROSCOPY AND EMERGENT MASS DISTRIBUTIONS

A Dissertation Presented

by

MICHAEL R. MEYER

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

February 1996

Department of Physics and Astronomy

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I would like to thank everyone, except lynne.

ABSTRACT

STELLAR POPULATIONS IN DEEPLY EMBEDDED YOUNG CLUSTERS: NEAR-INFRARED SPECTROSCOPY AND EMERGENT MASS DISTRIBUTIONS

FEBRUARY 1996

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Directed by: Professor Stephen E. Strom

The goal of this thesis is to test the following hypothesis: The initial distribution of stellar masses from a single “episode” of star formation is independent of the local physical conditions of the region. This is a direct test of whether or not the initial mass function (IMF) of stars is strictly universal over spatial scales of less than 1 pc and over time intervals of less than a few million years. We discuss the utility of embedded clusters in addressing questions concerning star formation and the (IMF). Using a combination of spectroscopic and photometric techniques, we aim to characterize emergent mass distributions of embedded clusters in order to compare them with each other and with the field star IMF. We outline the application of near-infrared classification spectroscopy to the study of embedded stellar populations. Medium resolution ($R = 1000$) near-infrared spectra obtainable with the current generation of NIR grating spectrographs can provide estimates of the photospheric temperatures of optically-invisible stars. Deriving these spectral types requires a three-step process; i) setting up a classification scheme based on near-infrared spectra of spectral standards; ii) understanding the effects of accretion on this classification scheme by studying optically-visible young stellar objects; and iii) applying this classification technique to the deeply embedded clusters. Combining near-infrared photometry with spectral types, accurate stellar luminosities can be derived for heavily reddened young stars thus enabling their placement in the H-R

diagram. From on their position in the H–R diagram, masses and ages of stars can be estimated from comparison with theoretical pre–main sequence evolutionary models. Because it is not practical to obtain complete spectroscopic samples of embedded cluster members, a technique is developed based solely on near–IR photometry for estimating stellar luminosities from flux–limited surveys. We then describe how spectroscopic surveys of deeply embedded clusters are necessary in order to adopt appropriate mass–luminosity relationships. Stellar luminosity functions can then be characterized in terms of emergent mass distributions for deeply embedded young clusters. Because of systematic uncertainties in these models at the low–mass end, we adopt the ratio of intermediate ($10M_{\odot} > M_{\star} > 1.0M_{\odot}$) to low–mass ($1.0M_{\odot} > M_{\star} > 0.1M_{\odot}$) stars in order to compare these mass distributions to the Miller–Scalo IMF. As an example of this analysis we present a study of the embedded cluster associated with the NGC2024 nebula. Although this cluster contains slightly more intermediate mass stars than expected if drawn from from a Miller–Scalo IMF, the result is not statistically significant. A detailed comparison between the stellar luminosity functions of the embedded clusters associated with the NGC2024 cluster and the embedded population found in the Ophiuchus cloud cores suggests that it is unlikely they were drawn from the same parent population. After finding the evolutionary states and accretion properties of both clusters to be similar, we interpret the difference in stellar luminosity functions as a difference in their emergent mass distributions. Synthesizing results for NGC2024 and Ophiuchus with those from other studies of embedded clusters, we arrive at the following conclusions: i) emergent mass distributions of embedded young clusters are not very sensitive to initial conditions; and ii) there is a hint that regions of high central stellar density contain a greater proportion of intermediate mass stars.

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C H A P T E R 1

INTRODUCTION

1.1 Motivation for Studying the Origin of the Initial Mass Function

One of the fundamental questions in the study of star formation and stellar evolution is the origin of stellar masses. Once the mass of a star is determined, much of its evolution is fixed during the main and post-main sequence phases. In recent years, considerable progress has been made in understanding the formation of single stars from the collapse of an individual molecular cloud core (e.g. Shu, Adams, and Lizano, 1987). After dissipation of some support mechanism (possible magnetic), cloud collapse begins from the inside-out. Low angular momentum material collects at the center of the cloud core to form a protostar surrounded by a circumstellar accretion disk which is feed by an extended envelope. This theory has enjoyed great success in its ability to interpret the spectral energy distributions of young stellar objects as an evolutionary sequence from; i) embedded protostellar infall phase; through ii) the T Tauri accretion phase; and finally iii) the post-accretion phase after the dissipation of a circumstellar disk. If most of the mass of a star passes through this accretion disk, then it is reasonable to assume that whatever process halts accretion regulates stellar masses. It is intriguing to consider whether this might be a self-regulating process; that the termination of accretion is somehow linked to the accumulation of a characteristic stellar mass.

An alternate view contends that stellar masses are fixed by the fragmentation processes of molecular cloud cores. In this picture a cloud that is unstable to collapse can break-up into subfragments as long as the cloud temperature does not increase with increasing density. The minimum mass reached by fragmentation is

fixed by the initial temperature as well as the chemical composition of the cloud. The concept of fragmentation is appealing because observations suggest that a substantial fraction of stars are formed in groups from low density aggregates (Strom, Merrill, and Strom, 1993) to rich clusters (Lada *et al.*, 1991a). The stellar densities of the richest groups ($> 1000 \text{ stars pc}^{-3}$) found associated with giant molecular cloud cores suggest that dozens stars are found within the dimensions considered in models of cloud core collapse sketched above for single stars. Even within the low mass Taurus dark cloud, sparse aggregates of tens of stars have been identified as stellar density enhancements ($< 100 \text{ stars pc}^{-3}$) by Gomez *et al.* (1993). The fact that pre-main sequence stars within these clusters and aggregates tend to be found in multiple star systems (Ghez *et al.*, 1993; Simon *et al.*, 1995; Padgett *et al.*, 1995) suggests the possibility that hierarchical fragmentation has taken place (Larson, 1995). In order to understand the formation of stars it is of the utmost importance to know whether or not there is a characteristic stellar mass which can fix the scale of the process.

The best estimates of the initial distribution of stellar masses come from studies of large numbers of stars in volume-limited samples defined in the solar neighborhood. We briefly summarize this procedure. Combining a variety of proper motion, spectroscopic, and photometric techniques, a luminosity function is derived for main sequence stars. Then a main sequence mass luminosity relationship is applied in order to derive the *present day mass function*, or PDMF from the luminosity function. Next, the effects of stellar evolution are taken into account in order to derive the *initial mass function*, or IMF. As high mass stars evolve more quickly than low mass stars, the PDMF will underestimate the number of stars with main sequence lifetimes less than the age of the galactic disk. The relative proportions of intermediate and high mass stars are typically drawn from young rich open clusters out to a distance of 2.5 kpc (e.g. Garmany, Conti,

and Chiosi, 1982) whereas the distributions of lower mass stars are drawn from well-mixed disk populations found in solar neighborhood within 1kpc. Because of their short main sequence lifetimes, the higher mass stars used in constructing the IMF tend to be quite young ($0.01 - 1 \times 10^8$ yr), while lower mass stars found in the solar neighborhood are systematically older ($1 - 100 \times 10^8$ yr). For these reasons, even a consistent definition of the IMF requires the assumption that it does not vary in time and space in the disk of the galaxy. The most comprehensive recent determination of the initial mass function is Miller and Scalo (1979; hereafter MS79) and subsequently updated in Scalo (1986). The reader is referred to Scalo (1986) for a detailed review of the IMF. There are two main features of the observed IMF that are (almost) universally agreed upon. First, for masses greater than about $5M_{\odot}$ the IMF is well-represented by a power law ¹. Secondly, the mass function becomes flatter for masses less than $1M_{\odot}$ (Kroupa, Tout, and Gilmore, 1993). There is considerable debate whether or not the IMF continues to rise, is flat, or turns over for masses between $0.1 - 0.5M_{\odot}$ (Tinney, 1993; Kroupa, 1995). The existence of characteristic stellar masses near $1.0M_{\odot}$ is an important constraint on theories for the origin of stellar masses. Of even greater importance would be the clear demonstration of a minimum mass at or near the hydrogen burning limit.

In addition, it is extremely important to know whether or not the time- and space-averaged distribution of masses characterizing the solar neighborhood is universal. Do all star forming events give rise to the same distribution of stellar masses? If star formation is essentially a self-regulating process, such as in the termination of accretion discussed above, then one might expect the IMF might to be strictly universal. Alternatively, if fragmentation is the process by which stellar

1

Massey, 1995, find a slope $\Gamma = -1.3$ for massive stars in clusters and a steeper power law for high mass stars in the field.

masses are fixed, one might expect gross differences in stellar mass distributions which depend on local conditions. Certainly the details of either process depend on the physical conditions of the clouds of gas and dust from which the stars form. The unanswered question is: how sensitively does the distribution of stellar masses depend on the initial conditions in the natal environment? In this thesis, we outline a technique for performing an initial reconnaissance of the distributions of stellar masses found in deeply embedded clusters. Such studies, capable of identifying regions with peculiar emergent mass distributions, should place important constraints on the universality of the time- and space-averaged initial mass function observed in the solar neighborhood. Our ultimate goal is to understand the physical mechanisms that are responsible for the origin of stellar masses.

1.2 The Utility of Young Clusters in Studying the IMF

Astronomers have long used studies of galactic clusters to answer questions concerning the formation and early evolution of stars. In addition to investigating the IMF, studies aimed at deriving the star forming history of a cluster can address whether there exists a temporal sequence of star formation as a function of mass or high and low mass stars form at the same time. The recent discoveries of dense clusters of stars still embedded in their sub-parsec sized parent molecular cores (e.g. Lada *et al.*, 1991) have enabled astronomers to take a new approach toward investigating the IMF. Because only 10 % of the stars in the galactic disk are found in bound stellar systems (Miller and Scalo, 1978), most of these clusters will probably emerge as unbound associations. Assuming a typical velocity dispersion of $\Delta V \sim 1 \text{ km sec}^{-1}$ stellar aggregates should expand to $\sim 1 \text{ pc}$ in size in 10^6 yrs . Thus the current stellar densities of these embedded aggregates suggest that they are very young with ages $< 1 \times 10^6 \text{ yrs}$.² As a result we anticipate these clusters

are coeval to within their inferred ages, allowing us to set aside the temporal question raised above and concentrate on addressing the universality of the IMF.

These clusters have attributes which make them ideal for studying the origin of the initial mass function. Because of their youth; i) no evolutionary corrections are needed to translate the present day distribution of stellar masses into an initial mass function; and ii) observations of such clusters not only probe distributions over the full range of stellar masses but are also more sensitive to low mass objects because the mass–luminosity relationship for stars in the pre–main sequence phase ($L_* \sim M_*^2$) is not as steep as for stars on the main sequence ($L_* \sim M_*^{3.5}$). Because of their compactness, they occupy small projected areas on the sky reducing the contamination of foreground stars that plague studies of larger optically–visible associations. Their coincidence with molecular cloud cores provides a natural screen against background stars which can also contaminate the sample. Thus, for the first time we can attempt to derive distributions of stellar masses for single star–forming events associated with individual molecular cloud cores.

1.3 Review of the Study of Young Clusters

Ironically it was the low stellar density of optically–visible T–associations, thus being unstable against dispersal by the galactic gravitational field, that led Ambartsumyan (1949) to conclude these associations were indeed comprised of young stars. By combining optical photometry and spectroscopy, ground–breaking efforts were made to construct color–magnitude diagrams for large numbers of stars in young associations (e.g. the classic study of NGC2264 by Walker, 1956). This work established the existence of a low luminosity pre–main sequence population

Pioneering work by Lada, Margulis, and Dearborn (1984) suggests that the dynamical evolution of embedded clusters is governed in part by the removal of molecular cloud material from the system.

in these clusters, which had been predicted theoretically by Henyey, LeLevier, and and Levée (1955). By concentrating on samples observed spectroscopically, researchers were able to derive distributions of stellar masses and ages from HR diagrams with the help of theoretical PMS evolutionary models (e.g. Cohen and Kuhi, 1979). This work suggested that star formation in these optically-visible associations which spread over tens of parsecs i) occurred over several million years; and ii) resulted in a distribution of masses similar to that characterizing field stars in the solar neighborhood. However the discovery of dense aggregates of embedded young stellar objects (YSOs) suggested that these optical studies did not sample completely the stellar populations in star-forming regions still associated with molecular clouds (e.g. Wynn-Williams, Becklin, and Neugebauer, 1972; Grasdalen, Strom, and Strom, 1973). This led to the speculation that perhaps the embedded phase was a natural precursor to the T Tauri phase and hence, clusters of embedded objects might be in an earlier stage of evolution from optically-visible T-associations (Strom, Strom, and Grasdalen, 1975).

Pioneering attempts at studying embedded clusters were based on the construction of K-band ($2.2\ \mu\text{m}$) luminosity functions (e.g. Vrba, Strom, and Strom, 1975) and bolometric luminosity functions constructed from spectral energy distributions (SEDs) from $1\text{--}100\ \mu\text{m}$ (e.g. Wilking, Lada, and Young, 1989). K-band luminosity functions (KLFs) have several advantages worth considering. K-band observations are more sensitive to stellar populations than longer wavelength surveys due to the relatively low thermal background ($\lambda < 2.3\ \mu\text{m}$). The K-band surveys are more sensitive to embedded sources than surveys conducted at shorter wavelengths because the K-band suffers about a factor of $\times 10$ less interstellar extinction than the V-band at $0.55\ \mu\text{m}$ and $\times 3$ less than the J-band at $1.25\ \mu\text{m}$. One major difficulty in the interpretation of the infrared luminosity functions is the effect of infrared excess emission. Studies of

optically-visible T Tauri stars in Taurus suggest that they have considerable excess emission beyond $1\ \mu\text{m}$ due to the presence of warm circumstellar dust (Mendoza, 1966; Cohen and Kuhi, 1979; Hartigan *et al.*, 1991). An obvious complication in the relationship of luminosity functions to the underlying distribution of stellar masses is the absence of a unique mass–luminosity relationship for PMS stars, in contrast to the well-known relationship for main sequence stars. In other words, the mass–luminosity relationship of young stars evolves over time.

Zinnecker *et al.* (1993) were the first to construct detailed models of the evolution of luminosity functions of embedded clusters by transforming the theoretical PMS evolutionary tracks into an observational plane. By assuming an input initial mass function, they constructed synthetic K-band luminosity functions for clusters with ages from 0.3–2 Myr. However, they note that their technique is limited by the fact that they have ignored complications due to infrared excess emission and differential extinction. Ali and DePoy (1995) have attempted to model these effects in their analysis of the KLF. Lada and Lada (1995) have extended these approaches by considering continuous star formation in their models of KLFs. Strom *et al.* (1993) built upon the work of Zinnecker *et al.* by attempting to deredden embedded sources based on their observed $(J - H)$ color. Further, they considered only dereddened J-band luminosity functions in order to minimize the effect of infrared excess emission. All of the above mentioned techniques rely on the assumption of an underlying mass distribution combined with analysis of the observed luminosity functions in order to derive the age (or age distribution) of embedded clusters. In principle, extensions of these techniques could place constraints on the distribution of stellar masses. By making the shape of the input mass spectrum a variable, certain distributions could be ruled out if found to be inconsistent with the observed luminosity function in a statistically

significant way. In practice, treating both mass and age distributions as variables makes it very difficult to find a unique best-fit solution.

1.4 A New Look at an Old Approach

We prefer a different approach to the study of embedded clusters, using spectroscopic studies to inform our photometric survey work. Analogous procedures have a long history in the study of open clusters at optical wavelengths and we briefly outline one example here. For over three decades, studies of open clusters, ranging in age from $30\text{--}300 \times 10^6$ yrs, have relied largely on photometric studies of proper-motion selected samples. Because of observed variations in the reddening law at optical wavelengths, many researchers relied on spectroscopic determinations of the ratio of total to selective extinction for some fraction of the photometric sample. Using these measurements to fix the reddening law, three color photometry was often used (via the Q-method of Johnson for example) in order to derive differential reddening measurements to individual stars. This permitted the construction of a luminosity function thought to be representative down to some limiting magnitude. Because of the age of these clusters, all stars with masses greater than about one solar mass (or less for older clusters) will have reached the main sequence. As a result, cluster luminosity functions could then be compared to initial luminosity functions calculated from the IMF and the well-known main sequence mass-luminosity relationship over a restricted range of absolute magnitudes unaffected by incompleteness.

Our analogous approach to the study of embedded clusters is as follows. We make use of color-color and color-magnitude diagrams in order to derive estimates of the extinction toward each star in our photometric survey sample. We focus on estimates of stellar luminosity uncontaminated for the most part by the affects of accretion. Then for a representative sub-set of this flux-limited sample we obtain

near-infrared classification spectra. The spectroscopic sample is chosen to span a range of extinction, infrared excess, and stellar luminosity. Near-IR spectra allow us to estimate photospheric temperatures for the embedded objects and place them in the H-R diagram. This in turn permits us to adopt an appropriate mass-luminosity relationship in order to interpret the reddening corrected luminosity function. We then characterize the emergent mass distribution for the cluster and compare it to the solar neighborhood IMF for a complete A_v -limited sample. Imposing an A_v -limit insures that our sample will not be biased toward higher mass (more luminous) stars which can be seen more deeply into the cloud.

1.5 Overview of the Present Study

The goal of this thesis is to test the following hypothesis: initial distribution of stellar masses from a single “episode” of star formation is independent of local physical conditions. While such a tightly worded hypothesis might seem obviously wrong, in practice it is extremely difficult to reject. Although most embedded clusters have mass distributions that are consistent with having been drawn from the field star IMF, it appears that the formation of intermediate mass stars is enhanced in regions of high stellar density.

In this presentation, we outline a broad approach to the study of embedded clusters. In Chapter II, we explore near-infrared spectroscopy as a tool for estimating the photospheric temperatures of embedded young stellar objects (YSOs). This work suggests that near-IR spectra can be used to derive spectral types (and infer photospheric temperatures) for stars which are optically-invisible. We comment on the utility of the H- and K-bands in deriving spectral types as well as signal-to-noise requirements. We also demonstrate that near-IR spectra of well-studied optically-visible T Tauri and Herbig Ae/Be stars yield spectral types consistent with those obtained through traditional optical spectroscopy. In

Chapter III, we derive a technique for estimating the extinction toward individual stars found in embedded clusters. Our method applies what we know about the spectral energy distributions of optically-visible YSOs to the study of embedded populations in order to estimate stellar luminosities, minimizing the effects of infrared excess emission. In Chapter IV, we present an example of this analysis for the embedded cluster associated with the eponymous H II region NGC2024. First we apply our dereddening technique to a near-IR photometric survey of the region. From the H-R diagram constructed for the near-IR spectroscopic sample, we show that the embedded cluster is extremely young and is forming stars over a wide range of stellar masses. This H-R diagram provides calibration of the mass-luminosity relationship necessary for interpreting the dereddened luminosity function in terms of stellar masses. While there are slightly more intermediate mass stars than one would naively predict from the Miller-Scalo (1979) IMF, the result is not statistically significant. We also examine the circumstellar properties of the young stars in the cluster as inferred from measurements of near-infrared excess emission.

In Chapter V, we make a detailed comparison of cluster properties between the embedded YSOs found in the molecular cloud cores of Ophiuchus and the cluster associated with NGC2024. Although the two populations are found to be quite similar in their evolutionary status and accretion properties, there is some evidence that the stellar luminosity functions were not drawn from the same parent population. We take this to imply that the two regions are forming stars with different emergent mass distributions. In Chapter VI, we examine the hypothesis that this is related to the difference in stellar density observed for the two regions. We find evidence that although most regions have quite similar IMFs, the stellar density of embedded clusters appears to be related to the shape

of their emergent mass distributions. We discuss the implications of these results for the origin of the IMF, and finally in Chapter VII we summarize our work.

CHAPTER 2

NEAR-INFRARED SPECTROSCOPY AND EMBEDDED YSOs

With the recent development of large-format infrared array detectors, high quality photometric surveys are routinely conducted at wavelengths between 1–2.5 μm . Because of the large number of assumptions required in order to derive quantities of astrophysical interest from near-IR photometry alone, such studies stand to benefit enormously from complementary spectroscopy. We investigated the utility of the near-infrared spectral regime for the classification of spectra obtained of deeply embedded young stellar objects. This required that we have at our disposal a grid of spectral standards in order to select wavelength regions, chose the necessary spectral resolution, and estimate the signal-to-noise ratio required for deriving accurate spectral types. A high quality, moderate resolution atlas ($R = 3000$) exists for the K-band window at 2.2 μm (Kleinmann and Hall, 1986). A comparable atlas was not available for the J- (1.25 μm) and H-band (1.65 μm) windows. Anticipating that some YSOs in our study will exhibit significant excess continuum emission at $\lambda > 2\mu\text{m}$, we examined the J- and H-bands as possible alternatives to the K-band for spectral classification.

In this Chapter we describe the assembly of an atlas for the H-band window and outline its attributes relevant to the classification of stellar spectra. Next we describe our lower resolution ($R = 1000$) H- and K-band spectroscopic survey aimed at obtaining classification spectra for embedded YSOs. We present our lower resolution standard star spectra and describe the criteria we used for classification. Comment is made on the relative merits of the H- and K-bands as

well as the signal-to-noise required for spectral classification. Finally we examine the effects on our classification scheme due to the pre-main sequence nature of young stellar objects. This is accomplished by analyzing spectra obtained for well-studied optically-visible young stars and deriving spectral types from their infrared spectra independent of the existing optical data.

2.1 Medium Resolution H-Band Survey of MK Spectral Standards

We set out to produce a J- and H-band atlas complementary to the K-band atlas of Kleinmann and Hall. However, we concentrate here only on the H-band survey for two reasons; i) difficulty in reducing the J-band data primarily due to temporal variations in the telluric absorption features of water vapor; and ii) the paucity of strong stellar absorption features that are temperature and luminosity sensitive. We present an atlas of H-band spectra for 88 stars of solar abundance observed at a resolving power of 3000 with the KPNO Mayall 4m FTS. The atlas spans a two-dimensional grid from spectral types O7–M6 and luminosity classes I–II, III, and IV–V as defined on the revised MK system. Line identifications are made based on comparison with the solar atlas (Livingston and Wallace, 1992) supplemented by the model calculations of Origlia, Moorwood, and Oliva (1993). We define several atomic and molecular indices which are temperature and luminosity sensitive. In addition, we explore the use of diagnostic line-ratios to determine effective temperatures and surface gravities. Such line ratios provide stellar parameters that are independent of continuum excess emission which can often complicate deriving spectral types for pre-main sequence as well as evolved stars.

2.1.1 Defining the Sample

In order to define our two-dimensional standard star grid, we adopted the temperature and luminosity scales of the revised MK system ¹. As our list of fundamental standards we chose; i) Morgan, Abt, and Tapscott (1978) for stars O6–G0; ii) Keenan and McNeil (1989) for stars G0–K5; and iii) Kirkpatrick *et al.* (1991) for dwarf stars K5–M5. A few secondary standards were added from the list of Jaschek, Conde, and de Sierra (1964) as well as additional late-type dwarf stars from the catalogue of Woolley *et al.* (1970). The grid was divided into 26 spectral type (i.e. photospheric ionization state) bins and three luminosity classes. Using the MK subclasses defined in the above references, we binned our temperature grid $\times 2$ more coarsely than the standard sequence with the goal of observing a star of *at least* every other subclass. The luminosity classes were coarsely divided between supergiants (I–II), giants (III), and subgiants/dwarf stars (IV–V). For stars earlier than G0 we obtained observations of stars filling 28 of the 51 bins (17 Sp. Type $\times$ 3 L.C.). For stars G0 and later, we filled 26 of the 27 bins (9 Sp. Type $\times$ 3 L.C.). Our coverage of this grid is shown graphically in Figure 2.1 where each star observed is plotted on the H–R diagram.

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In this updated system, several subclasses are dropped in order to sample late-type stars linearly in temperature. For example, K7 represents a half-subclass corresponding to T_{eff} halfway between K5 and M0.

Figure 2.1. H-R Diagram for all sources observed in the Kitt Peak 4m FTS MK spectral standards survey.

Table 2.1. Journal of Observations for the MK Standards Survey

Date	Type	# of Stars	Weather
March 9–10, 1993	Day	17	Light cirrus.
April 1–3, 1993	Day/Night	30	Mostly Clear.
May 18–19, 1993	Day	10	Cloudy.
January 30–31, 1994	Day/Night	42	Clear.

2.1.2 Observations and Data Calibration

The observations were obtained at the Mayall 4m telescope at Kitt Peak National Observatory in Arizona during four separate observing runs during 1993–1994 (Table 2.1). We used the Fourier Transform Spectrometer (FTS) dual-output interferometer Hall *et al.*, 1979). The FTS was ideal for this program for several reasons. First, the wavelength coverage of the FTS is limited only by the bandpass of the blocking filters, independent of the spectral resolution. Secondly, the spectral resolution is fixed by the path difference scanned with the interferometer so we were able to chose the highest resolution possible while maintaining adequate signal-to-noise ². Finally because of the novel background subtraction algorithm of the 4m FTS described below, we were able to observe many of the brightest sources in our sample during good daytime conditions (typically mornings). Combining daytime observations spread out over a variety of LST ranges, with targeted nighttime observations of key faint sources, the FTS provided a uniform set of high quality spectra for a large sample of spectral standards.

Data were collected simultaneously in the J– and H–bands with the use of a dichroic beamsplitter to separate the wavelengths longwards and shortwards of 1.5 μm . Four single element InSb detectors were used, two at each output for the J– and H–bands respectively, and cooled to 4K with liquid helium. Each star was

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For more details concerning the advantages and disadvantages of fourier transform spectroscopy, see Bell, R.J. (1974).

centered within an input aperture of 3.8 arcsec while sky background was measured through an identical aperture 50.0 arcsec away. The interferogram was scanned at a rate of 1 kHz as the path difference was varied continuously from 0.0–0.75 cm providing an unapodized resolution of 0.8 cm^{-1} . Data were obtained as separate scan pairs, with the path difference varied first in one direction and then the other. This produced two independent observations of each source. A forward–backward scan pair was treated as an “observation” and observations were repeated in beam–switching mode (A–B–B–A) with the initial sky aperture becoming the source aperture in going from “A” to “B” mode and returning to the original configuration in going from “B” to “A”. Because the sky background from each aperture produces an interferogram of opposite sign at each set of detectors, source spectra are background subtracted in fourier space as they are collected. This permits observations of bright stars to be obtained during good daytime conditions. These beam–switched observations were repeated and scans were averaged until adequate signal–to–noise ratio (SNR) was achieved. The interferograms were transformed at Kitt Peak National Observatory using the software package GRAMMY³ yielding spectra in units of relative flux versus wavenumber (cm^{-1}).

The transformed spectra were converted into fits format images and all data reduction was performed using the IRAF software package⁴. The data were calibrated in the following manner. First, the spectra were convolved with a gaussian filter of half–width $\sigma = 1.2 \text{ cm}^{-1}$. This procedure, commonly referred to as apodization, eliminates “ringing” observed in the FTS spectra due to the finite

³

GRAMMY is based on a modified Cooley–Tukey algorithm for the fast–fourier transform.

⁴

IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

scan path of the interferometer. The resulting apodized resolution (Rayleigh criterion) was $\delta\sigma = 2.1 \text{ cm}^{-1}$ giving a median resolving power of $R = 3000$ in the H-band. At this stage the J- and H-band spectra were separated for ease of reduction. The slope of the continuum was normalized to 1.0 using a four-segment spline fitting function. Care was taken to keep the residuals from this fit to within 1 %.

Next we corrected the spectra for telluric absorption features present in the spectra which varied with zenith angle. We attempted to construct an opacity map for the earth's atmosphere by dividing normalized spectra obtained of the A0 star standards at different airmass. Because of the simplicity of the A0 star spectra, showing only hydrogen lines in absorption, it was relatively easy to monitor the degree to which this procedure was successful. In dividing two spectra of the same star taken at different airmass, all stellar photospheric absorption features should directly cancel, leaving only those absorption features due to the earth's atmosphere. If we assume that the opacity of the telluric absorption is directly proportional to airmass we derive:

$$\tau(\sigma, X = 1.0) = \frac{1}{(X_2 - X_1)} \times \ln\left[\frac{I(\sigma, X_1)}{I(\sigma, X_2)}\right] \quad (2.1)$$

where τ is the atmospheric opacity, X_1 is the low airmass value, and X_2 is the high airmass value. A typical opacity map derived in this way for the H-band is shown in Figure 2.2. Again if the atmospheric opacity varies linearly with airmass we can simply scale the opacity for each star so that $\tau(\sigma, X_1) = X_1 * \tau(\sigma, X = 1.0)$. Using this technique we corrected the spectra to essentially zero-airmass;

$$I(\sigma, 0) = I(\sigma, X_1) \times e^{\tau(\sigma, X_1)} \quad (2.2)$$

We used the highest signal-to-noise A0 standard star spectra ($SNR > 100$) with the largest ΔX to define the opacity. We found some residual telluric absorptions,

possibly due to water vapor which do not vary strictly with airmass. Such features severely complicate the reduction of the J-band spectra.

Finally, the forward and backward scans of each star were averaged and residuals of the differenced spectra were calculated in order to evaluate the SNR. The observations were obtained with the goal of achieving SNR of 75 or greater. In most cases this was achieved with the highest quality spectra reaching values of several hundreds. The SNR for each stellar spectrum is included in Table 2.3–Table 2.6 below. In Figures 2.3– 2.6, we show a sub-set of the final reduced spectra as a function of T_{eff} for each of the three different luminosity classes; I–II, III, and IV–V.

Figure 2.2. Atmospheric opacity in the H-band at a resolving power of $R = 3000$. The opacity was derived from ratios of high signal-to-noise spectra of the same star observed at different airmass as discussed in the text.

Figure 2.3. Representative H-band spectra of the MK standards plotted as a function of effective temperature from high to low for luminosity class I-II stars.

Figure 2.4. Representative H-band spectra of the MK standards plotted as a function of effective temperature from high to low for luminosity class III stars.

Figure 2.5. Representative H-band spectra of the MK standards plotted as a function of effective temperature from high to low for luminosity class IV stars.

Figure 2.6. Representative H-band spectra of the MK standards plotted as a function of effective temperature from high to low for luminosity class V stars.

2.1.3 Line Identification and Variation with Stellar Parameters

There are several atomic and molecular features visible in these spectra many of which are temperature and/or luminosity sensitive. Line identifications were made with the aid of the solar photospheric and umbral atlases (Livingston and Wallace, 1991). In addition, we consulted the model atmosphere calculations of Oliva, Moorwood, and Origlia (1993) in order to identify the dominant contributor to obvious line blends. At our moderate resolving power of $R = 3000$ some of the features we observe have contributions due to more than one species when compared to the solar atlas. Prominent in the spectra of early-type stars are the lines of neutral atomic hydrogen belonging to the Brackett series ⁵. The very earliest type stars show He I absorption at 5882 cm^{-1} ($1.700 \text{ }\mu\text{m}$). Metallic lines of Mg I, Si I, Ca I, Al I, and Fe I begin to appear in stars F–G and increase in strength toward later-types. Finally molecular features of OH and CO dominate the spectra of the latest-type stars K5–M5. Of particular interest is the behavior of the second-overtone CO bandhead [$\nu, \nu' = 6, 3$] at 6177 cm^{-1} ($1.619 \text{ }\mu\text{m}$) which is luminosity sensitive, being much stronger in stars of lower surface gravity. The most useful features for classification in this wavelength regime are listed in Table 2.2, along with the ionization potential of the species.

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The Brackett series is produced by electronic transitions from the $n_i = 4$ state to higher energy levels ($n_f = 10 - 15$).

Table 2.2. H-Band Spectral Features Useful for Classification

Feature ¹	Frequency (cm ⁻¹) ¹	Bandp. (cm ⁻¹)	Wavelength (μ m)	I.P. (ev) ²
MgI(4s-4p)	5843.41	5839-5849	1.71133	7.65
OH($\delta\nu = 2$)	5920:	5910-5930	1.689	4.39
HI(4-11)	5948.50	5940-5960	1.68110	13.60
AlI(4p-4d tr)	5963.76	5960-5985	1.67679	5.99
	5968.31		1.67552	
	5979.60		1.67235	
SiI(5993)	5993.29	5988-5998	1.66853	8.15
¹² CO(8,5)bh	6018	6010-6025	1.662	11.09
¹² CO(6,3)bh	6177	6145-6195	1.619	11.09
SiI(4p-5s)	6263.92	6259-6269	1.59644	8.15
MgI(4s-4p tr)	6341.10	6335-6355	1.57701	7.65
	6347.88		1.57533	
	6351.22		1.57450	

¹ Species identification and frequencies from Atlas of the Solar Spectrum in the Infrared, Livingston and Wallace, 1991, KPNO Observatory Pubs.

² Ionization potentials from Allen (1973).

Table 2.3. H-Band Equivalent Widths for Luminosity Class I–II Stars

Source	T_e ¹	SN	Mg5843	OH	HI	AlI	Si5993	CO8-5	CO6-3	Si6264	Mg6348
HR1903	26000	203	-0.0262	0.0927	0.7459	0.1672	-0.0184	0.1149	0.2720	0.1118	0.4708
HR1903	26000	167	0.0142	0.0678	0.7321	0.1097	-0.0002	0.0891	0.1896	0.1200	0.3182
HR1203	20700	160	-0.0137	0.1216	0.7963	0.1804	0.0056	0.1067	0.2329	0.1070	0.5573
HR1713	11200	218	0.0380	0.0551	1.2741	0.2292	0.0490	0.0897	0.1904	0.1706	0.5024
HR3975	9730	068	-0.0847	0.1111	2.1174	0.2345	0.1171	-0.0868	0.3270	0.1959	0.5766
HR7924	9080	225	-0.0460	0.0001	1.3984	0.1998	-0.0220	0.0264	-0.1413	0.0824	0.0780
HR1865	7700	196	-0.0121	0.2188	2.2055	0.3194	0.1395	-0.1310	0.3019	0.2480	0.5188
HR1017	6640	248	0.0830	0.2523	1.8807	0.4269	0.0609	-0.0213	0.5348	0.4081	1.0531
HR7796	6100	324	0.1035	0.2930	1.5849	0.6855	0.1400	0.0300	0.7937	0.5977	0.9404
HR8232	5510	290	0.0934	0.3676	1.2776	0.6707	0.1742	0.0345	1.1849	0.6723	1.1854
HR8752	5510	084	-0.1305	0.3354	1.1578	0.1364	0.0663	0.0170	0.1602	0.1634	0.4073
α Sge	5333	096	0.1508	0.1265	1.1337	0.7020	0.1007	0.0031	0.9248	0.4054	0.6906
α Sge	5333	109	0.0991	0.2194	1.0721	0.4893	0.1099	0.0161	0.7643	0.5362	1.0378
HR7479	5333	182	0.1262	0.1244	1.0788	0.5599	0.0549	0.0663	0.9422	0.4852	1.0616
HR7479	5333	093	0.0594	-0.0164	1.1954	0.5307	0.0259	0.1433	1.0531	0.5351	0.9346
β Sct	4902	260	0.1671	0.1175	0.9416	0.8358	0.1366	0.2470	1.6587	0.7634	1.0622
θ Lyr	4420	193	0.2293	0.1492	0.8385	0.8821	0.1515	0.4646	2.2483	0.9959	1.5972
θ Lyr	4420	257	0.1549	0.1704	0.6733	0.5858	0.1016	0.3653	1.9094	0.8626	1.3597
93HER	4375	265	0.2153	0.1881	0.8097	0.8020	0.1623	0.3976	1.8622	0.7871	1.2490
HR8465	4295	308	0.1281	0.2850	0.6768	0.6999	0.1917	0.6312	2.3471	1.0229	1.7881
σ Oph	4260	247	0.2362	0.3030	0.8426	0.9996	0.2057	0.8308	2.7522	1.1120	1.8359
HR603	4130	453	0.2384	0.3351	0.6873	0.6063	0.1893	0.4873	2.0912	0.8716	1.4564
63CYG	3990	202	0.2080	0.4514	0.5000	0.6714	0.1358	0.6843	2.2596	0.9428	1.5926
ξ Cyg	3920	445	0.2415	0.6728	0.6172	0.7977	0.2373	1.0488	2.7015	1.0453	1.7156
α Ori	3550	327	0.5371	1.0801	0.3551	1.3909	0.2304	1.4594	3.9208	0.8853	2.2186
HR1155	3450	237	0.4625	1.3091	0.5826	1.1177	0.3828	1.3663	3.3457	1.1151	2.0310
HR921	2980	225	0.7716	1.4136	0.2906	1.2743	0.3742	1.1035	4.0833	0.6653	1.5164
HR7009	2925	292	0.6335	1.4328	0.7878	1.5460	0.5383	1.7876	4.6836	1.2632	2.2061
α Her	2800	319	0.5950	1.4073	0.8017	1.6568	0.5398	1.8490	4.9787	1.3054	2.3142

¹ Effective temperatures taken from the scale of Tokunaga (1996).

Table 2.4. H-band Equivalent Widths for Luminosity Class III Stars

Source	T_{eff}^1	SNR	Mg5843	OH	HI	AlI	Si5993	CO8-5	CO6-3	Si6264	Mg6348
HR1899	32000	164	-0.0327	0.1724	0.5358	0.1550	-0.0393	0.0327	0.1754	0.1049	0.4852
HR1899	32000	182	-0.0402	0.2030	0.6194	0.1089	0.0548	-0.0269	0.0677	-0.0005	0.0699
HR1552	20300	115	-0.0688	0.1295	1.2904	0.3125	0.1003	-0.0871	0.1213	-0.0054	0.0857
HR5291	10100	159	-0.0682	0.1891	2.6501	0.7798	0.0234	0.0498	0.2774	0.1139	0.4083
HR403	8100	202	-0.0183	0.3905	2.7910	0.7743	0.0859	-0.1321	0.2547	0.0826	0.5376
HR1412	7650	186	-0.0229	0.4315	2.7039	0.7137	0.0510	-0.1032	0.6012	0.2497	0.9071
HR4031	7150	193	0.0178	0.2851	2.2951	0.5410	0.1196	-0.0852	0.2504	0.1321	0.4806
β Cas	6870	245	0.0277	0.3151	1.9932	0.5513	0.0413	-0.1065	0.2033	0.2180	0.8212
HR21	6870	179	0.0122	0.2485	2.2055	0.6285	0.1258	-0.1373	0.4601	0.2387	0.6903
HR5017	6700	174	0.0414	0.2787	2.5815	0.8258	0.0681	-0.0289	0.4270	0.3576	0.9565
HR2706	6470	086	0.0076	0.3897	2.0772	0.4680	0.1574	-0.0983	0.1315	0.1955	0.6441
ν Peg	6270	059	0.0598	0.1261	1.0595	0.4485	-0.0122	-0.1641	0.2961	0.2752	1.0178
HR4883	5910	280	0.1488	0.2008	1.0703	0.5176	0.0914	0.0413	0.8981	0.4322	1.0214
HR4716	5050	133	0.1745	0.0997	0.9654	0.4651	0.1323	0.0705	1.2946	0.5413	0.9192
κ Cyg	4885	281	0.1944	0.1999	0.7823	0.5716	0.1122	0.1063	1.3299	0.6659	1.3497
ϵ Cyg	4810	369	0.2076	0.2434	0.7674	0.5866	0.1311	0.1795	1.3909	0.6742	1.3787
HR8317	4710	191	0.2916	0.1380	0.6338	0.5831	0.0798	0.2575	1.7942	0.8263	1.6404
κ Oph	4500	532	0.2557	0.0943	0.7679	0.8126	0.1013	0.4374	1.9161	0.7625	1.3979
HR165	4320	266	0.3375	0.2368	0.6357	0.5796	0.1811	0.4123	1.9822	0.8907	1.4465
γ Dra	3990	298	0.3928	0.5986	0.7686	1.1231	0.2599	0.9620	3.0510	1.1196	1.7549
γ Dra	3990	694	0.4099	0.6140	0.7602	1.0717	0.2546	0.8914	2.8663	1.0553	1.6639
HR152	3956	270	0.3660	0.8610	0.5771	0.9224	0.3445	0.8702	2.5912	0.7798	1.3998
HR4517	3780	673	0.6584	1.0556	0.3300	1.0720	0.2150	0.8867	3.1432	0.7009	1.9319
HR6242	3560	458	0.5174	1.1230	0.5666	1.1819	0.3902	1.4468	3.9270	1.1594	1.9645
HR6702	3420	056	0.4558	0.1539	0.7081	0.8597	0.0059	0.1721	1.3989	0.5707	1.4853
HR7886	3250	574	0.6137	1.5362	0.8875	1.7074	0.6414	2.2537	5.6925	1.4064	2.4218

¹ Effective temperatures taken from the scale of Tokunaga (1996).

Table 2.5. H-band Equivalent Widths for Luminosity Class IV Stars

Source	T_{eff} ¹	SN	Mg5843	OH	HI	AlI	Si5993	CO8-5	CO6-3	Si6264	Mg6348
HR6588	19000	162	-0.0252	0.1002	1.6456	0.4812	-0.0259	0.0238	0.1689	0.0738	0.4022
HR4033	8810	146	-0.0049	0.3345	2.6197	0.7264	0.0553	0.0249	0.2705	0.1325	0.3529
HR1351	7020	094	-0.0646	0.3980	2.1766	0.6165	0.1873	-0.1889	-0.0097	0.1031	0.2365
η Boo	5930	341	0.1594	0.1246	1.2072	0.8260	0.1109	0.0254	1.2967	0.6359	1.1350
HR5235	5930	263	0.1683	0.2631	1.2592	0.6766	0.1768	-0.0142	0.9659	0.4964	1.0328
HR5409	5830	158	0.1583	0.1585	1.0222	0.5137	0.1175	-0.0278	0.9122	0.4390	0.9452
86 μ Her	5680	211	0.3266	0.1199	0.8666	0.8669	0.0943	0.0878	1.2093	0.6947	1.3786
HR995	5620	143	0.2220	0.0837	0.8011	0.6085	0.2299	0.0270	1.0876	0.4753	1.1447
η Cep	5240	189	0.2163	0.0882	0.6813	0.6991	0.0678	0.1495	1.0380	0.4598	0.9903
η Cep	5240	192	0.0894	0.1773	0.5641	0.5198	-0.0088	0.0882	0.7528	0.4045	1.1698
HR5901	5125	395	0.3743	0.1319	0.5521	0.6231	0.0808	0.2115	1.6142	0.7365	1.6011
κ Cr B	5125	153	0.3686	0.0941	0.7473	0.9345	0.1479	0.2998	1.5426	0.7115	1.1290
HR6014	5068	072	0.3134	-0.1197	0.3852	0.5884	0.1415	0.0475	1.1024	0.6986	1.4047
HR6014	5068	133	0.4184	0.1147	0.5809	0.5547	0.1785	0.0930	1.4833	0.6493	1.2446

¹ Effective temperatures taken from the scale of Tokunaga (1996).

Table 2.6. H-band Equivalent Widths for Luminosity Class V Stars

Source	T_{eff}^1	SN	Mg5843	OH	HI	AlI	Si5993	CO8-5	CO6-3	Si6264	Mg6348
HR2456	38000	053	-0.0316	0.3563	0.3873	0.2556	0.1592	0.1186	-0.3227	0.1135	0.3094
HR2456	38000	073	-0.1218	0.1849	0.4773	0.0996	0.0590	-0.1501	0.1472	0.0331	0.1026
HR5191	19000	282	-0.0519	0.1902	1.7063	0.5672	0.0781	-0.0718	0.2212	0.0742	0.2441
HR3982	13000	241	-0.0802	0.1256	2.2210	0.4687	0.0450	-0.0918	0.2798	0.0272	0.1466
HR3982	13000	241	-0.0657	0.0938	2.1447	0.5076	0.0610	-0.0913	0.3240	0.1240	0.2627
HR7001	9480	678	-0.0516	0.3632	2.8261	1.0571	0.0252	-0.0290	0.4051	0.1488	0.5191
HR7001	9480	146	-0.0980	0.3844	2.8112	1.0155	0.0984	-0.0513	0.4282	0.1656	0.4096
HR2491	9145	111	-0.0681	0.3556	2.7149	0.8293	0.1619	-0.1417	0.3671	-0.0754	0.0980
HR2491	9145	148	-0.1353	0.4005	2.6708	0.9255	0.1164	-0.1259	0.3866	0.0498	0.1974
HR4534	8593	205	-0.0444	0.4459	2.6714	1.0117	0.1053	-0.1211	0.3033	0.0716	0.3367
HR4357	8377	192	-0.0539	0.3966	2.8264	0.9624	0.0883	-0.1201	0.2442	0.0614	0.3770
HR4931	6750	119	0.0413	0.2415	1.4689	0.6197	-0.0056	-0.0564	0.0865	0.0897	0.8626
HR1279	6677	080	0.0966	0.3248	1.6218	0.6685	0.1533	-0.0911	0.2609	0.1213	0.6415
HR2943	6530	327	0.0435	0.3346	1.6021	0.5683	0.1522	-0.1419	0.5432	0.2689	0.7356
HR1538	6385	281	0.0569	0.3450	1.2582	0.5258	0.1754	-0.1082	0.5099	0.2205	0.9032
HR4375	6085	254	0.2624	0.1472	0.6346	0.5614	0.1468	-0.0613	0.6837	0.3720	1.0905
HR4983	5930	123	0.2069	0.1586	0.7452	0.6571	0.0924	0.0393	0.7122	0.4525	1.2043
HR4983	5930	173	0.1909	0.2073	0.9023	0.5155	0.1894	-0.0623	0.8714	0.4658	0.9572
HR483	5855	059	0.2362	0.0167	0.6798	0.2886	0.0407	-0.1696	0.1817	0.3691	1.0885
HR483	5855	079	0.2362	0.1895	0.8984	0.4644	0.1935	-0.1058	0.6737	0.4793	1.3044
HR4374	5830	250	0.2753	0.1976	0.6218	0.6274	0.1010	-0.0070	0.8999	0.4708	1.3475
HR5072	5740	197	0.2591	0.1493	0.7442	0.5298	0.1634	-0.0354	0.9915	0.5339	1.2838
HR4496	5430	105	0.3473	0.1731	0.5892	0.5859	0.2077	-0.0818	1.1249	0.6083	1.4510
HR4496	5430	090	0.3146	0.1582	0.3941	0.4970	0.1291	-0.0384	0.6889	0.4298	1.0850
HR7462	5240	131	0.5243	0.0401	0.3768	0.7227	0.0934	0.0929	1.2049	0.6182	1.8893
HR7462	5240	095	0.5069	0.0680	0.3659	0.6866	0.1271	0.0586	1.1645	0.7154	2.0507
HR1084	5010	223	0.6086	0.1870	0.4394	0.7431	0.2424	-0.0089	1.5863	0.7557	2.0019
HR8832	4785	111	0.8817	0.1373	0.2920	1.0634	0.1673	0.1835	1.8822	0.8956	2.5018
GL570A	4340	120	0.9003	0.2230	0.3727	1.1261	0.2786	0.0438	2.0231	0.8996	2.2947
HR8085	4340	125	0.6515	0.1837	0.0080	1.1543	0.1149	0.1492	1.5858	0.6042	2.3800
HR8086	4040	170	0.7177	0.3891	0.0564	1.4615	0.1383	0.1130	1.7765	0.5031	2.0722
HR8086	4040	181	0.7209	0.3224	0.0694	1.4812	0.1520	0.1184	1.8555	0.5176	2.1791
GL338A	3650	072	0.9763	0.3697	0.0765	1.3637	0.1284	0.0249	1.5097	0.3369	1.7953
GL411	3535	202	0.4841	0.5289	-0.0429	1.2943	0.1590	0.0144	1.1702	0.0976	1.1931
GL411	3535	189	0.4735	0.5458	-0.0676	1.2895	0.1799	0.0636	1.2053	0.1202	1.2324
GL526	3180	068	0.6213	0.4159	-0.1290	1.3216	0.1644	0.0958	1.0418	0.0358	0.9233
GL725A	3180	083	0.5153	0.5701	-0.0969	1.1534	0.0574	0.0343	0.9306	-0.0031	0.9944
GL725A	3180	107	0.5411	0.5624	-0.1192	1.2473	0.0199	0.0771	1.1968	-0.0198	1.0926

¹ Effective temperatures taken from the scale of Tokunaga (1996).

In order to quantify the visual impressions made by the spectra, we defined narrow-band indices associated with the dominant spectral features listed in Table 2.2. Because all of our spectra have been normalized, integrating the relative flux over this bandpass results in an effective equivalent width for the feature defined by:

$$EW = \int \frac{I_{cont} - I(\sigma)\delta\sigma}{I_{cont}} \quad (2.3)$$

The widths of these bandpasses varied from 10 to 50 cm^{-1} and were chosen to minimize line blending, contamination from telluric absorption and other unresolved features, and sensitivity to radial velocity shifts (Table 2.2). We examined the behavior of these indices as a function of photospheric effective temperature (T_{eff}) by adopting the scale of Tokunaga (1996) for supergiants, giants, and dwarf stars from stars O7–M5 except for giants earlier than G0 which were taken from Schmidt–Kaler (1982). The indices are plotted in Figures 2.7– 2.15 as a function of T_{eff} in order of increasing frequency and are also tabulated in Table 2.3–Table 2.6 for each star in the survey.

Figure 2.7. Feature equivalent widths plotted as a function of effective temperature for Mg I (4s-4p).

Figure 2.8. Feature equivalent widths plotted as a function of effective temperature for $\text{OH}(\delta v = 2)$.

Figure 2.9. Feature equivalent widths plotted as a function of effective temperature for H I (4-11).

Figure 2.10. Feature equivalent widths plotted as a function of effective temperature for the Al I (4p-4d) triplet.

Figure 2.11. Feature equivalent widths plotted as a function of effective temperature for Si I (5993).

Figure 2.12. Feature equivalent widths plotted as a function of effective temperature for the $^{12}\text{CO}(8,5)$ bandhead.

Figure 2.13. Feature equivalent widths plotted as a function of effective temperature for the $^{12}\text{CO}(6,3)$ bandhead.

Figure 2.14. Feature equivalent widths plotted as a function of effective temperature for Si I (4p-5s).

Figure 2.15. Feature equivalent widths plotted as a function of effective temperature for Mg I (4s-4p tr).

We briefly summarize the empirical trends observed in the data. The Mg I and Si I equivalent widths all show similar behavior. The features increase in strength toward cooler temperatures for stars of higher surface gravity (luminosity classes IV–V) until about 4000K when they begin to decrease in strength toward the latest-type stars. This multi-valued behavior is not obvious in stars of lower surface gravity (luminosity classes I–II and III) as the features continue to grow in strength to very late-types. The OH feature seen in Figure 2.8 shows different behavior in the dwarf star spectra. At $T_{eff} > 5500K$ the $EW[OH]$ appears to increase in strength, however this is only an artifact of its proximity to the Brackett line at 5949 cm^{-1} . Because the Brackett lines are much broader in early-type dwarf stars than in the giants, these lines contaminate the OH and All bandpasses defined here for the early-type dwarf stars. Both the strengths of the $EW[OH]$ and the $EW[All]$ are inversely proportional to T_{eff} for stars $T_{eff} < 5500K$ down to very late types. Similar behavior is seen for the late-type giant stars. The 4–11 Brackett line of HI increases in strength with T_{eff} until it peaks at $T_{eff} = 10,000K$ corresponding to spectral type A0. The second-overtone features of ^{12}CO behave similar to Mg I and Si I in the dwarf star spectra. However, these features are several times stronger in the spectra of giant stars than in the dwarf stars.

We can gain a qualitative understanding of the temperature and surface gravity dependence of these features through straightforward application of the Saha and Boltzman equations governing the population of the ionization states and energy levels respectively. At high temperatures, where most of the species is ionized we expect the Saha equation to dictate the relative line strengths, predicting increased line strength with *decreasing* temperature for these neutral species. At sufficiently cool temperatures, where the species is mostly neutral, the Boltzman factors will determine the level populations, predicting increased line strength with *increasing*

temperature for these energy levels. In dwarf star atmospheres, Mg I and Si I are mostly ionized at $T_{eff} > 4000K$. Here the strength of the features is determined by the fraction of the population that is ionized, which is inversely proportional to T_{eff} . Below $T_{eff} = 4000K$, most of the species is neutral and level populations are fixed by the Boltzman factors giving rise to line strengths proportional to T_{eff} . The ^{12}CO molecule, whose dissociation energy is close to the ionization potential of Mg I and Si I, shows a similar trend. This elementary result can be seen most clearly in Figure 2.9 for the equivalent width of the 4–11 Brackett line of hydrogen. The different behavior of Al I can be understood because the ionization potential of Al I is much lower than that of Mg I or Si I (see Table 2.2). As a result, Al I remains partially ionized down to lower temperatures making it a better thermometer for cool stars. Analogous behavior is seen in the $EW[OH]$ whose molecular dissociation energy is even lower than the ionization potential of Al I. How do we account for the difference between the giant and dwarf star spectra as a function of temperature? It is easier to ionize atoms at lower surface gravities due to the increased number of states available to free electrons in phase space. For example, Mg I and Si I are still partially ionized in the atmospheres of giant stars at temperatures down to temperatures of the coolest stars (2800K). It is important to remember that the stellar effective temperatures do not represent the temperatures of the line formation regions. In particular, because the stellar opacity is dominated by H^- which has a minimum in the H-band, we are seeing deeper into the photosphere at these wavelengths. As a result, the temperatures where the lines are formed are much hotter than the effective temperatures of the stellar photospheres ($T \sim 1.5 \times T_{eff}$; Origlia, Moorwood, and Oliva, 1993).

The trends of ^{12}CO band-strength with surface gravity require more subtle explanations. According to the models of Origlia, Moorwood, and Oliva (1993) the second-overtone features in the H-band behave much differently than the

first-overtone CO features in the K-band. Because the first-overtone bands are saturated, broadening of the features due to microturbulence in the stellar atmosphere spreads the opacity over a larger frequency interval enhancing the observed equivalent width (McWilliams and Lambert, 1984). As microturbulence increases with decreasing surface gravity, these lines are stronger in giant stars than dwarf stars. However the $^{12}\text{CO}(6,3)$ bandhead may be a more direct tracer of surface gravity. Because this bandhead is *not* strongly saturated the line strength is proportional to $N_{12\text{CO}}$, the column density of ^{12}CO in the stellar atmosphere, as integrated from the line formation region to the outer atmosphere. The depth of this line formation region is fixed by the H^- opacity. N_{H^-} is proportional to the electron pressure, which in turn goes as cube-root of the surface gravity (Gray, 1992). Thus high surface gravity results in large H^- column density bringing the line formation region of the CO closer to the stellar surface and reducing $N_{12\text{CO}}$:

$$P_e \sim g^{1/3} \sim N_{\text{H}^-} \sim 1/N_{\text{CO}} \quad (2.4)$$

More careful study of this issue is required before the conjecture that the second-overtone features are superior to the first-overtone features as probes of surface gravity can be confirmed.

2.1.4 Two-Dimensional Spectral Classification

Clearly the H-band contains many features that are potentially useful for stellar classification. One might consider simply measuring two equivalent widths, one temperature sensitive and one luminosity sensitive, comparing these equivalent widths to those collected for a grid of standard stars such as presented in Table 2.3–Table 2.6, and deriving a spectral type and luminosity class. However it is worthwhile devising a more sophisticated scheme for two reasons. First, certain combinations of features may enhance ones ability to estimate stellar parameters

either removing the ambiguities in deriving T_{eff} from the relations shown in Figures 2.7– 2.15 or relaxing the required SNR necessary for accurate classification. Secondly, our primary goal is to construct a method for deriving spectral types for stars that cannot be observed in the optical. Two important classes of such objects, embedded young stellar objects and obscured evolved stars, may suffer from excess continuum emission in the near-infrared. As a result, straight equivalent widths which can be filled-in by these continuum excesses can be misleading⁶. We would prefer a system of *line ratios* for classifying stellar spectra in the near-infrared.

Guided by the behavior of the spectra discussed in the previous section certain features as a function of stellar parameters, we searched for temperature- and luminosity-sensitive combinations of the features listed in Table 2.2 that could be expressed as line ratios. We present the following as preliminary two-dimensional classification planes for late-type stars. For cool stars from K3–M5 we have identified the following two-dimensional plane:

$$\frac{EW[OH]}{EW[MgI(4s-4ptr)]} vs. \frac{EW[^{12}CO(6,3)+^{12}CO(8,5)]}{EW[MgI(4s-4ptr)]} \quad (2.5)$$

as illustrated in Figure 2.16. Here we have made use the temperature dependence of the OH feature at 5920 cm^{-1} ($1.689 \text{ }\mu\text{m}$) and divided it by the Mg I triplet at 6348 cm^{-1} ($1.575 \text{ }\mu\text{m}$) which has the opposite dependence for very cool stars. This not only provides a veiling-independent line ratio, but also improves upon the temperature sensitivity of the OH index alone. Along the ordinate we plot the sum of two ^{12}CO bands, the (8, 5) and (6, 3) which are luminosity sensitive, again divided by the Mg I feature. The ability to distinguish between giant and dwarf stars is clear and although there is some scatter along the temperature axis, formal errors in the EW suggest that this relationship can estimate spectral types within

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This process is observed in the optical for YSOs and is known as spectral “veiling”.

± 2 subclasses from K3–M5 using spectra with $SNR > 50$. For stars from G0–K3 we suggest the following classification plane:

$$\frac{EW[Mg\,I(4s-4p)]}{EW[Si\,I(4p-5s)]} \text{ vs. } \frac{EW[^{12}CO(6,3)]}{EW[Mg\,I(4s-4p)]} \quad (2.6)$$

presented in Figure 2.17. While both the $EW[Mg\,I(4s-4p)]$ and $EW[Si\,I(4p-5s)]$ increase in strength toward cooler temperatures in this range, the ratio is only temperature sensitive for dwarf stars. Along the y-axis we again make use of the $EW[^{12}CO(6,3)]$ as a luminosity discriminant divided by the $EW[Mg\,I(4s-4p)]$. While this diagram is not as diagnostic as that shown in Figure 2.16. it does distinguish giants from dwarf stars as well as provide an estimate of the photospheric temperature for dwarf stars.

Figure 2.16. Two-dimensional spectral classification for late-type stars K3-M5 using diagnostic line-ratios based on spectra with $SNR > 50$.

Figure 2.17. Two-dimensional spectral classification for stars G0-K3 using diagnostic line-ratios based on spectra with $SNR > 50$.

For stars earlier than G0 there are fewer features available at our moderate resolution and the formation of line ratios is not practical. The strength of the Brackett lines provides an estimate of photospheric temperature albeit multi-valued about $T_{eff} = 10,000K$. The presence of a He I absorption feature at 5882 cm^{-1} ($1.700\text{ }\mu\text{m}$) for stars earlier than B5 can help remove the ambiguity at high enough resolution and adequate SNR. Luminosity class is derived for these early-type stars on the basis of the shape of the Brackett lines as is done at optical wavelengths with the Balmer line profiles. Dwarf stars of higher surface gravity have stark-broadened H I absorption lines due to the increased electron pressure, while giant stars have narrower features in contrast.

2.1.5 Summary

We have described our efforts to produce an H-band atlas of spectral standards comparable to the Kleinmann and Hall (1986) K-band atlas. This atlas spans a wide range in stellar temperature (2,800–38,000K) and surface gravity ($\log[g] = 1.0 - 5.0$). The spectra contain a number of atomic and molecular features which are temperature and/or luminosity sensitive. In particular, the lines of OH and Al I increase in strength with decreasing temperature from K3–M5. While the atomic lines of Mg I and Si I are also temperature sensitive in late-type stars, they have a more complex behavior. This behavior can be qualitatively understood from straightforward application of the Saha and Boltzman equations. In early-type stars, the Brackett series of atomic hydrogen is prominent and a He I feature is seen in stars earlier than B5. For stars later than G0, the second-overtone features of ^{12}CO are sensitive to surface gravity and thus provide a determination of luminosity class. Based on these data, we recommend a two-dimensional classification plane for stars G0–K3 and another for stars K3–M5 that relies on line ratios rather than direct equivalent widths in order to estimate

stellar temperature and luminosity class. Based on this analysis, we conclude that; i) the H-band is an extremely promising wavelength regime for stellar classification; and ii) with $SNR \sim 50$ at a resolving power of $R \sim 3000$ one can classify late-type stars on the MK system within ± 2 subclasses.

2.2 Lower Resolution Spectroscopy in the H- and K-Bands

Our goal is to derive photospheric effective temperatures of optically-invisible young stellar objects deeply embedded in molecular cloud cores. This will allow us to place them in the H-R diagram and estimate their masses and ages. Based on the survey of Kleinmann and Hall (1986) and the H-band survey discussed above, we have concluded that spectral types can be inferred from both H- and K-band spectra of $SNR > 50$ at a resolving power of $R = 3000$. However, infrared photometric surveys ($R \sim 6$) of deeply embedded young clusters routinely reach flux-limits well beyond the limiting magnitudes of existing IR grating spectrographs ($R \sim 200 - 3000$). As a result, we are forced to observe cluster members at the lowest resolution possible. In designing our spectroscopic survey, we needed to define three parameters that are related in a complicated way; i) wavelength coverage; ii) resolving power; and iii) signal-to-noise ratio in order to derive accurate spectral types for embedded sources.

It is not obvious whether the H- or K-band spectral region is superior for deriving spectral types on the basis of near-IR spectra. The K-band flux of embedded sources experiences less extinction from intervening dust than in the H-band:

$$A_K = 0.6 \times A_H = 0.1 \times A_v \quad (2.7)$$

Despite this tremendous advantage, the K-band has the drawback that YSOs are known to have substantial continuum excess emission at $2.2 \mu\text{m}$ (Strom *et al.*, 1989) which can fill-in photospheric absorption features. Although the H-band

may suffer from the same problem, it is expected to be worse at longer wavelengths (see Chapter III). Concerning the intrinsic properties of each spectral region, the H-band has a larger number of strong features in a small wavelength range useful for stellar classification. However, the K-band contains a few key features which are very diagnostic; i) the Na I doublets at 2.206 and 2.34 μm are expected to be good temperature indicators for very late-type stars because of the low ionization potential of sodium; ii) the first-overtone ^{12}CO bands are quite prominent even at low SNR and are sensitive to surface gravity; and iii) the Br γ line is seen in emission in the spectra of many YSOs and may be a useful indicator of accretion activity (Carr *et al.*, 1990). Because of the difficulty in making a decision between the H- and K-band spectral regimes, we chose to survey both in our analysis of embedded cluster members.

Although driven to lower resolving power, we cannot observe at such low resolution that we lose our ability to classify the spectra. As more features become blended with our temperature and luminosity sensitive lines, they lose their diagnostic qualities. Furthermore weak lines will simply disappear, being dominated by continuum fluctuations at low resolution. Based on the previous K-band work of Kleinmann and Hall (1986; $R = 3000$), the H-band work of Origlia, Moorwood, and Oliva (1993; $R = 1500$), and the H/K work of Lancon and Rocca-Volmerange (1992; $R = 500$), as well as our H-band MK standards survey ($R = 3000$), we chose an intermediate resolving power of $R = 1000$ for our embedded cluster spectral survey as a suitable compromise between ; i) higher SNR (lower resolution); and ii) ability to resolve nearby lines and detect weak features (higher spectral resolution). We set out to achieve high signal-to-noise ratios compared to traditional optical spectroscopic work ($SNR \sim 50$).

Table 2.7. Journal of Observations for the KPNO CRSP Survey

Date	Telescope	Platescale	Seeing	Weather
February 25–March 1, 1994	2.1m	0.61''	2.0–3.0''	Marginal.
December 15–19, 1994	2.1m	0.61''	1.0–2.0''	Mostly clear.
January 17–18, 1995	4.0m	0.36''	1.0–3.0''	Marginal.

2.2.1 Observations and Data Reductions

Our low resolution near-IR spectroscopic survey was conducted at the Kitt Peak National Observatory, Arizona. We observed our brightest target objects during two runs on the 2.1m telescope in February, 1994 and December, 1994. This was followed by a single run on the 4.0m telescope in January, 1995 in order to observe our lowest luminosity targets. We used the Cryogenic infraRed Spectrograph (CRSP) following the upgrade of the detector to a 256×256 format InSb infrared-array. CRSP is an infrared grating spectrometer used with the $f/15$ secondary of the 2.1m and 4.0m telescopes. A field mirror is used to form an image of the telescope at a cold stop prior to the introduction of the slit, reducing contributions to the background from stray radiation. The spectrograph consists of a collimating mirror, grating, and an achromatic triplet camera lens which images the spectrum onto the detector. We chose grating # 1 (300 l mm^{-1}) blazed at $4.0 \mu\text{m}$ with the standard H- and K-band as order sorting filters. This provided a resolution of $6.8 \times 10^{-4} \mu\text{m pixel}^{-1}$ in the H-band and $5.1 \times 10^{-4} \mu\text{m pixel}^{-1}$ in the K-band in second order. Slit # 4 ($270 \mu\text{m}$ wide) sub-tended 2.7 pixels on the array resulting in a final resolving power of $R = 900$ in the H-band and $R = 1500$ in the K-band ⁷. Additional observing information and telescope dependent parameters are listed in Table 2.7.

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The reader is referred to the CRSP Spectrometer Users Manual, 1994, by Dick Joyce, KPNO, for further details.

The observing set-up was fixed early in the first run to insure that the spectra were obtained in a uniform way. Our observing procedure was to first mark the fiducial position of the slit with respect to a visible-light acquisition camera using a bright optically-visible star in zero-order where the grating acts as a mirror producing an image of the star. The slit position was checked every two hours or after large telescope slews. For optically-visible stars, sources were directly placed on the slit using the acquisition camera. For optically-invisible sources that were infrared-bright ($m_K < 10^m$) we merely adjusted the position of the source in the slit in order to peak-up the source counts. The preferred acquisition method used for fainter stars ($10^m < m_K < 12^m$) was to move the grating to zero-order and verify directly that the star was centered on the slit. If available, a guide star was acquired for exposures of 10 seconds or more. After checking the orientation of the instrument with respect to the telescope, spectra were obtained at five positions along the slit using guided offsets of the telescope of 10.0 arcsec and 7.0 arcsec per step for the 2.1m and 4m respectively. The slit was oriented east-west in order to minimize the effect of tracking errors on the signal level. In most cases five independent source spectra were obtained in each of three grating/filter combinations: H/2283 ($1.55 - 1.72\mu\text{m}$); K/3162 ($2.12 - 2.25\mu\text{m}$); and K/3343 ($2.23 - 2.36\mu\text{m}$). A complete set of observations was obtained before the next source was acquired.

Flat-field calibration frames were obtained by observing a dome target both with the dome lights on and off. The lights-off frames provided background measurement including dark and bias. Calibration spectra were obtained using arc lamps configured for use with existing optical spectrographs. These included the helium-neon-argon and thorium-argon lamps. Images were obtained both with the lamp lights on and off. A set of bright A0 standard stars was observed in order to correct for telluric absorption features. These standards were observed

to correct for telluric absorption features. These standards were observed throughout the night at a variety of airmass values.

The two-dimensional infrared-array images were processed using the IRAF. Because the length of the CRSP slit does not fill the array, all images were trimmed to the usable slit length of 135 pixels. The upgraded CRSP InSb array (manufactured by Santa Barbara Research Corporation) has a calibrated non-linear behavior when the detector wells reach above half of the full-well value of $94,000 \text{ e}^-$. We used the IRAF task IRLINCOR within the CTIO package in order to correct for this effect using coefficients provided by Dick Joyce of KPNO. Flat-field frames were constructed for each filter/grating combination in the following manner. First the “domeoff” frames were median filtered and subtracted from the “domeon” frames. This not only removes the dark current and residual bias offsets but also removes any thermal emission from the telescope. The differenced frames were then median filtered, corrected for bad pixels, and normalized to the mean. Each group of five data-frames corresponding to a set of spectra taken with a fixed filter/grating combination, was median filtered yielding a background frame containing both thermal background as well as molecular line emission from OH and O₂ (Oliva and Origlia, 1992). These background frames were subtracted from each dataframe. The differenced frames were divided by the appropriate normalized flat-field and bad pixels were interpolated over.

The arc lamp spectra were used for two purposes; i) to determine a dispersion solution in the spectral dimension; and ii) to correct for spatial distortions along the slit. The images of the arc lamp spectra were processed in a manner similar to that used for the domeflats. Using the IRAF package LONGSLIT, low order polynomials ($n = 2 - 3$) were fit in both dimensions to the arc lamp spectra taken

Because the readout scheme of the array is based on a double-correlated sampling algorithm (reset-read-integrate-read) the calibration of this non-linearity is not valid for short exposures of bright stars.

throughout the night, which all agreed within the errors at each grating/filter combination except for small linear shifts. In the H-band setting 2283, seven lines were used from the HeNeAr lamp. The K-band, seven lines were used for the 3162 setting and only three lines were used for the 3343 setting resulting in a fit with larger residual errors. The fits were applied to the dataframes using a coordinate transformation defined from the arc lamp templates.

The spectra were extracted using the IRAF task APALL. Apertures were automatically identified, centered, and edited by hand for verification. The default aperture size was ± 5 pixels and the background was fit linearly from nearby sampling regions and subtracted from the extracted spectrum. A 5th-order polynomial function was used to trace the spectra across the array, stepping every ten pixels. Because the dispersion solution was coded into the image headers as part of the transformation, these extracted spectra were wavelength calibrated. However, we noticed small shifts in the dispersion solution through the night due to small errors in grating repeatability and instrument flexure. Thus it was necessary to apply linear shifts to the dispersion solutions in order to match the telluric features of our atmospheric standards and program stars. Shifts were determined by comparing the position of telluric absorption features in common to all spectra to the position of those features in our telluric standard stars. This procedure worked well for high signal-to-noise spectra. For low SNR data where we were unable to determine reliable shifts, they were not applied to the dispersion solution which resulted in poor telluric correction with the procedures described below.

Finally telluric features were removed using two techniques; one for the H-band grating setting and another for the K-band settings. For each grating setting, the atmospheric opacity was calculated from ratioed spectra of an A0 standard star taken at different airmass. The derived opacities are shown in Figure 2.18–Figure 2.20 at a resolving power of $R \sim 1000$. The H-band data was

corrected for telluric absorption using a procedure identical to that described for the FTS survey above. Telluric corrections were calculated assuming that the opacity was linearly proportional to airmass and applied. This procedure removed most H-band atmospheric absorption features however was not a complete success for the strongest telluric lines. The K-band data were corrected by simply dividing each spectrum by that of a featureless early-type star taken at similar airmass. At grating setting 3343, this was straightforward as our A0 standard stars have no photospheric absorption features in this wavelength region. However, the Br γ feature appears in the 3162 grating setting complicating the procedure. We performed a two-component gaussian fit to the Br γ line profile in order to remove it from our telluric early-type standard stars. This worked well providing telluric templates that varied only as a function of airmass and did not induce unusual Br γ line behavior in our MK spectral standards ⁹. In general the removal of the K-band telluric absorption features was more successful than the H-band procedure.

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This procedure was not practical for the H-band due the the large number of Brackett lines in this wavelength region.

Figure 2.18. Atmospheric opacity at our grating setting of H/2283 at $R = 1000$: The opacity was derived from ratios of high signal-to-noise spectra of the same star observed at different airmass as discussed in the text.

Figure 2.19. Atmospheric opacity at our grating setting of K/3162 at $R = 1000$: The opacity was derived from ratios of high signal-to-noise spectra of the same star observed at different airmass as discussed in the text.

Figure 2.20. Atmospheric opacity at our grating setting of K/3343 at $R = 1000$: The opacity was derived from ratios of high signal-to-noise spectra of the same star observed at different airmass as discussed in the text.

2.2.2 Stellar Classification

We used two approaches in order to derive spectral types for young stellar objects from near-infrared spectra obtained with CRSP. The first approach, similar to the techniques described above for two-dimensional spectral classification from our FTS H-band spectral standards survey, relies on comparing temperature and luminosity sensitive line-ratios measured for our program stars with those obtained for a grid of spectral standards. The second approach, while less quantitative, makes use of all the spectral information in comparing our program stars on a feature by feature basis to our two-dimensional grid of spectral standards; visual classification. Our sample of spectral standards was selected from the same primary sources as our H-band MK standard star survey with additional late-type stars added from the list compiled by Ali *et al.* (1995). We observed 33 MK standards covering luminosity classes I-III (14 stars), and IV-V (19 stars) evenly spaced in effective temperatures corresponding to spectral types 07-M5. This range of standards covers basically the same regions of the H-R diagram as that shown in Figure 2.1, however supergiant stars are not well sampled in our lower resolution survey. Representative spectra for our standard stars are shown in Figure 2.21–Figure 2.23 (giant stars) and Figure 2.24–Figure 2.26. (dwarf stars) for each grating setting.

Figure 2.21. Representative H- and K-band spectra of MK standards of luminosity class III for wavelength setting H/2283 at $R = 1000$.

Figure 2.22. Representative H- and K-band spectra of MK standards of luminosity class III for wavelength setting K/3162 at $R = 1000$.

Figure 2.23. Representative H- and K-band spectra of MK standards of luminosity class III for wavelength setting K/3343 at $R = 1000$.

Figure 2.24. Representative H- and K-band spectra of MK standards of luminosity class V for wavelength setting H/2283 at $R = 1000$.

Figure 2.25. Representative H- and K-band spectra of MK standards of luminosity class V for wavelength setting K/3162 at $R = 1000$.

Figure 2.26. Representative H- and K-band spectra of MK standards of luminosity class V for wavelength setting K/3343 at $R = 1000$.

For our quantitative classification criteria, we adopted the same H-band features as outlined above for the FTS MK standards survey. In the K-band, we identified features in our spectra that are temperature and luminosity sensitive according to the standard star atlas of Kleinmann and Hall (1986). This set of features is nearly the same as those used by Greene and Meyer (1995) in their low resolution ($R = 500$) near-IR spectroscopic survey of embedded sources in the Ophiuchus dark cloud (see Chapter V). However, because of our higher resolution we were able to include the weak Mg I feature at $2.28 \mu\text{m}$ and the Na I feature at $2.35 \mu\text{m}$ in our study (see Table 2.8. We measured equivalent widths for these features using the IRAF task SPLOT setting the continuum levels by hand for all measurements. We were able to confirm the behavior of the H-band features found from the FTS survey at lower resolution. In particular the diagnostic line ratios discussed above provide similar estimates of effective temperature and luminosity at $R = 1000$ as that found at $R = 3000$. In the K-band, we used similar temperature and luminosity indices defined in Greene and Meyer (1995) except that we divided their indices by the MgI feature at $2.28 \mu\text{m}$ in order to form a line ratio. This Mg I feature shows behavior similar to the magnesium features in the H-band, increasing in strength with decreasing T_{eff} until the relationship turns over at about 4000K. Our two-dimensional K-band classification plane for late-type stars is:

$$\frac{EW[NaI+CaI]}{EW[MgI]} v.s. \frac{EW[^{12}CO(2,0)+^{12}CO(3,1)+^{12}CO(4,2)]}{EW[MgI]} \quad (2.8)$$

Here the Na I and Ca I equivalent widths trace effective temperatures down to the latest type stars while the first-overtone CO features are surface gravity sensitive.

Spectral types can also be estimated from visual classification. By comparing each program star to our grid of spectral standards normalized to the same scale, we can derive either a “best fit” classification or an upper/lower limit on the effective temperature based on the presence or absence of certain features in each

wavelength region. For example, the presence (absence) of first-overtone CO features in the K/3343 spectrum suggest a spectral type later (earlier) than G0–K3, depending on the signal-to-noise of the spectra. As another example, the presence of Brackett absorption lines in the H/2283 spectrum indicates a spectral type earlier than F0–G0. Again the lower limit placed on T_{eff} is dependent on the signal-to-noise. Note that for YSOs, we cannot use the absence of Brackett absorption as an upper limit to T_{eff} because it is possible that emission can fill-in the Brackett lines as is the case with the Herbig Ae/Be stars (see next section). Treating the three grating settings independently, we can derive plausible ranges of spectral types for our program stars. We then take the median value as the adopted spectral type and the range of plausible spectral types as the associated error. Because the range of possible spectral types is signal-to-noise dependent, those with the lowest SNR will have the largest associated uncertainties. Although the derived spectral types appear quite robust, this process is not without systematic uncertainties which are hard to quantify. For example, one needs to keep in mind the position of strong telluric absorption as well as night sky emission lines. These regions typically have lower SNR than the bulk spectrum and should be given less weight in deriving spectral types. Finally, we note that visual classification is implicitly a line-ratio technique which relies on distinguishing patterns of features which should be insensitive to continuum veiling of the features. However in low SNR spectra that contain few distinguishable features, late-type stars that exhibit strong continuum excess emission could be misclassified as earlier-type stars with weaker atomic and molecular absorption features.

2.2.3 Classification of YSO Spectra in the Near-IR

Because of the pre-main sequence nature of young stellar objects, we might anticipate some difficulties in applying the classification scheme outlined above. In

particular, YSOs are known to exhibit continuum infrared excess emission at wavelengths beyond $1\ \mu\text{m}$ (Strom *et al.*, 1989). This excess emission could fill-in stellar photospheric absorption features resulting in anomalous spectral types derived from measurements of line strength. Even using a method based on line-ratios could be susceptible to strong gradients in the veiling emission as a function of wavelength. At optical wavelengths, the most active YSOs exhibit intense line emission indicative of active accretion processes. Such emission at infrared wavelengths could also complicate our classification scheme if they contaminated a substantial fraction of the spectral region under study. Finally, because T Tauri stars and other YSOs have not yet reached the main sequence (presumably having larger stellar radii) they should have surface gravities somewhere in between giants and dwarf stars. As a result, if some of our temperature indices are also sensitive to surface gravity, we might expect systematic errors.

In order to look for these and other unforeseen effects, we set out to collect a set of near-infrared spectra of optically-visible young stellar objects with the goal of comparing spectral types derived in the infrared to those obtained in the optical. We selected a sample of low mass T Tauri stars with evidence for active accretion (classical T Tauri stars; CTTS) and those lacking evidence for accretion (weak-emission T Tauri stars; WTTS) from the list of Strom *et al.* (1989). In addition we observed a sample of more massive Herbig Ae/Be stars from the list of Hillenbrand *et al.* (1992). These objects were chosen to sample a range of T_{eff} , as derived from optical spectroscopy, and a range of accretion rates, as inferred from photometric infrared excess. We observed a sample of 32 CTTS and WTTS as well as 16 Herbig Ae/Be stars in a mode identical to our MK standard stars described above. Results from this survey will be described elsewhere. We present a subset of these data here, deriving spectral types for the nine T Tauri stars and five

Table 2.8. K-band spectral Features Useful for Classification			
Species ¹	Frequency (cm ⁻¹)	Wavelength (μm)	I.P. (ev) ²
HI(4-7)	4616.56	2.16612	13.60
NaI(4s-4p db)	4532.59	2.20624	5.14
	4527.00	2.20897	
CaI(4d-4f tr)	4422.02	2.26141	6.11
	4418.69	2.26311	
	4413.58	2.26573	
MgI(4d-6f)	4383.26	2.28141	7.65
¹² CO (2,0)	4360.09	2.29353	11.09
¹² CO (3,1)	4305.36	2.32269	11.09
NaI(4p-4d db)	4281.77	2.33548	5.14
	4276.15	2.33855	
¹² CO (4,2)	4250.87	2.35246	11.09

¹ Species indentification and frequencies from Kleinmann and Hall (1986).

² Ionization potentials from Allen (1973).

Herbig Ae/Be stars listed in Table 2.8. Representative spectra are shown in Figure 2.27–Figure 2.29.

Figure 2.27. Representative H- and K-band spectra of optically-visible young stellar objects for wavelength setting H/2283 at $R = 1000$.

Figure 2.28. Representative H- and K-band spectra of optically-visible young stellar objects for wavelength setting K/3162 at $R = 1000$.

Figure 2.29. Representative H- and K-band spectra of optically-visible young stellar objects for wavelength setting K/3343 at $R = 1000$.

We performed two independent classifications of these spectra visually and checked the results using the quantitative methods described above. The results of the visual classification of the infrared spectra agreed to within the errors quoted by both participants and are quoted in Table 2.8 along with the spectral types derived from optical spectra. Spectral types derived for the T Tauri stars in the infrared, both classical and weak-emission, agreed quite well with the optical determinations. This is illustrated in Figure 2.30 where we plot the effective temperature derived from optical spectroscopy against that derived from the IR spectra. In only two cases, did the spectral types derived from the infrared and optical differ significantly; for the early-type T Tauri star W 108 in NGC2264, and the peculiar CTTS BM And. The IR spectral type adopted for W 108 is $F0 \pm 5$, the large error bars being typical for our IR classification of early-type stars. The optical spectral type is reported to be F9 for W108, however is denoted to be uncertain. There is some evidence that the spectral type of BM And varies with wavelength in the optical. Walker (1980) quotes a spectral type of G0 in the blue, while Herbig (1977) reports a spectral type of K5 in the red. Further this star is variable at optical and infrared wavelengths and has an infrared excess (Cohen and Schwartz, 1976). We assigned a spectral type of $K0 \pm 2$ based primarily on the H-band spectrum. There is no evidence for strong emission-line activity in our spectra although it may have Br γ emission. Given the presence of late-type features in the H-band, it is unusual that we do not observe the first-overtone ^{12}CO features in the K-band. We conclude that our IR spectral type could be affected by excess IR emission, suggesting that it provides an upper limit on the photospheric temperature of the star. Examination of the luminosity class of these T Tauri stars reveals that they are intermediate between dwarf stars and giants, although they are closer to dwarf stars than giants. This can be seen through the behavior of the CO features, which are stronger than expected for the derived

spectral types. However, in most cases no consistent solution could be made from the sequence of giant star standards given the behavior of the temperature sensitive lines. Similar results have been obtained from high resolution optical and infrared spectroscopic studies of T Tauri stars (Basri and Bathala, 1990; see also Appendix B).

Figure 2.30. T_{eff} as derived from optical spectroscopy compared to values derived from infrared spectra for the YSOs listed in Table 2.9.

Table 2.9. Optically-visible YSOs Observed with CRSP

HBC	Source	Sp. Type (OPT)	Type	¹ EW(H α ¹)	² Sp. Type (NIR)
199	MWC 137	B0	HAeBe GrI	pr	< G0
317	MWC 1080	B0	HAeBe GrI	-75	< G0
193	LkH α 208	B7	HAeBe GrI	-8	< G0
3	LkH α 198	A5	HAeBe GrII	-85	< G0
325	V376 Cas	F0	HAeBe GrII	-37	< G0
???	SAO 76428	F8	WTTS	1.3	G2 $\pm$ 2
222	W 108	F9:	CTTS:	pr	F0 $\pm$ 5
388	TAP 35	K1	WTTS	0.5	K2 $\pm$ 2
318	BM And	K5:	CTTS	-25	K0 $\pm$ 2
378	V819 Tau	K7	WTTS	-1.7	M0 $\pm$ 2
379	LkCa 7	K7	WTTS	-4	M0 $\pm$ 2
38	DH Tau	M0	CTTS	-53	M2 $\pm$ 2
39	DI Tau	M0	WTTS	-2	K7 $\pm$ 2
55	GH Tau	M2	CTTS	-15	M0 $\pm$ 2

¹ Data for Herbig Ae/Be stars (HAeBe) from Hillenbrand *et al.* (1992) and the Herbig-Bell Catalogue (1988). Data for T Tauri stars from Strom *et al.* (1989) and the Herbig-Bell Catalogue (1988).

² Positive H α equivalent width indicates absorption and negative indicates emission.

We were unable to derive accurate spectral types for the Herbig Ae/Be stars in our sample. These stars show active emission-lines in the optical as well as a few weak photospheric features which permit classification of their early-type spectra (Hillenbrand, 1995). They also have strong IR excess emission (Hillenbrand *et al.*, 1992). Our IR spectra essentially show no photospheric absorption features in the infrared and display a wide variety of emission-line properties (see Table 2.9).

Without knowledge of their intrinsic nature, we would have assigned lower limits to their effective temperatures (< G0). However we note that it would be very difficult to distinguish between an early-type star with Brackett emission lines, and a heavily-veiled late-type star also with Brackett emission.

Our quantitative indices generally agreed with our visual classification yielding spectral types consistent with those derived from optical spectroscopy. We examine results for two T Tauri stars in detail. DH Tau and DI Tau are both found to be M0 stars in the optical. However DH Tau has IR excess and emission-lines indicative of active accretion (CTTS) while DI Tau lacks such evidence (WTTS). Based on our quantitative H-band temperature index $EW(OH + AlI)/EW(MgI)$, we assign DH Tau $T_{eff} = 3500K$ (M2) and DI Tau $T_{eff} = 3800K$ (M0). Using the K-band temperature index $EW(NaI + CaI)/EW(MgI)$, we derive for DH Tau $T_{eff} = 3800K$ and DI Tau $T_{eff} = 3500K$, in reasonable agreement considering that the formal errors in the effective temperatures give errors in T_{eff} of ± 300 (± 2 subclasses). Concerning the luminosity class based on our H-band surface gravity index $EW[^{12}CO(8,5) + ^{12}CO(6,3)]/EW[MgI]$ we conclude that these two T Tauri stars are intermediate between dwarf stars and giants, although they are closer to the dwarf star locus. Similar results are obtained from analysis of the K-band surface gravity indicators. Thus for stars of adequate signal-to-noise, both techniques yield identical results in both the H- and the K-bands. This provides a quantitative check on our visual classification technique.

The signal-to-noise of the EW measurements varies between 10–30 for bright T Tauri stars. These errors are derived from the standard deviations calculated from measurements of five independent spectra. The errors appear to be dominated by systematic uncertainties in defining the continuum and do not reflect the SNR of the spectra. The signal-to-noise of the YSO spectra varies from $SNR \sim 20 - 50$ per resolution element. This appears to be dominated by systematic errors such as those induced during the removal of the telluric absorption features. In examining results for stellar spectra of lower SNR, we find that the errors in equivalent width are considerably greater and our line ratio techniques do not have the diagnostic power exhibited by our visual classification.

For this reason, we adopt the results of our visual classification technique for stars with low SNR spectra.

Because both DH and DI Tau have the same spectral type, yet different infrared excess properties, we might expect to see evidence for continuum excess emission veiling the features of DH Tau. Although there is no evidence for this in the H-band, it is clear that the K-band features of DH Tau are not as strong as those observed for DI Tau. Attempts to quantify this effect using the methods outlined in Appendix B proved difficult. At wavelengths $\lambda > 2.25\mu\text{m}$ we were able to measure the ratio of excess to stellar continuum emission:

$$r_K = (F_{KEX}/F_{K*}) = 1.5 \pm 1.0 :$$

It is interesting to note that although GH Tau is also a late-type star with evidence for active accretion similar to DH Tau, there is no evidence for continuum veiling in its spectrum at wavelengths $\lambda < 2.35\mu\text{m}$. Deriving the ratio of continuum excess to stellar photospheric emission for T Tauri stars as a function of wavelength in the infrared could provide important constraints on the distribution of dust in their circumstellar disks. Higher resolution observations are needed to confirm these results (see also Appendix B).

2.2.4 Summary

We briefly summarize the results derived from our low resolution infrared spectroscopic study of spectral standards and optically-visible young stellar objects. We conducted an $R = 1000$ survey of MK standards in the H- and K-bands in order to devise a classification scheme for stellar spectra at low resolution in the near-infrared. Temperature and luminosity sensitive features appear in both the H- and K-bands at this resolution. Using visual classification of the spectra as well as quantitative classification schemes based on ratios of

equivalent widths, it appears that stellar spectra of $SNR \sim 20$ can be classified to within a few subclasses. The H-band is more useful for classification of early-type stars ($< G0$) and in principle can provide quite accurate spectral types. However, it requires at least $SNR \sim 20$ at this resolution in order to take full advantage of the diagnostic possibilities. The K-band spectral region has two advantages over the H-band; i) the correction for telluric absorption, which appears to limit the SNR of the spectra, is straightforward; and ii) it contains a few features which are very diagnostic in placing broad constraints on the range of spectral types possible for a given star, even at low SNR. However, it would be difficult to obtain very accurate spectral types (± 1 subclasses) from K-band spectra of $R = 1000$ even at high SNR .

Despite the pre-main sequence nature of T Tauri stars, our techniques for deriving spectral types from $R = 1000$ near-infrared spectra agree within the observational errors to those obtained from optical spectra for late-type stars ($> F0$). However, Herbig Ae/Be stars have near-infrared spectra consisting of a featureless continuum plus emission-lines. As a result it would be impossible to distinguish Herbig Ae/Be spectra from the spectra of heavily veiled late-type stars in the infrared. Secondly, YSOs appear to have surface gravities similar to dwarf stars, although the spectra do exhibit some “giant-like” characteristics such as enhanced CO absorption in late-type stars. Finally, it appears that a resolving power of $R = 1000$ is not high enough to accurately measure the ratio of continuum excess to stellar photospheric emission. We conclude that we can estimate spectral types for young stellar objects based on $R=1000$ H- and K-band spectra to within ± 3 subclasses for $SNR \sim 20$.

CHAPTER 3

EMERGENT MASS DISTRIBUTIONS: A METHOD OF PHOTOMETRIC RECONNAISSANCE

Studies of deeply embedded young clusters begin with flux-limited IR photometric surveys of dense molecular cloud cores. Given that it is not yet practical to consider gathering a complete sample of near-IR spectra for all sources detected in an infrared imaging survey, we seek to combine photometric and spectroscopic approaches in order to characterize the distribution of stellar masses for a deeply embedded young cluster.

In this Chapter, we introduce a photometric technique which applies what we know from optical studies of T Tauri stars to the interpretation of near-infrared photometric data of embedded cluster members. First, we outline a scheme for dereddening each embedded source individually, and thus obtaining an estimate of its intrinsic *stellar* luminosity. We rely on the H-R diagram constructed for some fraction of the photometric sample (via spectroscopy) in order to assess the evolutionary status of the cluster. This allows us to adopt the appropriate mass-luminosity relationship necessary to interpret absolute J-band luminosity functions. Next, we discuss the importance of defining an A_v -limited sample in constructing the stellar luminosity functions of embedded clusters. Then, we describe the characterization of the emergent mass distribution derived from the A_v -limited stellar luminosity function of a deeply embedded cluster in terms of the ratio of intermediate to low mass stars. Finally we present a simple statistical comparison of this ratio to the solar neighborhood initial mass function.

3.1 Lessons from the Taurus Dark Cloud

The fundamental assumption on which our technique rests is that embedded clusters are heavily reddened groupings of classical and weak-emission T Tauri stars, spanning similar ranges of masses and ages, and having similar near-infrared properties. We note that this assumption is being verified through comparisons of near-infrared spectroscopic surveys of embedded clusters with optically-visible T Tauri stars (e.g. Hodapp and Deane, 1993; Greene and Meyer, 1995; see also Chapter IV).

What can we learn from the Taurus dark cloud population that will facilitate our study of embedded clusters? First we consider a subset of this sample that has been well studied using high resolution echelle spectroscopy. This leads us to adopt the J-band as a preferred monochromatic near-infrared stellar luminosity estimate. We then deredden a larger sample of the T Tauri stars in order to look at the intrinsic near-infrared colors. While weak-emission T Tauri stars have near-infrared colors of main sequence stars, classical T Tauris have near-infrared excess emission that spans a narrow space in near-infrared color-color diagrams. We make use of this information in constructing a dereddening scheme for embedded YSOs which attempts to take into account intrinsic near-IR excesses. Finally we derive mass and age distributions for the fraction of our sample that are found within stellar density enhancements in the Taurus dark cloud. These Taurus aggregates are young, exhibit a restricted range of ages, and are comprised of primarily low mass stars.

In order to derive the masses, ages, and near-IR excess properties of T Tauri stars, we have selected a sample from the Taurus dark cloud taken from the study of Strom *et al.* (1989). We have chosen those objects with known spectral types, having both optical and infrared photometry in well-defined photometric systems. The sample consists of 30 classical T Tauri stars (CTTS) and 40 weak-emission T

Tauri stars (WTTS) as defined in Strom *et al.* (1989). All R- and I-band photometry was reported in the Cousins system, and the JHK photometry in the KPNO (OTTO) system. The IR photometry was converted into the standard *CIT* system using the transformations from Kenyon (1987).

3.1.1 Continuum Excess Emission in the Infrared

T Tauri stars suffer from both line and continuum excess emission at optical and infrared wavelengths (Hartigan *et al.*, 1991). High resolution spectroscopy can be used to determine the level of optical continuum excess emission and evaluate its effect on the SEDs of Tauri stars. This permits us to derive accurate values of the extinction and stellar luminosity uncompromised by these excesses. Hartigan, Edwards, and Ghandour (1995; hereafter HEG) report results based on echelle data for a representative sample of T Tauri stars spanning a wide range of accretion properties, 33 of which are also included in our sample. HEG suggest that the excess emission in the J-band is related to the excess in the V-band by $r_J = r_V \times 0.1$ where $r_\lambda = F_{\lambda excess}/F_{\lambda*}$ based on their models for the excess emission. Their models, constructed for typical classical T Tauri stars (spectral type K5–M0), assume that optical excess emission originates in a hot star/disk boundary layer of 10,000K and does not account for thermal emission from warm circumstellar dust that may contribute to the excess emission in the J-band. Thus their tabulations of r_V , or *optical veiling*, provide us with estimates of r_J for a “representative” sample of T Tauri stars. The distribution of r_J for this sample of 19 CTTS and 10 WTTS has a peak at 0.0 (which is also the median value) when binned by 0.1 interval widths and ranges from 0.0–0.5 (the highest value belonging to the heavily veiled DO Tau). This is consistent with the models of Kenyon and Hartmann (1990) who suggest that the SEDs of T Tauri stars are least

contaminated by continuum excess emission at wavelengths near $1\ \mu\text{m}$ (i.e. the I- and J-bands).

How much continuum veiling do T Tauri stars suffer in the H- and K-bands due to thermal emission from warm circumstellar dust? We combine information on the continuum excess in the J-band, spectral types, and extinction estimates with the near-infrared colors to calculate the distribution of continuum excesses in the H- and K-bands. We derive reddening values using

$$A_v = E(R_c - I_c) \times 4.76 \quad (3.1)$$

and use the intrinsic $(R_c - I_c)$ colors of dwarf stars from Schmidt-Kaler (1982) for stars B8-K5 and Bessell (1991) for stars K7-M5.¹ We adopt the reddening law quoted by Cohen *et al.* (1981) as measured in the CIT system;

$$E(J - H)_{\text{reddening}} = 0.11 \times A_v \quad (3.2)$$

and

$$E(H - K)_{\text{reddening}} = 0.065 \times A_v. \quad (3.3)$$

We define the *intrinsic color excesses*

$$E(J - H)_o = (J - H) - (J - H)_o - 0.11 \times A_v \quad (3.4)$$

and

$$E(H - K)_o = (H - K) - (H - K)_o - 0.065 \times A_v \quad (3.5)$$

where the first term is the observed color, the second term is the intrinsic color of the photosphere based on the known spectral type, and the third term is due to reddening. We have used the intrinsic infrared colors of main sequence stars from

1

Comparison of the HEG veiling-corrected extinction values with traditional color excess methods indicate that the $E(R - I)$ color excess is the best estimator, yielding extinction values within $\pm 1 A_v$ from the de-veiled values.

Bessell and Brett (1988) transformed into the CIT system. In terms of continuum excess emission or *infrared veiling* we write

$$E(J - H)_o = -2.5 \times \log[(1 + r_J)/(1 + r_H)] \quad (3.6)$$

and

$$E(H - K)_o = -2.5 \times \log[(1 + r_H)/(1 + r_K)]. \quad (3.7)$$

We use the r_J estimates based on the optical veiling measurements discussed above with the value for $E(J - H)_o$ to calculate r_H , performing a similar calculation for r_K given $E(H - K)_o$ and r_H . The distribution of r_K ranges from $[0.0 - 3.3]$ and translates into a range of magnitudes from $\Delta K \sim 0.0 - 1.6^m$. The medians of the CTTS in the HEG sample are $\langle r_H \rangle = 0.2$ and $\langle r_K \rangle = 0.6$ whereas for WTTS $\langle r_H \rangle = \langle r_K \rangle = 0.0$. Because of our assumption that r_J is dominated by hot boundary layer emission with no disk contribution, these calculations are *lower limits* for r_K . We conclude that the J-band flux is a better measure of stellar luminosity than the H- or K-band flux for T Tauri stars.

3.1.2 Intrinsic Near-Infrared Colors

Returning to our larger sample of 40 WTTS and 30 CTTS, we make use of the $E(R - I)$ reddening estimates to investigate the intrinsic (i.e. dereddened) near-infrared properties of T Tauri stars. In Figure 3.1 we plot the dereddened colors of T Tauri stars in Taurus. Note that the WTTS in the sample have colors consistent with normal main sequence stars. The CTTS show various amounts of near-infrared excess and occupy a reasonably well defined locus in this color-color diagram after dereddening. This was first noticed by Rydgren, Schmelz, and Vrba (1982).

We performed a linear least-squares fit to this locus from our sample of 30 CTTS with dereddened colors as shown in Figure 3.1:

$$(J - H)_{CTTS} = 0.58 \pm 0.08 \times (H - K)_{CTTS} + 0.53 \pm 0.04. \quad (3.8)$$

Hereafter we refer to this as the *locus of classical T Tauri stars* or CTTS locus. HEG show that near-IR excess is well correlated with spectroscopic accretion diagnostics and we suspect that this locus corresponds to a range of disk accretion rates and viewing inclinations. The CTTS locus intersects the reddening vector from an M6 dwarf at $A_v = 1.9^m$ and has been truncated in Figure 3.1 at $(H - K) = 1.0$ which is the maximum near-IR excess that can be understood in terms of “standard” accretion disk models (Lada and Adams, 1992). Because T Tauri stars are known to vary at optical and infrared wavelengths, it is possible that both the $E(R - I)$ extinction estimates and intrinsic IR excesses properties could be time variable. In order to investigate this effect, we also fit this locus using only those stars which had simultaneous optical and infrared photometry. The result was consistent with the one presented above for the larger sample within the statistical errors of the fit. In Section 3.2 we make use of the CTTS locus in estimating the extinction toward embedded sources.

Figure 3.1. Near-IR color-color diagram for *dereddened* T Tauri stars in Taurus-Auriga. The magnitude and slope of the interstellar reddening vector was taken from Cohen *et al.* (1981) for the CIT photometric system. The intrinsic colors of giant and dwarf stars were taken from Bessell and Brett (1988) and transformed into the CIT system. Region “A” defines the region occupied by reddened main sequence stars (WTTS and some CTTS) while region “B” is the space occupied by reddened classical T Tauri stars with near-IR excesses attributable to circumstellar disks. Objects that fall in region “C” have IR excesses that require more complicated geometries than a simple disk.

3.1.3 Masses and Ages from the HR Diagram

Many deeply embedded clusters, which are the targets of our research, are very compact. Because most will likely evolve into unbound associations, we suspect that they have not undergone significant dynamical evolution. Thus we anticipate that they are also very young. To test this assumption, we restricted our sample of T Tauri stars in Taurus to those found in relatively dense aggregates. We selected stars located within the groupings defined by Gomez *et al.* (1993) as being clustered at a level significant above the randomly distributed background. These clusters are all associated with dense gas as traced by NH_3 (Benson and Myers, 1989). This restricted our sample to 28 stars found associated with the Groups I–VI of Gomez *et al.* (1993).

In order to derive masses and ages for these stars, we compare their positions in the HR diagram with theoretical PMS evolutionary tracks. To place these stars in the HR diagram, we adopt the extinction estimates described above and use them to correct the J-band magnitudes for reddening (in CIT). A bolometric correction is applied based on the spectral type giving

$$M_J = m_J - 0.265 \times A_v - dm \quad (3.9)$$

and

$$M_{Bol} = M_J + (V - J) + BC_V. \quad (3.10)$$

Finally the stellar luminosity is computed

$$\log(L^*/L_\odot) = 1.89 - 0.4M_{Bol}. \quad (3.11)$$

We have adopted the temperature scale and bolometric corrections listed in Schmidt–Kaler (1982) for stars B8–K5 and Bessell (1991) for stars K7–M5 and intrinsic IR colors from Bessell and Brett (1988) transformed into the CIT system. Based on the work of Basri and Batalha (1990) and Schiavon *et al.* (1995) we

assume that PMS stars have surface gravities closer to main sequence dwarf stars than giant stars in choosing appropriate bolometric corrections and intrinsic colors.

How well can we estimate the ages of YSOs? The H–R diagram for this sample is shown in Figure 3.2 along with the theoretical PMS evolutionary tracks of D’Antona and Mazzitelli (1994; hereafter DM). We have adopted the DM model input physics chosen by Hartigan, Strom, and Strom (1994) with Alexander opacities and the Canuto and Mazzitelli convection prescription. This HR diagram suggests that these stellar groups are young with a restricted range of ages. The median age inferred from the range of luminosities for our Taurus “embedded cluster” sample is 3×10^5 yrs and all stars have ages $\tau < 3 \times 10^6$ yrs. Based on the unpublished PMS evolutionary tracks described in Swenson *et al.* (1994) this locus in the HR diagram is best described by a 1×10^6 yr isochrone. Careful investigation of this diagram reveals a trend of mass with age, the higher mass stars appearing older. Yet we must be very cautious in interpreting the physical meaning of these ages. Stahler (1988; see also Palla and Stahler, 1993) has pointed out that certain areas of the HR diagram are not accessible to young stellar objects undergoing spherical accretion. Instead the structure of accreting protostars is regulated primarily by deuterium burning and can be described by a mass–radius relationship, referred to as the “birthline”, which depends on the spherical accretion rate. According to this interpretation, a young stellar object would continue to build up a central protostellar mass until the end of spherical accretion. Then it would quickly assume an equilibrium configuration corresponding to the position on the HR diagram where the traditional Hyashi track for that mass intersects the appropriate mass–radius relationship. These mass–radius relationships do not take into account rotation or magnetic fields and as a result are highly uncertain. However, the concept of the birthline is important as it provides a physically meaningful reference from which to measure stellar ages as

opposed to the zero-points of the Kelvin-Helmholtz contraction times indicated in classical PMS evolutionary tracks. Furthermore, it is unknown what effect residual disk accretion may have on the evolutionary paths of classical T Tauri stars as they approach the main sequence although this is not expected to be a large effect. For stars older than 3×10^6 yr neither the position of the birthline nor disk accretion is expected to alter the contraction ages significantly. As a rule of thumb, we consider a cluster to be “young” ($\tau \ll 3 \times 10^6$) or “old” ($\tau \gg 3 \times 10^6$). Any finer distinction awaits better understanding of PMS evolution.

Figure 3.2. The Hertzsprung–Russell diagram for 28 optically–visible classical and weak–emission T Tauri stars found in the Taurus dark cloud stellar aggregates defined in Gomez *et al.* (1993). The PMS evolutionary tracks and isochrones of D’Antona and Mazzitelli (1994) are shown.

How well can we determine the stellar masses of young stellar objects? With the PMS tracks adopted here, Figure 3.2 shows that T Tauri stars found in these aggregates span a range of masses from $0.1\text{--}1.0M_{\odot}$. Hartigan, Strom, and Strom (1994) compare the masses derived from the DM tracks with the PMS tracks of Swenson *et al.* (1994) as well as the compilation of Cohen and Kuhn (1979). We defer a detailed comparison of these tracks to other authors, but note that Lee (1992) has found both modern sets of tracks are consistent with dynamical mass ratios calculated from the orbital elements of 5 PMS double-lined spectroscopic binaries within the errors ². Most of these tests concern stars more massive than $1.0M_{\odot}$. This region of the H-R diagram is dominated by stars whose main mechanism of internal energy transport is radiative. The physics of radiative energy transport is well understood compared to convective energy transport, the details of which are highly uncertain. The reader should be aware that while these two sets of tracks agree very well above $1M_{\odot}$, they can give masses that differ by as much as $\times 2$ near the hydrogen burning limit (see Figure 2 of Hartigan, Strom, and Strom, 1994). Despite the uncertainties in the isochrones, we are confident that the masses above $1.0M_{\odot}$ are accurate within $\sim 30\%$ and that masses below $1.0M_{\odot}$ are accurate to within a factor of $\times 2$.

While this is not a complete sample, it is large enough that it should be representative for the Taurus aggregates. The reader is referred to Kenyon and Hartmann (1995) for a detailed study of the stellar population in Taurus. We use this sample to characterize T Tauri stars we expect are representative of the young stellar objects discovered in near-IR surveys of embedded clusters.

2

Similar results are found for the spectroscopic binaries W134 (Padgett and Stapelfeld, 1994) and V773 Tau (Welty, 1995)

3.1.4 Summary

In our review of the properties of T Tauri stars in Taurus we have uncovered several important facts to help us refine our analysis of young stellar objects embedded in molecular cloud cores. First, J-band fluxes do a better job of estimating stellar luminosity than H- or K-band fluxes. The CTTS in our sample display typical excess emission characterized by $\Delta J = 0.0^m$, $\Delta H = 0.2^m$, and $\Delta K = 0.5^m$. Second, the intrinsic colors of classical T Tauri stars occupy a well defined region in the $(H - K)$ versus $(J - H)$ color-color diagram which motivates our dereddening technique described below. Finally when we consider T Tauri stars found in spatially coherent groups, we find that they are indeed young low-mass pre-main sequence stars with a restricted range of ages.

3.2 Methodology

Our goal is to investigate the stellar populations of deeply embedded young clusters based primarily on information derived from J-, H-, and K-band imaging photometry. By “deeply embedded” we mean clusters associated with opaque molecular cloud cores. Dust associated with such cores provides a natural screen which helps to block out background stars. By “young” we mean star-forming events that have occurred within the past 3×10^6 yr. As discussed below, this technique does not perform well for populations older than 3×10^6 yr. However, we do not expect such populations to meet our first criterion of deeply embedded and are best studied through traditional optical techniques. Finally, we define a “cluster” as a stellar density enhancement significantly above fluctuations in the field star or distributed population surface density. The more compact the cluster, the smaller the contamination from field stars and the more coherent we expect the ages of cluster members to be. We require that the imaging photometry have well determined completeness limits, and that contamination due to foreground or

background stars seen through the molecular cloud cores is minimal. We reiterate that the T Tauri aggregates described above should serve as analogs of the deeply embedded young clusters defined here.

3.2.1 Extinction Estimates

How can we derive the extinction in the absence of intrinsic colors based on known spectral types? The near-infrared $(H - K)$ vs. $(J - H)$ color-color diagram (e.g. Figure 3.1) allows us to distinguish objects with small, intermediate, or large near-infrared excess and guides our choice of dereddening techniques. We divide this diagram up into three regions; i) stars that fall within the reddened main sequence; ii) objects that appear to be reddened classical T Tauri stars; and iii) objects with near-infrared colors similar to Herbig Ae/Be stars or accreting protostars.

This first region of the near-IR color-color diagram, labeled “A” in Figure 3.1, contains objects with colors that appear to be normal reddened photospheric colors. However, T Tauri stars with small near-IR excesses can also fall in this portion of the color-color diagram. How representative of stellar photospheres are the near-IR colors of T Tauri stars in this part of the color-color diagram? The distribution of the intrinsic color excess, $E(J - H)_o$, for the T Tauri stars in our sample that fall within the reddened main sequence is strongly peaked at zero (mode=median=mean) with a standard deviation of 0.09^m . This indicates that $(J - H)$ can be used to estimate reddening for stars that fall in this part of the diagram ($\Delta E(J - H) \sim 0.09 \Rightarrow \Delta A_v \sim 0.8^m \Rightarrow \Delta A_J \sim 0.2^m$). However, dereddening a star in this color-color diagram does not yield a unique value for the extinction because the reddening vector intersects the locus of main sequence colors at two points corresponding to different values of the extinction. One solution yields a luminous early-type star; the other solution a lower luminosity

late-type star. For this reason, we turn to the $(J - H)$ versus M_J color-magnitude plane in order to deredden these sources. Using theoretical PMS evolutionary tracks (D’Antona and Mazzitelli, 1994, with Alexander opacities and Canuto–Mazzitelli convection), we can derive a unique color-magnitude relationship from each isochrone. The theoretical calculations provide relationships between effective temperature and luminosity for stellar masses as a function of age. Temperature and luminosity can be translated into absolute magnitudes and colors using tabulations of temperature, bolometric corrections, and intrinsic colors referenced in the previous section that are needed to place stars in the HR diagram. Details of these transformations are given in Appendix C. Figure 3.3 we present the DM isochrones from $0.1 - 3 \times 10^6$ yr translated into the $(J - H)$ versus M_J color-magnitude plane. From a star’s position in this plane, we can deredden it along the reddening vector until it intersected one of the isochrones yielding a value for the extinction towards the star. Note that for these ages, the reddening vector is nearly perpendicular to the assumed isochrones. For isochrones corresponding to ages greater than 3×10^6 yrs and later, the reddening vector becomes increasingly parallel to the isochrones rendering this dereddening procedure ineffective. For clusters with ages $< 3 \times 10^6$ yrs, the assumed age has little effect on the derived extinction. We can take advantage of this in order to derive age-independent extinction estimates by defining a “locus” of points in this diagram corresponding to the “mean” position of the PMS isochrones from 0.1–3.0 Myr. The $(J - H)$ colors of the stars represent stellar spectral types from G8–M5 range from 0.36–0.62. The absolute magnitudes range from -0.76 ($2.5M_\odot$ star at 1×10^5 yr) to 6.58 ($0.1M_\odot$ star at 3×10^6 yr). This locus, shown in Figure 3.3, was fit such that dereddening to it instead of any individual isochrone results in as small an error in extinction as possible (i.e. $\Delta A_v < 1.25^m \Rightarrow \Delta A_J < 0.3^m$). Polynomial fits to each isochrone as well as that of the “mean isochrone” are presented in Appendix C. If

the projected reddening vector of a given star falls above or below the edges of this mean isochrone, it is dereddened to the main sequence.

Figure 3.3. Near-infrared color-magnitude diagram with the PMS isochrones of DM transformed into this observational plane. Four different isochrones are plotted as well as a "mean isochrone" and the zero-age main sequence for comparison. Polynomial fits to these isochrones are shown and given in the Appendix C. The reddening vector is taken from Cohen *et al.* (1981). All photometry is presented in the CIT photometric system.

Objects in region “B” of Figure 3.1 can be successfully modeled as classical T Tauri stars with circumstellar disks and so we deredden them along the reddening vector in the color-color diagram until they intersect the locus of classical T Tauri stars. However, we note that some objects with flat or rising SEDs from 1–100 μm (flat spectrum and Class I protostars) can occupy the same positions in the color-color diagram as reddened classical T Tauri stars (Kenyon and Hartmann, 1995). IRAS surveys for YSOs in Taurus (Kenyon *et al.*, 1990) and Ophiuchus (Greene *et al.*, 1994) find that only about 10–20 % of those detected are flat spectrum or Class I protostars. Further only half of Class I sources in the sample of Kenyon and Hartmann (1995) fall within the reddened CTTS locus. As a result we expect contamination in the CTTS locus from these objects to be modest ³

Objects found in region “C” in Figure 3.1, *cannot* be modeled as reddened T Tauri stars with standard accretion disks (Lada and Adams, 1992). This region (anything outside the reddened main sequence and reddened CTTS locus) can be populated by Herbig Ae/Be stars (Hillenbrand *et al.*, 1992), as well as accreting protostars such as HL Tauri (Calvet *et al.*, 1993). Such infrared colors imply either large holes in the inner circumstellar disks, “non-standard” accretion disks (i.e. radial temperature dependence shallower than $T_{\text{disk}} \sim r^{-3/4}$), or extensive envelope contributions. These YSOs have extremely complicated circumstellar environments with near-IR colors that may be affected by scattered-light envelopes. Estimates of reddening toward such objects requires detailed modeling. We do not attempt to deredden objects in region “C” and they are not considered further in our analysis. In practice, we allow sources that fall just below the CTTS locus to remain in the sample and assign them an $A_v = 0.0^m$. The absolute cutoff depends on the errors in the color indices (typically $\sigma(J - H) < 0.3$).

3

If an extremely young cluster does contain a large number of accreting protostars, we would expect to be alerted by sources appearing in region “C” of the JHK color-color diagram.

How different are the extinctions derived from this technique from those calculated directly from the $E(R - I)$ color excess calculated with the knowledge of the optical spectral type? In Figure 3.4 we show a frequency distribution of these differences for our sample of 28 optically-visible T Tauri stars (16 CTTS; 12 WTTS) found within the aggregates of Gomez *et al.* (1993). This sample includes sources found within the reddened main sequence (region “A”) as well as those that lie within the reddened CTTS locus (region ‘B’). Errors in the combined sample have a mean and standard deviation of $\Delta A_v = 0.6^m \pm 1.3$. This offset (overestimation of the extinction by our technique) is due primarily to those classical T Tauri stars that fall within the reddened main sequence and are dereddened to the mean isochrone in the color-magnitude diagram. Over 90 % of the sources (25/28) have $\Delta A_v < \pm 2.0^m$. This translates into an error of $\Delta J \sim 0.5^m$. Under the assumption that most embedded sources are T Tauri stars, this method provides the best estimate of the extinction in the absence of known spectral types.

Figure 3.4. Frequency distribution of ΔA_v for our sample of 28 T Tauri stars found in the aggregates of Gomez *et al.* (1993). The difference indicated is that determined from our photometric technique minus that derived from the $E(R - I)$ color excess. Those sources that fall within the CTTS locus in Figure 3.1 are hatched while those that fall within the reddened main sequence are not.

3.2.2 Mass–Luminosity Relationships

Armed with our best estimate of the stellar photospheric flux in the near-infrared (absolute J-band magnitudes), we would like to characterize the stellar mass distribution. In order to accomplish this we need a mass–luminosity relationship appropriate for the embedded cluster under study. The relationships between absolute J-band magnitude and stellar mass are shown in Figure 3.5 for four isochrones from DM; 1×10^5 , 3×10^5 , 1×10^6 , and 3×10^6 yr. The polynomial fits to these isochrones shown in this figure are given in Appendix C. By observing some fraction of our photometric cluster sample spectroscopically, we can place constraints on its evolutionary status. For example from the H–R diagram shown in Figure 3.2 for the spatially-segregated Taurus aggregates we deduced a median age of 3×10^5 yr. If we adopted the mass–luminosity relationship for this isochrone, we could then directly translate M_J into stellar mass. However, as noted above Figure 3.2 indicates a weak trend of mass with age; lowest mass stars appearing to have the youngest ages. The difference in apparent age as a function of mass for a presumably co-eval cluster can be understood in terms of the birthline and suggests that these isochrones need to be re-evaluated (Hillenbrand, 1995; see also Chapter IV).

Figure 3.5. Theoretical PMS tracks of D'Antona and Mazzitelli (1994) transformed into absolute J-band magnitudes from $0.1 - 2.5 M_{\odot}$ for four different ages. Polynomial fits to these data are also shown and are given in Appendix C. The $1 M_{\odot}$ locus of absolute J-band magnitudes is highlighted. Defining M_J corresponding to $1 M_{\odot}$ is crucial in order to translate stellar luminosity functions into a ratio of intermediate to low mass stars.

Despite the uncertainties in the interpretation of the PMS isochrones, we can use the locus of points on the H–R diagram defined by the spectroscopic sample as a guide in deriving a mass–luminosity relationship. Even if the *isochrones* are suspect, dynamical mass ratios from the growing sample of spectroscopic binaries provide a check on the masses derived from the tracks. Each star observed spectroscopically has a unique mass determined from its position in the H–R diagram and an associated M_J . Thus for each cluster under study, we can derive a semi-empirical mass–luminosity relationship that provides a self-consistent calibration useful in interpreting the stellar luminosity function of the entire flux-limited photometric sample.

3.2.3 Characterizing Emergent Mass Distributions

Once we have adopted a mass–luminosity relationship we can interpret our stellar luminosities as photometric mass estimates. Further, the mass–luminosity relationship provides an estimate of our sample completeness as a function of mass. For example according to Figure 3.5, adopting the 3×10^5 yr isochrone for the Taurus aggregate at the low mass end implies that our stellar luminosity function must be complete down to $M_J = 5.4^m$ in order to completely sample the mass function down to $0.1M_\odot$. For our flux-limited infrared photometric surveys, this implies an extinction limit where the reddening vector from the $0.1M_\odot$ limit of our chosen isochrone intersects our photometric completeness limit. If this A_V -limit were not imposed, we would always preferentially observe higher mass stars which are intrinsically more luminous, and sample a larger volume.

Because there seems to be a trend of stellar mass with age in many young clusters, we cannot simply adopt a mass–luminosity relationship from the PMS isochrones. In practice, the mass–luminosity relationship we derive is from an H–R diagram showing this trend is somewhat ambiguous. As a result we are usually

forced to restrict the precision of our photometric mass determination to answering the question whether or not a given star is greater than or less than $1.0M_{\odot}$. Even that question can usually only be answered in a statistical sense. We can derive an estimate of M_J corresponding to $1.0M_{\odot}$ for the cluster under study. All stars fainter than the absolute magnitude corresponding to this “break-point” are considered to be less than a solar mass and all stars brighter are assigned masses greater than $1.0M_{\odot}$. As a result, we use our A_V -limited stellar luminosity function to calculate the ratio of intermediate ($M_* > 1.0M_{\odot}$) to low mass ($M_* < 1.0M_{\odot}$) stars. The choice of the break-point is motivated by; i) significant departure in the available PMS tracks below about $1.0M_{\odot}$; and ii) evidence that the slope of the IMF in the solar neighborhood may change at $1.0M_{\odot}$ (Kroupa *et al.*, 1993). We assign uncertainties to this ratio of intermediate to low mass stars based on the systematic uncertainty in defining the absolute J-band magnitude which corresponds uniquely to $1.0M_{\odot}$.

In order to compare this ratio to that expected if our sample were drawn from a Miller–Scalo IMF, we use a statistical comparison similar to that described by Hillenbrand *et al.* (1995). We sample the IMF using a Monte Carlo technique for the appropriate fixed number of stars. The same ratio of intermediate to low mass stars is computed for 10,000 independent samplings of the Miller–Scalo IMF to achieve high signal-to-noise in the resulting binomial probability distribution. If our sample consisted of an infinite number of stars, then this probability distribution would be a δ -function

$$P(R) = \delta(R - 0.17) \quad (3.12)$$

where the value 0.17 is obtained by integrating the IMF over the intervals $0.1-1.0M_{\odot}$ and $1.0-10.0M_{\odot}$. The fewer the number of stars in our sample, the wider this probability distribution becomes. The wider the probability distribution becomes, the more difficult it is to detect statistically significant deviations from

the Miller–Scalo IMF. As a final note, we caution that the effect of unresolved binary star systems will have a profound effect on the very low mass end of the derived distribution of stellar masses. Statistical comparisons should only be made between samples that have the same physical resolution limits. Because of the difficulties inherent in deriving stellar masses from near-infrared photometry alone, our technique is useful only in identifying regions that have mass distributions grossly different from the field star IMF (e.g. Hillenbrand *et al.*, 1995).

3.3 Summary

We have described a technique based primarily on analysis of near-infrared photometry, for characterizing distributions of stellar masses for deeply embedded young clusters. The basic assumption of our method is that embedded YSOs discovered in near-infrared photometric imaging surveys are heavily extincted pre-main sequence stars with properties similar to T Tauri stars in Taurus.

Our analysis of a sample of stars from Taurus suggests that absolute J-band magnitudes provide a good estimate of stellar luminosity. Further, T Tauri stars with near-IR excess have a well-defined locus of colors in the $(H - K)$ versus $(J - H)$ color-color diagram which we refer to as the classical T Tauri star locus. Those stars with known spectral types can be placed directly in the HR diagram and their masses and ages inferred from direct comparison with theoretical PMS evolutionary models. Using this technique, a sample of T Tauri stars located in the stellar density enhancements of Gomez *et al.* (1993) appears to be extremely young and composed of primarily low mass stars.

We use this information to construct a method for estimating stellar masses for heavily obscured T Tauri stars. Guided by the near-IR properties of T Tauri stars in Taurus, we devise a method for dereddening YSOs which gives results within $\Delta A_v = \pm 2^m$ over a wide range of parameters. Based on HR diagrams

constructed for some fraction of our sample via spectroscopic techniques, we derive a mass–luminosity relationship for the embedded population under study.

Adopting a mass–luminosity relationship allows us to define an A_v –limited sample from our flux–limited photometric database. From this we can construct a stellar luminosity function known to be complete over a well–defined range of stellar masses. We can compute the ratio of intermediate to low mass stars from the stellar luminosity function by defining the “break–point” at $1.0M_\odot$ from the mass–luminosity relationship. Finally, we can compare this ratio statistically to the IMF observed for field stars in the solar neighborhood. Our goal is to perform an initial photometric reconnaissance of the embedded clusters in order to identify those regions with very unusual emergent mass distributions.

CHAPTER 4

THE DEEPLY EMBEDDED CLUSTER ASSOCIATED WITH NGC2024

We now apply the spectroscopic and photometric techniques outlined in previous Chapters to our dataset for the deeply embedded young cluster associated with the eponymous H II region, NGC2024. Our intent is to compare the emergent mass distribution of this region, known to be still in the process of forming high mass stars, with those in well-studied sites of primarily low mass star formation, such as the embedded clusters located within the nearby Ophiuchus dark cloud. The extent of the NGC2024 cluster was first uncovered by Lada *et al.* (1991a) who performed a K-band survey of a large fraction of the L1630 molecular cloud (also known as Orion B). We defer a detailed review of the literature for this region to Appendix D. However, we note here that NGC2024 is a region of massive star formation, as evidenced by the optically-visible H II region and radio continuum studies, and that the observed ionizing flux suggests the presence of an early-type O9.5 star, although the exciting source has never been identified (e.g. Barnes *et al.*, 1989). The region encompassing this rich cluster has been the subject of numerous molecular studies and contains a massive molecular cloud core ($\sim 500M_{\odot}$) and a few large scale molecular outflows (see Appendix D for details).

Here we present results from both an initial photometric reconnaissance and a follow-up, deeper near-infrared photometric survey. We combine these data with near-infrared classification spectra ($R=1000$) in order to construct an H-R diagram for some fraction of the photometric sample. We investigate the mass-luminosity relationship of the cluster based on this H-R diagram and

proceed to characterize the emergent mass distribution from an A_v -limited stellar luminosity function as outlined in Chapter III. Finally, we examine the circumstellar properties of the embedded population as traced by near-infrared excess emission.

4.1 Photometric Survey

4.1.1 Observations and Data Reductions

We performed an initial photometric survey of the embedded cluster associated with NGC2024 using the NICMASS infrared camera at the MDM Observatories. This preliminary survey, fully described in Appendix B, was used to; i) examine the nature of the embedded stellar population using JHK photometry; ii) select targets for our spectroscopic survey described in the next section; and iii) derive accurate positions for the embedded sources for which we planned to obtain spectra.

The follow-up survey of NGC2024 was conducted in December, 1994 on the 3.8m United Kingdom Infrared Telescope, at Mauna Kea Observatory, Hawaii. The detector used was a 256×256 InSb array mounted in the IRCAM3 near-infrared camera (Aspin, *et al.*, 1994). The platescale of $0.289 \text{ arcsec pixel}^{-1}$ resulted in a field of view 1.2 arcsec on a side. A mosaic grid of 3×3 was observed with offsets of 60.0 arcsec , providing 20 % overlap between steps in the mosaic for registration. At each grid position four frames were obtained with 8.0 arcsec dither steps between each in order to replace bad pixels. Both long and short exposure mosaics were obtained in the J- and H-bands with total on-source integration times of 120 seconds per frame in the long exposures. The long exposure J-band mosaic was repeated three times in order to improve signal to noise. The K-band mosaic was obtained with a total on-source integration time of 24 seconds per frame. The total area covered in each of the J-, H-, and K-band mosaics was $3.4 \text{ arcmin} \times 3.4 \text{ arcmin}$.

The data were reduced in a manner similar to the NICMASS survey described in Appendix B with the following exceptions. Dark frames were obtained before each set of integrations and were subtracted from each image before further processing. Multiple flat-fields were constructed for each night from dark subtracted and median filtered sets of images taken within one hour of each other in regions of low source density and free of extended emission. The consistency of the flat-fields constructed in this manner was better than 1 % throughout the night in the J-, H-, and K-bands. Dark subtracted images were divided by the appropriate flat-fields and final mosaics were constructed from the registered frames using the IRAF SQUIID software. A median filter was used to combine images after the application of a bad pixel mask. The final mosaicked K-band image is shown in Figure 4.1.

Figure 4.1. Near-infrared K-band ($2.2\ \mu\text{m}$) image of the embedded cluster associated with NGC2024. North is up and east is to the left. This mosaic is $3.4\ \text{arcmin} \times 3.4\ \text{arcmin}$ with a platescale of $0.289\ \text{arcsec pixel}^{-1}$. The seeing-limited spatial resolution is about $1.0\ \text{arcsec}$ and the completeness limit is $K < 16.0^m$. The bright source to the east is IRS2 while the bright source to the west is IRS1. Data were obtained with the United Kingdom Infrared Telescope with the IRCAM3.

Sources were identified using the DAOFIND algorithm in IRAF. A detection threshold of 5σ above the sky background was chosen for the K-band mosaic frame. Automated source identifications were visually inspected for bogus detections and the addition of missed sources. Additions and subtractions from the initial source list were a few percent of the total sample (233 sources). All sources found in J- and H-bands were initially identified in the K-band frames. Aperture photometry was performed using APPHOT with a synthetic aperture of diameter of 3.5 arcsec for most sources. For 17 stars with nearby companions, a smaller aperture of 2.3 arcsec was used. Aperture corrections, as derived from 15 stars that lacked companions and surrounding nebulosity, were applied to all photometry. The sky background was sampled with an annulus of inner diameter 5.78 arcsec and width of 0.87 arcsec. Sky conditions were photometric and the seeing was typically between 0.7–1.1 arcsec. Slight telescope jitter limited the “seeing” in the east–west direction to about 1.0 arcsec. Calibration was performed in the J-, H-, and K-bands using the faint UKIRT standards (Casali, 1992). Based on residuals in the photometric calibration fit, the minimum errors in this photometry are 0.03^m in the J-, H-, and K-band. In order to investigate residual flat-fielding errors, a standard star was imaged at 25 different positions on the array in each filter. The residual errors are on the order of 1–2 % and within the calibration errors quoted. Photometry was obtained for 202 sources in the K-band, 174 sources in the H-band, and 147 sources in the J-band with formal errors $\sigma < 0.8^m$. Comparing UKIRT photometry of bright stars with the previous NICMASS survey suggests that the data agree within $\pm 0.15^m$, consistent with expected intrinsic source variability and the errors of the NICMASS photometry (see Appendix B for further details of this comparison).

In order to assess the completeness limits of the UKIRT survey, artificial stars were added to the final mosaicked source frames using a point spread function

Table 4.1. Photometric Survey Completeness Limits

Magnitude Range ¹	% Recovered J	% Recovered H	% Recovered K
15.0–15.5			94
15.5–16.0			96
16.0–16.5		100	89
16.5–17.0		97	68
17.0–17.5	99	97	12
17.5–18.0		94	
18.0–18.5	96	87	
18.5–19.0	92	20	
19.0–19.5	25		

¹ 100 stars randomly chosen within this interval and added to data frame.

built from stars in the frames. One hundred stars were added with magnitudes spanning 0.5^m bins and sources were identified using the same procedure as for the data frames. Because of the high source density in the region, sources were artificially prevented from being placed within 2.0 arcsec of an existing star. In Table 4.1 the fraction of stars recovered is presented in each band. The completeness limit was defined to be the magnitude at which 90 % or more of the stars are recovered averaged over regions with and without nebosity. These completeness limits are $J = 18.75^m$, $H = 18.0^m$, and $K = 16.0^m$.

Astrometry was performed on the final K-band mosaic, the wavelength at which we detected the greatest number of stars. The positions of seven optically-visible stars were used as astrometric reference stars. Using the astrometry program available from the NOAO IRAF programming group, a two-dimensional astrometric solution was found by solving for six independent coefficients. The RMS residuals in the fit were 0.35 arcsec in right ascension and 0.05 arcsec in declination. These positions agree with those derived from the NICMASS survey to within ± 0.75 arcsec although there are systematic differences between the two datasets just above the level of the RMS deviations.

These positions are reported in Table 4.2 for all 233 sources detected in this survey, as are the J-, H-, and K-band magnitudes and associated errors; all

photometry is presented in the natural UKIRT IRCAM3 system. There are 111 sources in our survey region with high quality J-, H-, and K-band measurements, which we define to be errors in all bands $\sigma < 0.25^m$. For ten sources, we have substituted data from the NICMASS survey because of saturation in our IRCAM3 survey frames, as discussed in Appendix B. In order to compare our photometry with standard color relations, the data were transformed into the CIT photometric system using the equations given by Casali (1992). The minimum color errors after transformation are thought to be 0.05^m in both $(J - H)$ and $(H - K)$ ¹.

1

However, we note that we have extrapolated these transformations to colors far redder than those of the standards from which they were derived

Table 4.2. Photometry for Embedded Cluster Associated with NGC2024

ID	RA(1950.0)	DC(1950.0)	m_J	σ_J	m_H	σ_H	m_K	σ_K	Note
001	05:39:03.50	-01:54:55.0	99.99	9.99	14.99	0.04	12.63	0.03	
002	05:39:03.51	-01:56:56.6	17.46	0.48	15.20	0.10	13.29	0.04	
003	05:39:03.58	-01:56:44.6	15.40	0.11	14.68	0.08	13.85	0.05	
004	05:39:03.69	-01:54:38.8	18.07	0.36	15.45	0.08	99.99	9.99	
005	05:39:03.83	-01:55:09.3	19.29	0.29	19.50	0.78	17.65	0.44	
006	05:39:03.89	-01:57:42.0	13.61	0.04	12.98	0.03	12.71	0.03	
007	05:39:03.91	-01:55:18.1	99.99	9.99	99.99	9.99	99.99	9.99	
008	05:39:03.93	-01:55:45.8	16.63	0.05	14.69	0.03	13.05	0.03	
009	05:39:03.98	-01:54:57.3	19.29	0.56	99.99	9.99	18.43	0.62	
010	05:39:04.05	-01:57:35.5	18.96	0.42	17.44	0.27	15.92	0.14	
011	05:39:04.24	-01:55:14.6	16.40	0.04	15.10	0.03	14.54	0.04	
012	05:39:04.25	-01:57:48.7	15.78	0.04	12.91	0.03	11.19	0.03	
013	05:39:04.30	-01:55:48.4	16.80	0.10	14.76	0.04	13.54	0.03	
014	05:39:04.39	-01:55:03.4	15.32	0.04	13.95	0.03	13.18	0.03	
015	05:39:04.57	-01:55:45.7	99.99	9.99	99.99	9.99	14.95	0.05	
016	05:39:04.68	-01:55:00.7	99.99	9.99	99.99	9.99	17.69	0.29	
017	05:39:04.68	-01:55:50.5	11.75	0.03	10.08	0.03	99.99	9.99	
018	05:39:04.71	-01:57:16.6	99.99	9.99	99.99	9.99	18.01	0.64	
019	05:39:04.78	-01:54:50.7	16.38	0.04	14.42	0.03	13.25	0.03	
020	05:39:04.81	-01:55:05.6	13.92	0.04	12.34	0.03	11.52	0.03	
021	05:39:04.82	-01:55:13.2	99.99	9.99	16.70	0.08	15.19	0.05	
022	05:39:04.85	-01:57:21.3	12.79	0.03	11.42	0.03	10.92	0.03	
023	05:39:04.93	-01:56:07.5	15.21	0.04	13.70	0.03	12.89	0.03	
024	05:39:04.94	-01:55:16.0	99.99	9.99	17.14	0.14	15.77	0.10	
025	05:39:05.03	-01:54:45.1	14.45	0.04	12.74	0.03	11.93	0.03	
026	05:39:05.03	-01:55:29.7	99.99	9.99	99.99	9.99	99.99	9.99	
027	05:39:05.08	-01:55:20.8	11.89	0.03	10.36	0.03	09.71	0.03	
028	05:39:05.10	-01:57:17.5	99.99	9.99	99.99	9.99	99.99	9.99	
029	05:39:05.15	-01:55:41.4	16.85	0.07	15.10	0.04	14.03	0.03	
030	05:39:05.17	-01:55:34.5	13.36	0.04	11.71	0.03	11.03	0.03	
031	05:39:05.29	-01:55:01.1	99.99	9.99	18.25	0.34	16.51	0.14	
032	05:39:05.31	-01:55:25.1	12.36	0.03	10.74	0.03	09.95	0.03	
033	05:39:05.31	-01:56:14.2	14.36	0.04	12.63	0.03	11.68	0.03	
034	05:39:05.43	-01:55:05.5	14.36	0.04	12.57	0.03	11.57	0.03	
035	05:39:05.85	-01:54:39.5	99.99	9.99	99.99	9.99	99.99	9.99	
036	05:39:05.97	-01:55:45.9	99.99	9.99	99.99	9.99	16.22	0.24	
037	05:39:06.09	-01:55:12.9	99.99	9.99	99.99	9.99	14.20	0.04	
038	05:39:06.11	-01:55:50.7	12.86	0.03	11.16	0.03	10.50	0.03	
039	05:39:06.11	-01:55:50.7	99.99	9.99	99.99	9.99	99.99	9.99	
040	05:39:06.19	-01:55:57.8	99.99	9.99	99.99	9.99	11.60	0.03	
041	05:39:06.20	-01:55:53.0	99.99	9.99	99.99	9.99	14.24	0.10	
042	05:39:06.20	-01:55:57.9	99.99	9.99	99.99	9.99	10.64	0.03	
043	05:39:06.21	-01:55:17.7	10.72	0.03	99.99	9.99	99.99	9.99	
044	05:39:06.22	-01:56:35.9	16.40	0.05	14.58	0.03	13.56	0.03	
045	05:39:06.23	-01:56:07.3	13.13	0.06	11.56	0.03	10.54	0.03	

Continued, next page.

Table 4.2 continued

ID	RA(1950.0)	DC(1950.0)	m_J	σ_J	m_H	σ_H	m_K	σ_K	Note ¹
046	05:39:06.30	-01:56:03.6	99.99	9.99	99.99	9.99	99.99	9.99	a
047	05:39:06.34	-01:55:57.9	12.13	0.03	10.36	0.03	09.72	0.03	
048	05:39:06.39	-01:54:37.2	11.76	0.03	10.54	0.03	09.89	0.03	
049	05:39:06.47	-01:54:44.7	15.94	0.05	14.08	0.03	12.96	0.03	
050	05:39:06.55	-01:56:57.7	99.99	9.99	99.99	9.99	16.43	0.17	
051	05:39:06.57	-01:55:23.3	13.54	0.04	11.51	0.03	10.59	0.03	
052	05:39:06.58	-01:55:59.5	14.06	0.04	12.86	0.03	11.84	0.03	
053	05:39:06.63	-01:54:51.5	17.17	0.06	15.26	0.04	14.21	0.04	
054	05:39:06.67	-01:56:21.1	15.07	0.04	13.01	0.03	11.77	0.03	
055	05:39:06.67	-01:56:46.8	19.25	0.33	17.32	0.09	16.24	0.09	
056	05:39:06.69	-01:57:02.4	13.04	0.04	11.67	0.03	10.98	0.03	
057	05:39:06.70	-01:55:43.5	17.77	0.36	15.54	0.09	14.05	0.05	
058	05:39:06.80	-01:55:46.6	99.99	9.99	99.99	9.99	99.99	9.99	
059	05:39:06.81	-01:54:54.4	16.63	0.09	14.49	0.04	13.41	0.04	
060	05:39:06.82	-01:54:59.2	13.41	0.04	12.84	0.03	12.49	0.03	
061	05:39:06.87	-01:57:24.5	15.90	0.04	13.20	0.03	11.88	0.03	
062	05:39:06.89	-01:57:21.3	99.99	9.99	17.89	0.21	15.17	0.06	
063	05:39:06.94	-01:54:43.9	99.99	9.99	99.99	9.99	14.78	0.06	
064	05:39:06.96	-01:55:51.2	11.96	0.03	11.32	0.03	11.22	0.03	
065	05:39:07.07	-01:54:48.8	99.99	9.99	99.99	9.99	99.99	9.99	
066	05:39:07.09	-01:57:24.1	99.99	9.99	99.99	9.99	99.99	9.99	
067	05:39:07.20	-01:55:55.1	17.02	0.20	14.27	0.04	12.87	0.04	
068	05:39:07.23	-01:57:28.6	13.96	0.04	12.08	0.03	11.04	0.03	
069	05:39:07.45	-01:55:19.6	18.61	0.23	99.99	9.99	14.56	0.04	
070	05:39:07.46	-01:57:11.7	18.31	0.21	15.58	0.06	14.08	0.04	
071	05:39:07.51	-01:57:52.8	16.40	0.22	13.02	0.03	11.32	0.03	
072	05:39:07.54	-01:55:35.3	99.99	9.99	99.99	9.99	15.86	0.13	
073	05:39:07.54	-01:56:26.9	17.36	0.10	14.74	0.03	13.37	0.03	
074	05:39:07.58	-01:55:24.2	12.16	0.03	10.17	0.03	99.99	9.99	
075	05:39:07.68	-01:55:40.0	13.88	0.04	11.19	0.03	09.54	0.03	
076	05:39:07.74	-01:55:28.0	16.23	0.04	14.11	0.03	12.89	0.03	
077	05:39:07.85	-01:54:47.9	99.99	9.99	99.99	9.99	15.62	0.10	
078	05:39:07.98	-01:54:52.7	13.35	0.04	10.87	0.03	09.57	0.03	
079	05:39:07.99	-01:54:59.6	14.73	0.04	12.38	0.03	11.06	0.03	
080	05:39:08.05	-01:56:07.7	17.97	0.16	14.41	0.04	12.60	0.03	
081	05:39:08.13	-01:57:21.4	17.92	0.10	16.82	0.08	15.89	0.08	
082	05:39:08.39	-01:55:05.8	18.44	0.27	16.12	0.07	14.60	0.04	
083	05:39:08.55	-01:54:55.1	99.99	9.99	99.99	9.99	16.59	0.53	
084	05:39:08.57	-01:55:01.3	15.44	0.04	12.64	0.03	11.33	0.03	
085	05:39:08.64	-01:55:21.7	99.99	9.99	17.77	0.17	15.18	0.04	
086	05:39:08.69	-01:54:59.9	15.02	0.04	11.93	0.03	09.94	0.03	
087	05:39:08.70	-01:55:33.1	17.90	0.07	13.93	0.03	11.55	0.03	
088	05:39:08.82	-01:56:48.3	19.23	0.28	17.14	0.14	15.51	0.11	
089	05:39:08.98	-01:54:52.9	19.71	0.35	15.50	0.04	13.34	0.03	
090	05:39:09.07	-01:56:44.5	15.84	0.04	12.71	0.03	11.27	0.03	

(a) IRS#1 optically-visible B0.5p from Garrison (1967);

Table 4.2 continued

ID	RA(1950.0)	DC(1950.0)	m_J	σ_J	m_H	σ_H	m_K	σ_K	Note ¹
091	05:39:09.14	-01:55:14.0	17.52	0.07	14.57	0.03	12.82	0.03	
092	05:39:09.40	-01:55:34.4	99.99	9.99	16.00	0.04	13.44	0.03	
093	05:39:09.60	-01:54:59.0	99.99	9.99	16.71	0.04	14.10	0.03	
094	05:39:09.81	-01:57:15.1	99.99	9.99	16.48	0.10	15.32	0.11	
095	05:39:09.86	-01:54:58.4	19.51	0.14	13.97	0.03	10.95	0.03	
096	05:39:09.86	-01:56:03.6	17.82	0.12	14.74	0.04	12.80	0.03	
097	05:39:09.88	-01:56:10.4	17.96	0.05	13.64	0.03	11.42	0.03	
098	05:39:09.89	-01:55:18.0	17.40	0.05	13.68	0.03	11.73	0.03	b
099	05:39:09.90	-01:54:41.2	20.77	0.49	17.97	0.15	15.01	0.04	
100	05:39:09.91	-01:54:53.8	99.99	9.99	18.06	0.17	14.98	0.06	
101	05:39:09.94	-01:55:23.5	99.99	9.99	18.26	0.24	15.43	0.08	
102	05:39:09.98	-01:56:05.1	15.74	0.04	12.56	0.03	10.93	0.03	
103	05:39:10.00	-01:56:39.1	99.99	9.99	99.99	9.99	16.25	0.20	
104	05:39:10.13	-01:55:37.9	17.45	0.07	14.34	0.04	99.99	9.99	
105	05:39:10.13	-01:55:37.9	17.76	0.09	13.96	0.04	11.73	0.03	
106	05:39:10.15	-01:56:06.3	99.99	9.99	15.76	0.08	12.96	0.03	
107	05:39:10.18	-01:55:39.4	17.39	0.07	14.01	0.04	12.20	0.03	
108	05:39:10.22	-01:55:00.2	19.65	0.50	19.71	0.59	16.74	0.21	
109	05:39:10.22	-01:55:10.0	99.99	9.99	17.63	0.14	14.14	0.04	
110	05:39:10.28	-01:56:25.8	17.41	0.06	14.06	0.03	12.36	0.03	
111	05:39:10.33	-01:55:44.8	19.93	0.49	99.99	9.99	17.11	0.55	
112	05:39:10.39	-01:54:38.4	99.99	9.99	99.99	9.99	16.43	0.68	
113	05:39:10.48	-01:55:49.6	15.35	0.04	12.37	0.03	10.55	0.03	
114	05:39:10.51	-01:57:24.6	19.46	0.29	16.37	0.08	14.02	0.04	
115	05:39:10.52	-01:55:09.7	19.31	0.38	18.40	0.24	14.81	0.04	
116	05:39:10.56	-01:56:30.9	99.99	9.99	99.99	9.99	17.19	0.45	
117	05:39:10.61	-01:54:57.5	99.99	9.99	99.99	9.99	16.70	0.17	
118	05:39:10.69	-01:56:35.7	12.63	0.03	11.17	0.03	10.46	0.03	
119	05:39:10.80	-01:56:23.6	19.40	0.33	99.99	9.99	99.99	9.99	
120	05:39:10.88	-01:54:40.6	19.39	0.46	18.46	0.14	14.40	0.04	
121	05:39:10.94	-01:56:28.3	15.80	0.04	12.61	0.03	10.64	0.03	
122	05:39:10.99	-01:55:35.3	14.92	0.04	12.58	0.03	11.41	0.03	c
123	05:39:11.01	-01:57:30.5	99.99	9.99	99.99	9.99	16.56	0.11	
124	05:39:11.01	-01:57:43.4	14.39	0.04	12.17	0.03	11.37	0.03	
125	05:39:11.02	-01:57:03.3	20.46	0.56	14.95	0.04	12.66	0.03	
126	05:39:11.04	-01:55:28.5	16.49	0.05	13.52	0.03	11.73	0.03	
127	05:39:11.11	-01:55:12.2	99.99	9.99	99.99	9.99	15.24	0.08	
128	05:39:11.11	-01:56:11.5	15.24	0.04	12.38	0.03	10.89	0.03	
129	05:39:11.17	-01:55:57.0	18.32	0.13	16.59	0.10	15.39	0.11	
130	05:39:11.26	-01:56:05.0	17.95	0.15	15.24	0.06	13.75	0.06	
131	05:39:11.26	-01:56:07.1	18.51	0.32	16.86	0.21	15.92	0.37	
132	05:39:11.29	-01:55:41.5	99.99	9.99	99.99	9.99	99.99	9.99	
133	05:39:11.30	-01:56:01.9	14.48	0.04	11.91	0.03	10.61	0.03	
134	05:39:11.36	-01:57:48.0	99.99	9.99	15.56	0.03	13.21	0.03	
135	05:39:11.39	-01:54:41.7	99.99	9.99	17.09	0.08	13.67	0.04	

(b) FIR1 from Mezger *et al.* (1992)?; (c) FIR2 from Mezger *et al.* (1992)?;

Table 4.2 continued

ID	RA(1950.0)	DC(1950.0)	m_J	σ_J	m_H	σ_H	m_K	σ_K	Note ¹
136	05:39:11.52	-01:56:06.1	99.99	9.99	99.99	9.99	99.99	9.99	
137	05:39:11.62	-01:55:22.8	18.92	0.09	14.95	0.04	12.93	0.03	
138	05:39:11.67	-01:54:43.7	19.20	0.18	16.05	0.07	13.76	0.04	
139	05:39:11.71	-01:55:40.4	19.10	0.24	16.55	0.10	14.77	0.05	
140	05:39:11.74	-01:55:59.9	17.37	0.13	14.54	0.07	12.88	0.06	
141	05:39:11.78	-01:54:58.1	99.99	9.99	99.99	9.99	14.94	0.05	
142	05:39:11.82	-01:56:32.3	99.99	9.99	99.99	9.99	17.60	0.66	
143	05:39:11.86	-01:54:55.5	18.32	0.13	14.89	0.04	12.76	0.03	
144	05:39:11.95	-01:55:37.8	18.29	0.08	14.67	0.03	11.23	0.03	
145	05:39:12.00	-01:54:49.9	16.27	0.04	13.42	0.04	11.86	0.03	
146	05:39:12.01	-01:54:51.7	99.99	9.99	14.79	0.04	13.11	0.03	
147	05:39:12.03	-01:56:37.3	19.20	0.12	17.53	0.12	14.56	0.04	
148	05:39:12.05	-01:56:06.0	16.70	0.08	14.05	0.04	12.65	0.04	
149	05:39:12.07	-01:55:22.2	19.75	0.18	14.77	0.03	12.15	0.03	
150	05:39:12.24	-01:56:02.5	99.99	9.99	99.99	9.99	99.99	9.99	
151	05:39:12.28	-01:56:06.7	18.58	0.46	14.98	0.18	99.99	9.99	
152	05:39:12.29	-01:56:06.7	16.31	0.07	13.59	0.05	12.01	0.04	
153	05:39:12.29	-01:57:47.9	99.99	9.99	16.35	0.04	13.51	0.03	d
154	05:39:12.36	-01:55:03.9	20.24	0.76	16.85	0.05	13.75	0.03	
155	05:39:12.39	-01:55:59.7	99.99	9.99	99.99	9.99	99.99	9.99	
156	05:39:12.43	-01:54:54.6	17.84	0.08	14.20	0.03	12.38	0.03	
157	05:39:12.43	-01:55:16.8	16.59	0.04	14.79	0.03	13.37	0.03	
158	05:39:12.47	-01:56:02.0	99.99	9.99	15.14	0.16	13.47	0.10	
159	05:39:12.52	-01:56:33.1	19.18	0.19	15.40	0.04	13.46	0.03	
160	05:39:12.53	-01:55:28.5	99.99	9.99	18.45	0.40	15.75	0.16	
161	05:39:12.57	-01:56:08.4	99.99	9.99	14.78	0.03	13.07	0.13	
162	05:39:12.59	-01:56:10.4	18.37	0.47	14.92	0.10	99.99	9.99	
163	05:39:12.59	-01:56:10.4	99.99	9.99	15.08	0.10	12.04	0.04	e
164	05:39:12.63	-01:55:07.9	99.99	9.99	17.60	0.09	14.94	0.05	
165	05:39:12.64	-01:55:12.8	20.90	0.51	15.11	0.03	12.31	0.03	
166	05:39:12.65	-01:55:02.9	19.06	0.11	14.78	0.03	12.37	0.03	
167	05:39:12.66	-01:56:46.0	18.05	0.06	14.30	0.03	11.70	0.03	
168	05:39:12.66	-01:56:46.0	99.99	9.99	99.99	9.99	99.99	9.99	
169	05:39:12.72	-01:56:49.5	99.99	9.99	99.99	9.99	11.85	0.03	
170	05:39:12.74	-01:55:30.6	18.47	0.09	14.32	0.03	11.89	0.03	
171	05:39:12.74	-01:56:43.9	99.99	9.99	99.99	9.99	14.53	0.11	
172	05:39:12.75	-01:56:20.9	99.99	9.99	15.05	0.04	12.24	0.03	
173	05:39:12.81	-01:56:50.5	14.67	0.04	12.51	0.03	11.43	0.03	
174	05:39:12.87	-01:55:45.8	18.42	0.26	14.40	0.04	12.32	0.04	
175	05:39:12.89	-01:56:48.5	13.47	0.04	11.36	0.03	10.24	0.03	f
176	05:39:12.90	-01:55:01.4	99.99	9.99	16.11	0.05	13.69	0.04	
177	05:39:12.93	-01:56:48.0	99.99	9.99	11.91	0.03	10.17	0.03	
178	05:39:13.03	-01:55:22.6	99.99	9.99	17.55	0.10	15.50	0.06	
179	05:39:13.09	-01:57:19.0	19.22	0.16	18.24	0.27	15.64	0.10	g
180	05:39:13.19	-01:55:45.9	99.99	9.99	15.92	0.20	14.18	0.15	

(d) IRS#31 from Barnes *et al.* (1989); (e) FIR4 from Mezger *et al.* (1992)?;(f) IRS#3 from Mezger *et al.* (1992)?; (g) associated with outflow NS1 from Chernin (1995)?;

Table 4.2 continued

ID	RA(1950.0)	DC(1950.0)	m_J	σ_J	m_H	σ_H	m_K	σ_K	Note ¹
181	05:39:13.21	-01:55:56.6	18.97	0.59	99.99	9.99	16.06	0.42	
182	05:39:13.27	-01:55:14.0	19.15	0.12	15.35	0.04	12.92	0.03	
183	05:39:13.34	-01:55:50.6	13.14	0.04	10.44	0.03	99.99	9.99	
184	05:39:13.35	-01:56:01.3	15.61	0.05	12.60	0.03	10.87	0.03	
185	05:39:13.44	-01:55:27.0	99.99	9.99	19.07	0.39	16.67	0.18	
186	05:39:13.49	-01:56:07.8	99.99	9.99	99.99	9.99	15.92	0.48	
187	05:39:13.55	-01:56:20.3	99.99	9.99	15.01	0.05	12.67	0.04	
188	05:39:13.58	-01:55:31.8	17.59	0.05	12.98	0.03	10.31	0.03	
189	05:39:13.63	-01:56:12.6	15.23	0.04	11.73	0.03	09.68	0.03	
190	05:39:13.75	-01:55:48.3	16.99	0.05	13.40	0.03	11.51	0.04	
191	05:39:13.81	-01:54:60.0	19.01	0.16	16.01	0.04	13.97	0.03	
192	05:39:13.81	-01:57:37.8	99.99	9.99	99.99	9.99	17.65	0.25	
193	05:39:13.83	-01:56:28.2	17.19	0.07	13.94	0.03	12.19	0.03	
194	05:39:13.86	-01:55:49.3	99.99	9.99	13.39	0.04	13.08	0.07	
195	05:39:13.90	-01:55:21.7	18.81	0.11	14.68	0.03	12.65	0.03	
196	05:39:13.94	-01:57:42.6	11.64	0.03	11.11	0.03	10.84	0.03	
197	05:39:14.01	-01:55:54.0	12.15	0.03	99.99	9.99	99.99	9.99	
198	05:39:14.04	-01:55:45.7	99.99	9.99	99.99	9.99	14.89	0.40	
199	05:39:14.18	-01:55:50.4	99.99	9.99	99.99	9.99	10.62	0.03	
200	05:39:14.20	-01:56:30.3	17.63	0.08	13.71	0.03	11.75	0.03	
201	05:39:14.22	-01:56:14.9	16.25	0.06	13.52	0.03	11.63	0.03	
202	05:39:14.23	-01:56:23.5	17.59	0.13	15.73	0.09	14.21	0.07	
203	05:39:14.28	-01:55:31.6	99.99	9.99	99.99	9.99	99.99	9.99	
204	05:39:14.38	-01:55:10.2	16.56	0.05	13.93	0.03	12.55	0.03	
205	05:39:14.38	-01:55:56.2	11.33	0.03	99.99	9.99	99.99	9.99	h
206	05:39:14.41	-01:55:36.4	16.56	0.04	12.98	0.03	11.01	0.03	
207	05:39:14.42	-01:57:52.1	99.99	9.99	15.32	0.03	11.18	0.03	
208	05:39:14.47	-01:56:27.3	16.52	0.05	12.83	0.03	10.70	0.03	
209	05:39:14.60	-01:55:07.4	99.99	9.99	99.99	9.99	15.76	0.24	
210	05:39:14.63	-01:55:40.1	18.63	0.07	14.31	0.03	12.19	0.03	
211	05:39:14.72	-01:56:58.7	99.99	9.99	99.99	9.99	14.16	0.12	
212	05:39:14.74	-01:55:12.1	13.91	0.04	11.30	0.03	10.13	0.03	
213	05:39:14.91	-01:55:43.5	99.99	9.99	99.99	9.99	15.29	0.19	
214	05:39:15.07	-01:56:12.3	99.99	9.99	14.74	0.04	11.87	0.03	
215	05:39:15.20	-01:56:10.2	99.99	9.99	18.84	0.31	14.48	0.08	
216	05:39:15.30	-01:56:14.4	99.99	9.99	16.60	0.09	14.04	0.05	
217	05:39:15.42	-01:56:12.2	19.35	0.14	19.49	0.64	15.71	0.23	
218	05:39:15.55	-01:56:18.2	99.99	9.99	99.99	9.99	99.99	9.99	
219	05:39:15.83	-01:56:12.1	99.99	9.99	16.12	0.06	13.13	0.03	
220	05:39:15.94	-01:56:51.7	99.99	9.99	99.99	9.99	14.83	0.10	
221	05:39:16.04	-01:56:32.3	18.96	0.27	17.49	0.34	15.08	0.14	
222	05:39:16.17	-01:55:00.6	18.71	0.18	17.29	0.10	16.37	0.12	
223	05:39:16.20	-01:55:20.3	18.78	0.24	16.60	0.08	15.05	0.04	
224	05:39:16.33	-01:57:48.1	18.16	0.08	99.99	9.99	99.99	9.99	
225	05:39:16.43	-01:57:06.9	99.99	9.99	99.99	9.99	15.30	0.09	

¹ (h) IRS#2 from Grasdalen (1974).

Table 4.2 continued

ID	RA(1950.0)	DC(1950.0)	m_J	σ_J	m_H	σ_H	m_K	σ_K	Note ¹
226	05:39:16.49	-01:55:23.6	18.68	0.17	14.64	0.03	12.65	0.03	
227	05:39:16.62	-01:56:41.7	99.99	9.99	99.99	9.99	99.99	9.99	
228	05:39:16.64	-01:56:30.9	17.48	0.19	15.46	0.10	14.54	0.10	
229	05:39:16.67	-01:57:51.4	18.47	0.15	99.99	9.99	99.99	9.99	
230	05:39:16.70	-01:57:27.3	99.99	9.99	13.50	0.03	11.06	0.03	
231	05:39:16.75	-01:57:43.6	99.99	9.99	18.26	0.44	15.38	0.10	
232	05:39:16.77	-01:56:53.6	18.76	0.50	17.01	0.65	99.99	9.99	
233	05:39:16.83	-01:55:51.5	17.57	0.09	15.41	0.05	14.00	0.04	

4.1.2 Color–Color and Color–Magnitude Diagrams

In Figure 4.2A, we present the near-infrared $(J - H)$ versus $(H - K)$ color–color diagram for this sample of 118 stars. Given the expected number of foreground and background stars based on the small projected area of our survey and the large column density of extinction provided by the dense molecular cloud core, we expect that our survey is dominated by cluster members (e.g. predictions based on the model by Jarrett, 1992). The intrinsic colors of main sequence and giant stars are shown, as are the slope and magnitude of the interstellar reddening vector. The CTTS locus as defined in Chapter III is also indicated. Because of the small projected area of the cluster and the large column density of the cloud, we can assume that background contamination in the photometric sample is negligible. About half of the stars in this sample have colors similar to those of reddened main sequence stars, WTTS, or CTTS with modest near-IR excess emission. The other half of the sample contains a mix of colors suggesting the presence of a few early-type stars with IR excess emission, significant numbers of heavily accreting CTTS, and a few objects with extreme IR colors. The near-infrared $(J - H)$ versus M_J color–magnitude diagram is shown in Figure 4.2B. For comparison with the data, the zero-age main sequence is shown along with the 3×10^5 yr isochrone from the PMS evolutionary models of D’Antona and Mazzitelli (1994) assuming a distance modulus of 8.36 ($d = 470$ pc). The choice of 3×10^5 yr is motivated by the fact that our survey area is 0.5×0.5 pc² suggesting that stars residing within it have ages $< 1 \times 10^6$ yrs ². Our completeness limit of $J = 18.75^m$ is indicated and the ISR vector is shown projected up to 19^m of visual extinction. This represents the limit for which we completely sample the 3×10^5 yr isochrone down to $0.1M_\odot$. A large fraction of our

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² The peculiar motions of a star moving at 1 km sec^{-1} for 10^6 yrs would take it a distance of 1 pc, beyond our survey area.

sample lies within the area spanned by this isochrone and the ISR vector. If this isochrone accurately represents the mass–luminosity relationship appropriate for this cluster then it appears that our photometric sample is comprised of stars with masses from the hydrogen burning limit to greater than $2.5 M_{\odot}$.

Figure 4.2. A. Near-infrared color-color diagram for the embedded cluster associated with NGC2024. All colors are presented in the CIT photometric system. B. Near-infrared color-magnitude diagram for the same cluster. The cluster is shown compared with the isochrone corresponding to the median age of 3×10^5 yr. The completeness limits of the survey ($J_{comp} = 18.75^m$ and $H_{comp} = 18.0^m$) are indicated.

4.2 Spectroscopic Survey

4.2.1 Observations and Data Reductions

We obtained near-infrared spectra for 33 sources selected from our preliminary near-infrared photometric survey described in Appendix B. H- and K-band spectra were obtained with the CRSP instrument as described in Chapter II on the 2.1m and 4.0m telescope at Kitt Peak National Observatory in Arizona. Sources were chosen to sample the color-magnitude and color-color planes in a representative fashion. The data were reduced using a procedure identical to the MK standards and optically-visible YSOs discussed in Chapter II with the following exceptions. When the H-band integration time exceeded 60 seconds, variations in the OH night-sky emission lines dominated the background fluctuations. As a result, our median-filtered background frames were not appropriate and single frames that did not contain overlapping spectra were subtracted from each other to remove the background. For spectra with low SNR, we were unable to determine accurate linear shifts to our dispersion solutions. In these instances, we did not attempt to apply shifts to the spectra before making the telluric corrections. Each observation consisted of a set of 5 independent spectra and these were averaged to produce the final spectra shown in Figure 4.3–Figure 4.5. Spectral types were derived for 22 embedded sources from comparison with the grid of MK standards using visual classification. The remaining objects were either assigned upper or lower limits to their effective temperatures (4), categorized as continuum plus emission-line sources (4), or unclassifiable (3). Classifications were assigned twice independently for each source and in all cases the spectral types agreed to within the errors quoted. These classifications are listed in Table 4.3.

Table 4.3. Embedded Sources in NGC2024 Observed with CRSP

ID	IREX ¹	Sp. Typ ²	lg(T_{eff})	lg($L^*/L_{\odot}$)	A_V	M_J	$M^*/M_{\odot}$	Note ³
027	RMS	M2 $\pm$ 2	3.544	0.644	7.36	1.39	0.12	
064	RMS	M1:	3.562	-0.20	0.00	3.53	0.30	
056	RMS	M1:e	3.562	0.033	5.87	2.95	0.26	
051	RMS	M1 $\pm$ 3	3.562	0.453	11.42	1.90	0.21	
032	RMS	M0e $\pm$ 2	3.580	0.549	7.92	1.70	0.25	
078	RMS	M0 $\pm$ 3	3.580	0.962	15.10	0.67	0.21	
126	CTTS	M1 $\pm$ 3	3.580	-0.04	17.0	3.24	0.33	
038	RMS	K7:	3.602	0.453	8.73	1.99	0.34	
212	RMS	K5 $\pm$ 2	3.638	0.962	16.69	0.81	0.57	
184	CTTS	K1:e	3.705	0.539	17.80	2.13	1.61	
175	RMS	K0 $\pm$ 3	3.720	0.974	14.04	1.12	2.36	a
183	CTTS	G8e $\pm$ 3	3.740	1.320	15.80	0.35	> 3.00	
043	CTTS	G5 $\pm$ 3	3.760	1.100	3.40	1.00	2.68	
065	CTTS	F5 $\pm$ 5	3.809	1.129	3.60	1.14	1.90	
B029	CTTS	F0 $\pm$ 5	3.857	1.280	0.00	0.97	2.07	b
B002	CTTS	F0 $\pm$ 5	3.857	1.788	7.70	-0.30	> 3.00	b
197	CTTS	F0:e	3.857	1.971	14.90	-0.76	> 3.00	
074	CTTS	A5e $\pm$ 5	3.914	1.133	6.50	1.72	1.94	
B028	RMS	A0 $\pm$ 5	4.000	2.074	10.39	-0.06	2.81	b
046	FS	B5 $\pm$ 5	4.188	3.7:	5.0:	-2.65	> 3.00	c
205	FS	cont+e		> 3.0				d
201	CTTS	cont+e			12.7	4.13		
121	CTTS	> G5e	< 3.760		18.2	2.19		
086	CTTS	cont+e			16.7	1.82		
017	CTTS	cont+e			3.9	2.11		
B003		< G5	> 3.760					e
F060		> K0	< 3.720					
F222		> K0	< 3.720					
ANON2		K0III	3.676					e, f
B027		M1:	3.562					e

¹ Based on the near-IR color-color diagram discussed in Chapter III.

² "e" denotes the presence of emission-lines in the IR spectrum.

³ Notes: (a) source has a close companion; (b) NICMASS photometry was used; (c) IRS#1 optically-visible B0.5p from Garrison (1967); (d) IRS#2 from Grasdalen (1974). (e) no photometry was available; (f) possible background star;

Figure 4.3. Representative spectra of embedded YSOs in NGC2024 taken at our grating setting H/2283.

Figure 4.4. Representative spectra of embedded YSOs in NGC2024 taken at our grating setting K/3162.

Figure 4.5. Representative spectra of embedded YSOs in NGC2024 taken at our grating setting K/3343.

4.2.2 The Hertzsprung–Russell Diagram

Given the estimates of the spectral types derived above for our spectroscopic sample in NGC2024, we can place 19 of these sources on the H–R diagram in order to estimate their masses and ages. Stellar luminosities were derived from bolometric corrections applied to absolute J-band magnitudes as described in Chapter III. The extinction toward each source was estimated from the near-infrared colors as follows. For sources with infrared colors that lie within the locus reddened main sequence stars in the $(J - H)$ versus $(H - K)$ color-color diagram, we estimated the extinction from the color excess

$$E(J - H) = (J - H) - (J - H)_o$$

where intrinsic $(J - H)_o$ color is given by the spectral type. For sources with colors similar to reddened classical T Tauri with obvious IR excesses, we estimate the reddening relative to the CTTS locus defined in Chapter III. We used the JHK photometric survey data described above for 16 stars in our spectroscopic sample and NICMASS data for three additional stars described in more detail in Appendix B. We have adopted the temperature scale of Schmidt–Kaler (1982) for spectral types B8–K5 and Bessell (1991) for spectral types K5–M5. The resulting H–R diagram is shown in Figure 4.6 for 19 stars ³. The uncertainties in luminosity are dominated by uncertainties in J-band photometry, extinction estimates, and errors in bolometric corrections. The typical formal error in luminosity is indicated in Figure 4.6 as $\sigma(\log[L_*/L_\odot]) = 0.2$. Errors in our derived spectral types are typically ± 3 subclasses. This translates into an error in T_{eff} of $\sigma(\log[T_{eff}]) = 0.04$. An error bar corresponding to this typical error is also shown in Figure 4.6. For

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Of the 22 stars for which we derived spectral types, one appears to be a background giant star (Anon 1) which lies outside our photometric survey, one lacks accurate photometry (B027), and one is an early-type B5 star (ID046).

comparison, we plot the PMS evolutionary models of D'Antona and Mazzitelli (1994) with Alexander opacities and Canuto and Mazzitelli convection.

Figure 4.6. An HR diagram for 19 embedded cluster members with spectral types derived from near-infrared spectroscopy. Also plotted are the PMS isochrones and mass tracks of DM adopting Alexander opacities and Canuto–Mazzitelli convection.

Inspection of the H–R diagram indicates that many of the stars appear to be extremely young. The median age of the group is 3×10^5 yr according to the DM tracks and 1×10^6 yr according to the Swenson tracks. However, as discussed in Chapter III, it is difficult to assign physical ages to PMS stars directly based on the Kelvin–Helmoltz contraction times given by the PMS evolutionary tracks. It is interesting to note that the upper envelope of points on this H–R diagram is qualitatively similar to the stellar birthline of Stahler (1988) and Palla and Stahler (1993). The effect of taking into account the stellar birthline is to make the ages of the higher mass stars younger, bringing them into better agreement with the ages found for the low mass stars. Because of the high stellar density in this region, the cluster is expected to be very young. If the high mass stars in the cluster were actually 3×10^6 yr old, they would have expanded into a volume $\times 10$ that which they currently occupy ($\sim 0.1 \text{ pc}^{-3}$) given a velocity dispersion of $1\text{--}2 \text{ km sec}^{-1}$. It is clear that a re-evaluation of the theoretical isochrones is in order. Further, the locus of points in the H–R diagram matches well those observed in other star-forming regions thought to be extremely young such as Ophiuchus (Greene and Meyer, 1995) and the Trapezium Cluster (Hillenbrand, 1995). Studies of other, lower-density star-forming regions such as Taurus (Kenyon and Hartmann, 1995) and L1641 (Allen, 1995), suggest that they might be older and exhibit a large range of ages. By placing many stars on the H–R diagram, one might have enough confidence in the locus to derive an empirical birthline or, perhaps more appropriately, “birthband” from the data. Such a locus could place important constraints on the evolutionary status and accretion history of a young cluster. The H–R diagram suggests that the cluster is quite young and co-eval to within the inferred age ($\Delta t \ll 3 \times 10^6$ yr) as suggested by the high stellar density.

The masses of cluster members stars inferred from the H–R diagram range from less than $0.3 M_{\odot}$ to greater than $2.5 M_{\odot}$. This spectroscopic sample appears

to contain several intermediate mass stars; 10/19 have masses $> 1.0M_{\odot}$. This reflects an observational bias towards the observation of high luminosity stars in the cluster. Our spectroscopic survey is thought to be representative of stars with $M_J < 2.5^m$. We have indicated this completeness limit on the H–R diagram of Figure 4.6 by making appropriate bolometric corrections as a function of T_{eff} . We reiterate that these tracks agree with dynamical mass ratios calculated from spectroscopic binary orbits suggesting uncertainties $\sim 30\%$ in mass. However these tests do not extend much below $1.0 M_{\odot}$. Based on comparison of the PMS sequence models of DM and Swenson *et al.*, we estimate that mass estimates based on PMS tracks below $1.0 M_{\odot}$ are uncertain to within $\times 2$. The masses inferred for each star are listed in Table 4.3.

4.2.3 Deriving the Mass–Luminosity Relationship

As discussed in Chapter III, we need to define the mass–luminosity relationship for an embedded cluster in order to interpret the stellar luminosity function in terms of stellar masses. From the H–R diagram presented above, we can infer a mass for each star from the theoretical mass tracks. By plotting absolute J–band magnitude against stellar mass we can attempt to derive a mass–luminosity relationship for the embedded cluster associated with NGC2024 in spite of the difficulty we face interpreting the theoretical isochrones. In Figure 4.7 we present this mass–luminosity plot for the spectroscopic sample observed in NGC2024 along with the relationships derived from the DM isochrones. There is clearly a trend of mass with luminosity in this diagram. However, there is a large amount of scatter in absolute J–band magnitude for a fixed mass range. In particular, stars with masses $M_{\star} < 0.5M_{\odot}$ span a range of $\Delta M_J = 3.0^m$! We conclude that it is not possible to derive a unique mass– M_J relationship for the embedded cluster associated with NGC2024.

Figure 4.7. The mass–luminosity relationship for the embedded cluster associated with NGC2024. Masses are inferred from the H–R diagram in Figure 4.6 and plotted against M_J . Shown for comparison are the PMS isochrones of DM. As discussed in the text, we adopt $M_J = 1.5 \pm 0.5^m$ as the absolute J–band magnitude corresponding to $1 M_{\odot}$.

Despite this complication, there are still two quantities we can extract from the observed mass-luminosity relationship which will permit us to characterize the distribution of stellar masses in the embedded cluster. First, we note that the lowest mass stars have apparent ages corresponding to the youngest PMS isochrones. If we adopt a mass-luminosity relationship associated with one of the isochrones, we can estimate the absolute magnitude down to which we must probe in order to completely sample the cluster at $0.1M_{\odot}$. For the 3×10^5 yr isochrone, corresponding to the median age of the cluster inferred from the H-R diagram, this value is $M_J = 5.4^m$. Further, we can constrain the relationship of mass and absolute J-band magnitude in a crude way, by estimating the luminosity M_J corresponding to $1.0 M_{\odot}$. This quantity enables us to calculate the ratio of intermediate to low mass stars from the stellar luminosity function. Inspection of Figure 4.7 indicates this is not a straightforward task. There is clearly an envelope of absolute J-band magnitudes $M_J = 1.0 - 2.0^m$ which spans a range of masses around $1.0 M_{\odot}$. Taking the average of M_J for the two points on either side of $1.0 M_{\odot}$ yields $M_J(1.0M_{\odot}) = 1.5^m \pm 0.5^4$. The uncertainties come from the spread in M_J about $1.0 M_{\odot}$. Adopting this as the “break-point” between greater than or less than $1.0 M_{\odot}$ leaves two stars with masses $> 1.0M_{\odot}$ below this threshold and three stars with masses $< 1.0M_{\odot}$ above. Using this value of M_J as the absolute magnitude for a $1.0 M_{\odot}$ allows us to determine the ratio of intermediate to low mass stars in a statistical sense. The uncertainty in our determination of M_J can be translated into uncertainties in the calculated ratio of intermediate to low mass stars.

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This value also corresponds with the point on the 3×10^5 yr isochrone for $1.0 M_{\odot}$.

4.3 Characterizing the Emergent Mass Distribution

We now use the technique of Chapter III in order to characterize the emergent mass distribution for the photometric database. Each was dereddened according to their position in the color-color diagram. Stars that lie within the reddened CTTS locus were dereddened to that locus and stars that lie within the reddened main sequence were dereddened to the “mean isochrone” in the color-magnitude diagram. With our completeness limit of $J_{comp} = 18.75^m$, we fully sample the 3×10^5 yr isochrone down to $0.1 M_{\odot}$ for visual extinctions of $A_v < 19^m$. The stellar luminosity function for this A_v -limited sample of 72 stars is shown in Figure 4.8.

Figure 4.8. Stellar luminosity function constructed for NGC2024 using A_v -limited sample of 72 stars. Also shown are the adopted absolute magnitudes for a $1 M_{\odot}$ star as discussed in the text and a $0.1 M_{\odot}$ star from the 3×10^5 yr isochrone of DM.

From the above calibration of the mass–luminosity function we can directly calculate the ratio of intermediate to low mass stars from this luminosity function. There are 14 stars with $M_{J_*} < 1.5^m$ ($M_* > 1.0M_\odot$) and 58 stars with $M_{J_*} > 1.5^m$ ($M_* < 1.0M_\odot$) resulting in a ratio:

$$N(10M_\odot > M_* > 1M_\odot)/N(0.1M_\odot < M_* < 1M_\odot) = 0.24 \pm 0.14$$

where the uncertainties come from calculation of the ratio using the plausible limits of $M_J(1.0M_\odot)$. The most likely value expected from integrating the Miller–Scalo IMF is 0.17. In order to assess the significance of this result, we have constructed the probability distribution for this ratio using the technique described in Chapter III. For a sample of 72 stars we computed the probability distribution for observed values of the ratio of intermediate to low mass stars as drawn from a Miller–Scalo IMF. This probability distribution is shown in Figure 4.9. We find that the probability of observing this ratio *or higher* is about 0.24 for 72 stars drawn from a Miller–Scalo IMF. In other words we would observe this ratio or higher in one out of every four clusters sampled if the regions had emergent mass distributions identical to the Miller–Scalo IMF. Although the cluster associated with NGC2024 is forming more intermediate mass stars than one would naively predict from the Miller–Scalo IMF, the result is not statistically significant. We note that there are five stars included within our A_V -limited sample with luminosities below the $0.1 M_\odot$ limit, indicating that they are either lower mass stars or have ages greater than 3×10^5 yr.

Figure 4.9. The probability distribution for observed ratios of intermediate to low mass stars for 72 stars drawn from a Miller–Scalo IMF. The observed ratio for the embedded cluster associated with NGC2024 is 0.24 ± 0.14 .

4.4 Circumstellar Properties of Embedded Cluster Members

Having defined a complete A_v -limited sample in the previous section, we can determine the frequency of embedded cluster members having near-infrared excess emission in an unbiased way. For our sample of 72 stars, the fraction of objects that lie to the left of the reddened main sequence in the $(J - H)$ versus $(H - K)$ color-color diagram is $F_{IREX} = 0.45 \pm 0.08$. This is similar to the fraction of T Tauri stars in Taurus that lie in this region of the color-color diagram. However, the true fraction of objects in Taurus with active disk accretion is higher than those selected in the near-infrared color-color diagram. Only 2/3 of T Tauri stars with spectroscopic evidence for disk accretion are diagnosed with obvious near-infrared excess emission in the JHK diagram.⁵ If the accretion properties of the cluster associated with NGC2024 are similar to those of T Tauri stars in Taurus, then the true fraction of objects with active accretion disks is $F_{acc} = 0.68$. Confirmation of this results awaits the acquisition of longer wavelength photometric data.

Given the distinction made in the previous section between stars of intermediate and low mass, we can investigate the circumstellar properties of our photometric sample as a function of mass. In Figure 4.10 we present the near-infrared color-color diagram for the 72 stars in our A_v -limited sample this time indicating those stars with masses greater than $1 M_\odot$. There is no significant difference in the frequency of obvious near-IR excess emission between the intermediate mass and low mass samples. The fraction of objects with discernible near-IR excess emission among the higher mass sources is

$$F_{IREX}(M_* > 1.0 M_\odot) = 0.50 \pm 0.19$$

5

However we note that there is nearly a one-to-one correspondence between the presence of spectroscopic evidence for accretion and detectable $(K - L)$ excess among T Tauri stars in Taurus (HEG).

and among the lower mass stars

$$F_{IREX}(M_* < 1.0M_{\odot}) = 0.43 \pm 0.09$$

where we have indicated Poisson errors in the excess frequency. Previous work has suggested that circumstellar disks may evolve more quickly around stars of higher mass. Hillenbrand *et al.* (1993) observe that young clusters rich in intermediate mass stars contain few Herbig Ae/Be stars, intermediate mass YSOs with IR excesses indicative of circumstellar disks and/or envelopes. These authors suggest that perhaps the Herbig Ae/Be phase is much shorter than the analogous T Tauri phase of lower mass YSOs thought to last $\sim 3 \times 10^6$ yr (Strom, Edwards, and Skrutskie, 1993). However even among the spectroscopic sample, there is no suggestion that higher mass stars have weaker infrared excess emission. In fact as seen in Table 4.3, 8/10 of the intermediate mass stars for which we derived spectral types have near-IR excess. Perhaps in extremely young clusters such as that associated with NGC2024, even the most massive stars have not had time to dissipate their circumstellar disks.

Figure 4.10. The color-color diagram for NGC2024 restricted to the 72 stars with $A_V < 19^m$. There is no difference in the frequency of detectable near-IR excess as a function of stellar mass or depth of extinction in the cloud.

Finally, we investigate the frequency of near-IR excess emission as a function of A_V for our high luminosity (and presumably higher mass) sample. This might be expected if the A_V we derive in our photometric estimate was dominated by circumstellar obscuration in an extended envelope which might accompany hotter material responsible for IR excess emission. For those stars with inferred masses above $1 M_\odot$ we consider the IR excess frequency for an A_V -limited sample down to $A_V = 33^m$. There is no discernible difference in the fraction of IR excesses as function of A_V ⁶. We conclude that there is no evidence that the accretion properties of the more deeply embedded sources are any different from those suffering less extinction.

4.5 Summary

We have conducted an infrared spectroscopic and photometric study of the deeply embedded young cluster associated with the NGC2024 nebula. Combining near-infrared photometry with spectral types derived from H- and K-band spectra, we present an H-R diagram for some fraction of our photometric sample. Based on this diagram, we find the cluster to be extremely young and forming stars over a wide range of stellar masses. Adopting the mass-luminosity relationship of the 3×10^5 yr isochrone of DM at the low mass end, we have defined a sample of 72 stars with $A_V < 19^m$. Combining masses inferred from the H-R diagram with absolute J-band magnitudes, we adopt $M_J = 1.5^m$ as the “break-point” between intermediate and low mass stars. With this result we calculate the ratio of intermediate to low mass stars. There are more intermediate mass stars than expected for a Miller-Scalo IMF although this result is not statistically significant.

6

The frequency of IR excess emission for the high A_V ($M_* > 1M_\odot$) sample is

$$F_{IREX}(19^m < A_V < 33^m) = 0.29 \pm .14$$

For this complete sample, we compute the frequency of near-infrared excess emission among cluster members and find it to be similar to YSOs in the Taurus dark cloud. Further, there is no observable trend in the circumstellar properties of cluster members as a function of mass or depth into the cloud.

CHAPTER 5

COMPARISON OF EMBEDDED POPULATIONS IN NGC2024 AND OPHIUCHUS

Understanding the relationship (if any) between emergent mass distribution and star forming environment will require that we perform studies similar to the one outlined in Chapter IV for a large number of deeply embedded young clusters. One such complementary study exists for the embedded population found in the Ophiuchus molecular cloud cores. While NGC2024 is a region known to be forming high mass stars, the Ophiuchus cloud is forming predominantly intermediate and low mass stars. If environment plays a role in determining the emergent mass distribution, we might expect to see differences in the stellar mass distributions of these regions. We combine the photometric database of Strom, Kepner, and Strom (1995) with the near-infrared spectroscopic survey of Greene and Meyer (1995) in order to assess the properties of the embedded sources in Ophiuchus. We compare the stellar luminosity functions of the cluster associated with NGC2024 and the embedded population found in the Ophiuchus molecular cloud cores. There are three factors which could effect the shape of the luminosity function for an embedded cluster; age, accretion properties, and emergent mass distribution. We find that although the evolutionary states and accretion properties of both regions are quite similar, the stellar luminosity functions are different. We interpret this as a difference in their emergent mass distributions. Another difference between the two regions is the estimated stellar volume density, which is $\times 3$ higher in NGC2024. This suggests that there may be a relationship between emergent mass distribution and stellar density.

5.1 Evolutionary Status

Greene and Meyer (1995) have presented an H–R diagram for the Ophiuchus core population from effective temperatures derived from near-infrared spectroscopy of embedded YSOs . We reproduce this diagram in Figure 5.1 for comparison with our H–R diagram of the embedded cluster associated with NGC2024 in Chapter IV. Casual inspection of these H–R diagrams suggests that the evolutionary states of both clusters are quite similar. In both embedded populations, the median age is 3×10^5 yrs; early-type stars have apparent ages of about 3×10^6 yr, solar mass stars appear to be 1×10^6 yrs old, and the latest-type stars lie above the 1×10^5 yr isochrone. In order to quantify this comparison of the evolutionary states, we fit a power law to the locus of points observed in each H–R diagram of the form

$$\log(L/L_{\odot}) = \beta \times \log(T_{eff}) + \alpha.$$

The results of these fits are summarized in Table 5.1. Within the errors, the fits are consistent with each other. In particular, the coordinates of the loci at $1 M_{\odot}$ are in agreement and correspond to a radius of $\sim 3.5 R_{\odot}$ (Table 5.1). As a further test, we compared the mass–luminosity relationships observed for both clusters in the M_J vs. $M_{\star}$ diagram (e.g. Figure 3.5). A two-dimensional KS test (Press *et al.*, 1995) indicates that both samples are consistent with having been drawn from the same parent population. Finally, we note that the mass–bolometric luminosity relationship for both NGC2024 and Ophiuchus appears to be flatter than that predicted by the PMS isochrones in the H–R diagram (thus the observed trend of age with mass discussed in Chapter IV). We find that $L_{\star} \sim M_{\star}$ rather than the $L_{\star} \sim M_{\star}^2$ predicted by the theoretical models ¹. Whether the positions of the stars represent descent down conventional Hyashi tracks or the intrinsic mass–radius

1

The mass–luminosity relationship on the main sequence is $L_{\star} \sim M_{\star}^{3.5}$.

Table 5.1. H-R Diagram Cluster Loci

Region	α	$\Delta\alpha$	β	$\Delta\beta$	$lg(L^*/L_{\odot})^1$	$(R^*/R_{\odot})^1$
NGC2024	-13.16	± 2.16	3.79	± 0.58	0.75	3.6
Ophiuchus	-16.82	± 1.78	4.77	± 0.49	0.67	3.3

¹ Luminosity and radius calculated from locus for 1 M_⊙ at $T_{eff} = 4677K$.

relationship defined by the accretion history of the cluster, this agreement suggests that both clusters have similar evolutionary states.

Figure 5.1. An HR diagram for 19 embedded cluster members with spectral types derived from near-infrared spectroscopy. Also plotted are the PMS isochrones and mass tracks of DM94 adopting Alexander opacities and Canuto–Mazzitelli convection.

5.2 Accretion Excess

Next we compare the accretion properties of both clusters. Excess emission due to accretion luminosity could contribute to the estimated stellar luminosity as discussed in Chapter III. Although we have minimized the effects of this excess emission by estimating stellar luminosities in the J-band, if the bulk accretion properties of NGC2024 cluster and the Ophiuchus samples were different, this could effect the observed luminosity functions. For the Ophiuchus sample, there are 32 stars with $A_v < 19.3^m$ when analyzing the data of Strom, Kepner, and Strom (1995) using the technique outlined in Chapter III. This is the A_v -limit imposed by requiring the SKS survey to sample completely the 3×10^5 yr isochrone down to $0.1 M_\odot$. The color-color diagram for the embedded population associated with the Ophiuchus cloud cores from Strom, Kepner, and Strom (1995; hereafter SKS) is shown in Figure 5.2 for this A_v -limited sample. Comparing this to Figure 4.10 indicates that when we restrict our consideration to the A_v -limited samples for both regions, we find no distinguishable difference. The two-dimensional KS test performed on these color-color diagrams indicates that the samples are consistent with having been drawn from the same parent population. The frequency of objects with discernible near-IR excess $F_{IREX} = 0.59 \pm 0.14$. If we assume this diagram uncovers the same fraction of objects with IR excess as it does in Taurus (see discussion Chapter IV), the true frequency of objects with active accretion disks in Ophiuchus is $F_{acc} = 0.89$. As this region is dominated by low mass stars, it is not worthwhile to compute statistics based on the segregation in mass ². It appears that the general accretion properties of the two clusters are quite similar. The fraction of objects with

2

Among the stars with masses $1.0\text{--}10.0 M_\odot$, two out of three show evidence of near-IR excess.

discernible IR excess for the A_v -limited samples in both clusters are consistent within the errors.

Figure 5.2. The color-color diagram for Ophiuchus restricted to the 32 stars with $A_V < 19.3^m$. There is no difference in the frequency of detectable near-IR excess as a function of stellar mass.

5.3 Emergent Mass Distributions

Armed with the knowledge that the evolutionary states and accretion properties of the two regions are similar, what can we say about their respective emergent mass distributions? We found in Chapter IV that although the embedded cluster associated with NGC2024 has more intermediate mass stars than one would naively predict from the Miller–Scalo IMF, this result is not statistically significant. Using a similar method, Greene and Meyer (1995) showed that adopting the 3×10^5 yr isochrone for the photometric sample of SKS, the ratio of intermediate to low mass stars was less than predicted from the Miller–Scalo IMF³. However this result was found not to be statistically significant. Within our ability to distinguish a difference, both regions appear to be forming stars with mass distributions consistent with the Miller–Scalo IMF. Yet given that both surveys are of similar sensitivity and physical resolution, it is advantageous to compare directly the derived luminosity functions rather than rely upon the translation of each into a mass function for comparison to the solar neighborhood IMF. The physical resolution is quite similar between the two surveys (450 AU in Ophiuchus vs. 470 AU in NGC2024) as is the A_v -limit for completeness (19.3^m in Ophiuchus vs. 18.9^m in NGC2024). Based on the above discussion, we believe the evolutionary states and accretion properties of both clusters to be comparable. As a result, the translation of absolute J-band magnitude into mass should be the same for both regions. Therefore a comparison of the stellar luminosity functions of both can be interpreted as a comparison of the emergent mass distributions, without the need to rely on PMS evolutionary tracks for the translation of luminosity into mass.

3

This ratio was found to be $N(2.5M_\odot > M_\star > 1.0M_\odot)/N(1.0M_\odot > M_\star > 0.1M_\odot) = 0.08$.

In Figure 5.3 we plot the absolute J-band luminosity functions for both of the embedded populations in Ophiuchus and the cluster associated with NGC2024. Both distributions have been normalized to unity; in Ophiuchus $N = 32$ whereas in NGC2024 $N = 72$ within the A_v -limited samples. Inspection of this figure suggests there is a hint that the NGC2024 cluster has a greater proportion of higher luminosity stars. We performed a KS test on the two distributions shown graphically in Figure 5.3. The KS test operates on the unbinned cumulative distributions and predicts the probability of observing the measured maximum difference (or greater) in the cumulative distributions if the two samples were drawn from the same parent population (Press *et al.*, 1995). The probability returned from this test on these distributions was $P(d > obs) = 0.04$. Thus we can reject the hypothesis that the luminosity functions of both regions were drawn from the same parent population at the 96 % confidence level. In other words, there is a 1/25 chance that we are making a mistake in rejecting this hypothesis. This difference in luminosity functions suggests that these regions are forming stars with different emergent mass distributions. The EMD of the embedded cluster associated with NGC2024 is forming a greater proportion of higher mass stars than the aggregates associated with the molecular cloud cores in Ophiuchus.

Figure 5.3. Comparison of the stellar luminosity functions constructed for the embedded cluster associated with NGC2024 and Ophiuchus. Both have been normalized to the total number of stars in each sample (72 for NGC2024 and 32 for Ophiuchus). The “break-point” between intermediate and low mass stars derived for NGC2024, $M_J(1.0 M_{\odot}) = 1.4^m$ is indicated.

5.4 Stellar Densities

Because the K-band observations probe more deeply into the cloud cores, source counts at this wavelength should provide the best comparison of the stellar volume densities. The surveys have K-band completeness limits that correspond to comparable absolute magnitudes. In Ophiuchus, this limit ($M_K = 8.2^m$) corresponds to an extinction limit of $A_v < 41^m$ for a $0.1 M_\odot$ star on the 3×10^5 yr isochrone. The extinction limit for which we are complete down to $0.1 M_\odot$ in NGC2024 is $A_v < 34^m$ ($M_K = 7.6^m$).

SKS report 119 sources detected down to their completeness limit at K-band in the three aggregates associated with the molecular cloud cores A (46 stars), B (42 stars), and E/F (31 stars). We measured the semi-major and semi-minor axes of the ellipses used to define the cloud core boundaries from Figure 1 of SKS and calculated volume densities assuming the stellar aggregates were distributed uniformly inside these regions. We took average values assuming the volumes were oblate and prolate spheroids. This resulted in densities of 850 pc^{-3} (core A), 1150 pc^{-3} (core B), and 340 pc^{-3} with a mean value of 780 pc^{-3} for all three aggregates. Because these aggregates cover the $A_v > 50^m$ contours of the cloud cores, there is a good chance that this K-band sample is incomplete. In that sense these stellar densities are lower limits. The near-IR survey of Comeron *et al.* (1993), thought to be complete to $K < 15.5^m$, indicates that the source counts as a function of magnitude flatten out or turn over between $K \sim 14 - 15^m$. As a result, the true volume density of stars is unlikely to be more than a factor of two higher. We also note that the three stars with the highest absolute J-band magnitude (those with inferred masses $> 1.0 M_\odot$) are all found in core A.

For the embedded cluster associated with NGC2024 we detected 218 sources at K-band within a projected area of 0.21 pc^{-2} . Again we assume that stars are distributed uniformly within a volume defined by the linear dimension observed on

the sky. Taking this volume to be a sphere we calculate $\rho_* = 3000 \text{ pc}^{-3}$ while taking it to be a cube gives $\rho_* = 2200 \text{ pc}^{-3}$. Our entire survey region is also contained within the $A_v > 50^m$ contour in the NGC2024 cloud core. However, our observations indicate that the distribution of sources as a function of K-band magnitude turns over at $K \sim 12 - 13^m$, nearly three magnitudes above our completeness limit. This is in agreement with previous observations by Lada *et al.* (1991a) and Hodapp (1994) over larger spatial scales. Again the stellar density quoted above is probably a lower limit, but the absolute number is probably within a factor of $\times 2$ higher.

From this analysis we conclude that the average stellar volume density in the Ophiuchus cloud cores is between 500–1500 stars pc^{-3} . In the cluster associated with NGC2024 the stellar average volume density is between 2000–5000 stars pc^{-3} . Regardless of the absolute values, it appears that the stellar volume density in NGC2024 cluster is about $\times 3$ that found in the Ophiuchus aggregates. This is consistent with the estimates of Lada *et al.* (1991a) in their comparison of stellar densities in Ophiuchus and NGC2024. Because these are *average* values, the *central* stellar densities could be much higher. This is likely the case in NGC2024 where there is evidence for subclustering, particularly in the vicinity of the two most luminous stars IRS#1 and IRS#2 (see Figure 4.1).

5.5 Summary

We have presented a detailed comparison of the embedded populations associated with NGC2024 and the Ophiuchus cloud cores. Based on comparison of the H–R diagrams for both clusters constructed from near-IR spectroscopic surveys, we conclude that the evolutionary states of both clusters are similar. Further, from comparison of the JHK color–color diagrams for complete samples in both clusters, we conclude that the accretion properties of NGC2024 and

Ophiuchus are similar. However, the K-S test reveals that there is only a $1/25$ chance that the stellar luminosity distributions were drawn from the same parent population. We interpret this as a difference in their emergent mass distributions. Finally, the computed stellar density for the embedded cluster associated with NGC2024 has a stellar volumes density $\sim \times 3$ higher than that observed in the Ophiuchus cloud cores. This suggests the possibility of a relationship between stellar density and emergent mass distribution in these embedded clusters.

CHAPTER 6

EMERGENT MASS DISTRIBUTIONS AND STAR FORMING ENVIRONMENT

In the previous Chapter we demonstrated that there is only a 4 % chance that the luminosity functions of the embedded populations associated with NGC2024 and with the Ophiuchus cloud cores are drawn from the same parent population. If we can interpret this difference as a difference in emergent mass distributions, then we can reject the null hypothesis proposed in the introduction at the 96 % confidence level: the initial distribution of stellar masses from a single “episode” of star formation is independent of local physical conditions. We have identified one variable which could be related to the emergent mass distribution. We offer the alternative hypothesis that the emergent mass distribution of a star-forming episode is related to the stellar density: regions of high stellar density form a greater proportion of intermediate mass stars than regions of lower stellar density. In this chapter we examine this possibility utilizing results from several studies of embedded clusters. We find some evidence for a trend in the ratio of intermediate to low mass stars as a function of stellar density. We discuss the implications of these results for the universality of the IMF and the formation of intermediate mass stars.

6.1 Synthesizing Results for Embedded Clusters

In order to investigate the proposed relationship between stellar density and emergent mass distribution, we seek to combine results for other embedded clusters with those obtained above for NGC2024 and Ophiuchus. We examine four well-studied star forming regions within 1 kpc of the sun. We have chosen those

regions which have been studied using techniques similar to those employed here with the exceptional inclusion of the Taurus aggregates defined in Chapter III. The nearby Taurus dark cloud does not suffer from the same complications that plague most other studies. As a result, results in Taurus can be compared to results obtained for the deeply embedded young clusters in a meaningful way. Our goal is to estimate the ratio of intermediate to low mass stars as a characterization of the emergent mass distribution. Further we determine the mean stellar density for each star-forming episode in order to see if these quantities are correlated.

6.1.1 The Taurus Aggregates

Although not strictly speaking an “embedded cluster”, the aggregates of Gomez *et al.* and the group associated with L1495E (Strom and Strom, 1994) can be thought of as analogous star-forming events (see Chapter III). Kenyon and Hartmann (1995; KH) present a comprehensive study of the stellar population in the Taurus dark cloud. The PMS tracks of DM suggest ages from $0.3 - 3 \times 10^6$ yr for the entire cloud population, however the aggregates tend to be younger as a group. The group surrounding the WTTS V410 Tau in L1495E also appears to be quite young, however there are a few stars with apparent ages of 3×10^6 yr or greater. KH discuss the incompleteness of the Taurus sample and find that it should be complete down to $0.2 M_{\odot}$. The ratio of intermediate to low mass stars in the aggregate population is

$$R_{int/low} = N(10.0M_{\odot} > M_{*} > 1.0M_{\odot})/N(1.0M_{\odot} > M_{*} > 0.1M_{\odot}) = 0.08$$

while in L1495E this ratio is 0.17. The expected Miller–Scalo value is 0.17 and both results are consistent with having been drawn from a Miller–Scalo IMF. These are probably upper limits on the ratio of intermediate to low mass stars, because both may contain more stars at very low masses. We determine the stellar

densities for the Taurus aggregates from Tables 3 and 4 of Gomez *et al.* (1993) in the manner described in the previous section. In their groups I–VI there are typically 10–20 stars within regions of radius 0.5–1.0 pc. Assuming the stars to be uniformly distributed in a sphere we calculate a mean stellar density of about 10 stars pc^{-3} . The same calculation for the 27 stars found within $r = 1.2$ pc in L1495E gives a stellar volume density of 4 stars pc^{-3} . These numbers are lower limits due to incompleteness, but are probably within a factor of $\times 2$ the correct value.

6.1.2 The Embedded Cluster Associated with the OMC2 Cloud Core

The embedded cluster associated with the OMC2 molecular cloud core in Orion A was the subject of an infrared survey by Jones *et al.* (1994); their data have been analyzed in a manner similar to that outlined in Chapter III (Meyer *et al.*, 1995). The evolutionary status of the cluster appears to be similar to that described above for NGC2024 and Ophiuchus¹. The ratio of intermediate to low mass stars for this cluster is $R_{int/low} = 0.07$ as defined above within an A_V -limited sample of $< 5^m$ and is consistent with the Miller–Scalo IMF. We calculate the stellar density based on the data presented in Jones *et al.* (1994). There are ~ 150 stars distributed over a projected area of radius ~ 1 pc. Assuming the stars are distributed uniformly in a box we calculate a stellar density of about 100 stars pc^{-3} . The survey of Jones *et al.* (1994) indicate that the KLF of the embedded cluster associated with the OMC2 cloud core turns over 1–2 magnitudes above the completeness limits of the survey ($K_{comp} = 14^m$). However, it should be remembered that the complete sample probed here is only the “surface population” found in the outer 5^m of visual extinction in the core. There is some

1

However due to a bias in the spectroscopic sampling of the stellar population, the cluster may be somewhat older.

evidence for sub-clustering within the inner radius of $\sim 0.3 \text{ pc}^2$. We adopt a stellar density of $\sim 500 \text{ stars pc}^{-3}$ with errors estimated on the order of $\times 2$.

6.1.3 The BD+40°4124 Stellar Aggregate

The stellar aggregate associated with BD+40°4124 is discussed by Hillenbrand *et al.* (1995; hereafter HMSS). This grouping of partially-embedded stars, surrounding the $13 M_{\odot}$ star BD+40°4124, is typical of the small clusters of lower luminosity companions found in the vicinity of Herbig Ae/Be stars (Hillenbrand, 1995). The cluster appears to be quite young based on the H-R diagram presented in Figure 7 of HMSS. All of the stars have ages less than $3 \times 10^6 \text{ yr}$. The ratio of intermediate to low mass stars was found to be $R_{int/low} = 0.45$ where the authors adopted the mass-luminosity relationship from the $3 \times 10^5 \text{ yr}$ isochrone. The ratio was found to be inconsistent with the hypothesis that the BD+40°4124 aggregate was drawn from a Miller-Scalo IMF at the 99 % confidence level. The stellar volume density inferred for the aggregate is $1500 \text{ stars pc}^{-3}$ based on the entire sample of 32 stars found within a spherical region of radius 0.17 pc .

6.1.4 The Coronet Cluster in Corona Austrinae

Willing *et al.* (1996) present a very deep near-infrared survey of the “Coronet” cluster associated with luminous young stellar object, R Cr A. The H-R diagram constructed from optically-visible sources that fall within the IR survey region suggest an older evolutionary state than described above for the other clusters. The $1 \times 10^6 \text{ yr}$ isochrone is probably a more accurate description of the locus for this cluster than the $3 \times 10^5 \text{ yr}$ isochrone. For a sample defined by the $1 \times 10^6 \text{ yr}$ isochrone, 45 probable association members are identified with

The stellar density inferred from Table 3 of Ali and DePoy (1995) for the OMC2 peak is $\sim 850 \text{ stars pc}^{-3}$.

$A_v < 40^m$. The ratio of intermediate to low mass stars is $R_{int/low} = 0.25$. This result is similar to that for the embedded cluster associated with NGC2024. There are more intermediate mass stars than expected, but the observed ratio is consistent with having been drawn from the Miller–Scalo IMF. The stellar density calculate over the entire 0.5 pc diameter mosaic gives 200–500 stars pc^{-3} , while the central stellar density for the inner 0.11 pc is 1950 stars pc^{-3} . For about 50 stars drawn from within a radius of 0.23 pc, we adopt a stellar volume density of 1000 stars pc^{-3} and consider the number accurate to within a factor of $\times 2$.

6.1.5 EMD as a Function of Stellar Density

We now combine the results for these four regions with those derived in Chapter V for NGC2024 and Ophiuchus. Relevant parameters for comparison between the six clusters under consideration are listed in Table 6.1. In Figure 6.1 1 we plot stellar density as a function of the ratio of intermediate to low mass stars as defined above about the “break-point” of $1 M_\odot$. The uncertainties given for the stellar density estimates are the $\times 2$ uncertainties discussed above. The uncertainties in the ratio of intermediate to low mass stars reflect the uncertainties in adopting the correct calibration of absolute J-band magnitude and stellar mass. We have examined the H–R diagrams for each cluster and found the $\pm 0.5^m$ uncertainty derived for NGC2024 as representative of those inferred from individual calibration of the mass–luminosity relationships. The range of possible values for $M_J(1M_\odot)$ result in a range of values for $R_{int/low}$ as derived from the A_V –limited luminosity functions of each cluster. We performed a linear least–squares fit to these data and the result is shown in Figure 6.1. The correlation coefficient for the fit is $r = 0.6$ which suggests that the distribution of points is marginally distinguished from random. There is a 1/5 chance of drawing these six points from a uniform distribution. Thus there is a hint that the ratio of

Table 6.1. Properties of Embedded Clusters

Name	N_*	Age	A_V -limit	$R_{int/low}$	D(pc)	$\rho_*(\text{pc}^{-3})$	T_{gas}
NGC2024	72	3×10^5 yr	18.9^m	0.24 ± 0.14	0.5	2000–5000	50K
Ophiuchus	32	3×10^5 yr	19.3^m	0.1 ± 0.04	0.5	500–1500	20K
Taurus	28	3×10^5 yr	5.0^m	0.08 ± 0.04	0.5	5–15	10K
OMC2 Orion A	107	1×10^6 yr	5.0^m	0.07 ± 0.04	1.0	200–1000	50K
BD+40°4124	32	3×10^5 yr	20.0^m	0.45 ± 0.15	0.34	800–3000	30K
R Cr A	45	1×10^6 yr	40.0^m	0.25 ± 0.07	0.5	500–1500	15K

intermediate to low mass stars is related to the stellar density of the star-forming region. Also indicated in Figure 6.1 is the ratio expected for a population drawn from a Miller–Scalo IMF ($R_{int/low} = 0.17$).³ Because each cluster contains a different number of stars, the probability of drawing each ratio from the MS79 IMF is different (see Figure 4.9). Only for the aggregate associated with the Herbig Ae/Be star BD+40°4124, is the ratio of intermediate to low mass stars inconsistent with the Miller–Scalo IMF. This illustrates the added power of inter-comparing results for several clusters rather than testing each against the field star mass function. While most of our clusters cannot be distinguished from the Miller–Scalo IMF, we see some evidence for a trend of emergent mass distribution with stellar density among the whole sample.

3

The ratio of intermediate to low mass stars calculated from the Kroupa *et al.* IMF is $R_{int/low} = 0.10$ while the corresponding Salpeter (1955) value is $R_{int/low} = 0.04$.

Figure 6.1. The ratio of intermediate to low mass stars shown as a function of stellar density for six embedded clusters. The errors bars are calculated as described in the text. The value for this ratio as calculated from the Miller-Scalo IMF is 0.17 while the Kroupa IMF yields 0.10 and the Salpeter IMF 0.04. The correlation coefficient given for the fit indicates that these six points have a 1:5 chance of being drawn from a random distribution.

6.2 Implications for the Origin of the IMF

In the preceding section, we demonstrated two features of the emergent mass distributions of deeply embedded young clusters: i) star-forming episodes which give rise to mass distributions radically different from the field star IMF are relatively rare; and ii) there appears to be a relationship between stellar density and the frequency of intermediate mass stars found in embedded clusters. What implications could these results have for the origin of the initial mass function?

Although we have rejected the hypothesis that the IMF is strictly universal, we find that gross deviations from the field star IMF appear to be rare. This suggests that the physics responsible for the IMF between $0.1\text{--}1.0M_{\odot}$ is similar under a range of initial conditions. For example, the ratio of intermediate to low mass stars does not appear to change abruptly with cloud temperature. The three lowest stellar density regions, all with $R_{int/low} < 0.17$, span a range of cloud temperature $T_{cl} = 10 - 40K$. Predictions based on theories of sheet fragmentation suggest that the minimum mass star formed scales as $M_{*min} \sim T_{cl}^2/\mu$, where μ is the mass surface density (Larson, 1992; 1985). Thus a change in cloud temperature from 10K to 20K would correspond to changing the minimum stellar mass from $0.1M_{\odot}$ to $0.4M_{\odot}$. For a fixed Miller–Scalo IMF this corresponds to changing the ratio of intermediate to low mass stars from $R_{int/low} = 0.17$ to $R_{int/low} = 0.4$. The similarity of the emergent mass distributions at the low mass end seems to suggest that there is some more universal process at work than fragmentation of Jean’s mass sheets or filaments.

However, there is some evidence for a relationship between stellar density and emergent mass distribution. Regions of high stellar density appear to contain intermediate mass stars in greater proportions than regions of lower stellar density. Because stellar density varies with radius in many embedded clusters, we have tried to restrict this analysis to cluster regions of roughly the same physical size

(see Table 6.1). In fact, if this relationship is valid we would *expect* the total ratio of intermediate to low mass stars to decrease as the survey volume is increased to regions of lower stellar density. No matter what the central stellar density, when examined at sufficiently large radii where the mean stellar density is low ($<< 1000 \text{ pc}^{-3}$), we expect most clusters will exhibit a ratio of intermediate to low mass stars very close to the Miller–Scalo value. Thus on larger spatial scales $> 1 \text{ pc}$, we expect that the IMF does not vary significantly between star-forming sites.

How can we explain the suggested trend of $R_{int/low}$ and stellar density? We examine two possibilities; i) it is the result of dynamical evolution; or ii) the observation reflects the conditions necessary for the formation of intermediate mass stars. Although mass segregation resulting from dynamical evolution is a possibility that deserves serious consideration, we tend to favor the former explanation for the following reasons. First, our correlation is observed for a variety of star-forming regions all thought to be extremely young. The timescale for mass segregation would have to be $<< 3 \times 10^6$ years in order to appreciably affect our observed ratio of intermediate to low mass stars. The calculations of Lada, Margulis, and Dearborn (1984) suggest this timescale is on the order of 3×10^6 yrs for a set of model parameters relevant to our sample clusters (see their model # 5). Secondly, this effect appears in their models after removal of the molecular gas and results in expanded remnant clusters of *lower* stellar density than the less evolved clusters. This is opposite to what we observe where the ratio of intermediate to low mass stars is higher in regions of higher stellar density. However, the details of these calculations depend strongly on the gas removal timescale which is poorly constrained. Although more extensive modeling is required before we can definitively rule out the possibility, it seems that the explanation of our observed correlation being the effect of dynamical evolution is unlikely.

Another explanation for the relationship between emergent mass distribution and stellar density is that high stellar densities are necessary for the formation of intermediate mass stars. This interpretation is also supported by the work of Hillenbrand (1995) where it was observed that; i) intermediate mass stars are almost always formed with an accompanying aggregate of lower mass stars; and ii) the most massive star in an aggregate was correlated with the stellar density. Perhaps higher mass stars are built up from coalescence of lower mass protostars in dense cluster environments. Such a process would be important if the collision rate between protostars were high enough that the time between interactions was shorter than the collapse time for an individual protostar. This interaction timescale can be estimated from the calculations of Ostriker (1994) where the encounter rate between star-disk systems is given as a function of stellar density and disk sizes (equation 3-18). Using a value of central stellar density, $\rho_c = 1 \times 10^4$ stars pc^{-3} and protostellar envelope radius of 1000 AU (instead of a more conventional disk diameter ~ 100 AU) results in an encounter rate of $\Gamma_{enc} \sim 6 \times 10^5$ yrs. This can be compared with estimates of the timescale for protostellar collapse from Kenyon *et al.* (1993) thought to be $\sim 10^5$ yr. Although the time between encounters we have estimated (already perhaps an upper limit) is greater than the collapse times of protostars, they are of the same order of magnitude suggesting that protostellar interactions are at least plausible. Further it is possible that some form of hierarchical fragmentation could enhance this process by creating regions of enhanced protostellar interaction within a massive core or along a cloud filament. Recent 3D hydrodynamic calculations by Burkert and Bodenheimer (1993) describe the fragmentation of a filament into 8 protostellar seeds, some of which may merge to form higher mass stars. More work is needed in order to assess whether or not the formation of intermediate mass stars through coalescence of lower mass protostars is feasible.

6.3 Summary

Having set aside the null hypothesis offered in Chapter I, we further investigate the relationship between emergent mass distribution and stellar density. We have combined results for four additional star-forming regions with those discussed in Chapter V for the embedded cluster associated with NGC2024 and the embedded populations of the Ophiuchus cloud cores. Only one out of six regions has a ratio of intermediate to low mass stars significantly different from that expected if drawn from a Miller–Scalo IMF. However, plotting the ratio of intermediate to low mass stars as a function of stellar density for these six regions supports the notion that the emergent mass distribution is related to the local stellar density. The first result suggests that the process responsible for determining the low mass end of the IMF is not very sensitive to initial conditions. The second result suggests that high stellar densities may be required in order to form intermediate mass stars. More work is needed in order to confirm these results and provide a better theoretical framework through which they can be interpreted.

CHAPTER 7

CONCLUSIONS

7.1 Summary of Results

We have investigated the hypothesis that stellar mass distributions are independent of the environmental conditions found in star forming regions. We began by reviewing the utility of embedded clusters in studying emergent mass distributions. Such regions are distinct in their ability to relate the initial conditions of star formation to the outcome of individual star forming events.

We have examined near-infrared spectroscopy as a tool for studying deeply embedded young star clusters. We have demonstrated that such spectra can be used to derive estimates of the stellar photospheric temperatures of embedded young stars for which optical spectra cannot be obtained. As a first step in this process, we examined a set of fundamental MK spectroscopic standards at near-infrared wavelengths in order to assess the suitability of this wavelength regime for spectral classification. We examined several atomic and molecular features at moderate resolution ($R=3500$) in the H-band which are temperature and luminosity sensitive. This allowed us to define diagnostic line-ratios useful for classifying late-type stars. Such ratios should be less sensitive to continuum excess emission (often associated with pre-main sequence stars as well as evolved stars with circumstellar envelopes) than direct equivalent widths. Because it is simply not feasible to obtain large samples of high resolution spectra, we investigated the efficacy of lower resolution spectroscopy ($R=1000$) in the H- and K-bands for spectral classification of young stars. We observed a sample of optically-visible T Tauri stars spanning a range of spectral types and a variety of accretion

properties. Based on comparison of spectral types derived from optical spectroscopy with those derived from near-infrared spectra, we concluded that $R=1000$ H- and K-band spectra with signal-to-noise ratios $\sim 30 - 50$ are sufficient to obtain estimates of stellar photospheric effective temperature to within ± 3 spectral subclasses.

Yet even at lower spectral resolution, it is not possible to obtain spectra for complete samples of embedded sources detected during broadband imaging surveys with the current generation of near-infrared spectrographs. For this reason, we devised a technique based on near-infrared photometry of constructing stellar luminosity functions for complete samples of embedded cluster members. The basic assumption of our method is that embedded YSOs discovered in near-infrared photometric imaging surveys are heavily extincted pre-main sequence stars with properties similar to those of the T Tauri stars in Taurus. Guided by this assumption, we developed a method for dereddening heavily obscured YSOs. Embedded cluster members exhibiting near-IR colors consistent with those expected for heavily reddened classical T Tauri stars are dereddened in the $(J - H)/(H - K)$ color-color diagram. Sources that lie within the reddened main sequence in the near-IR color-color diagram are dereddened in the $(J - H)$ vs. M_J color-magnitude diagram to intercept a locus defined by the pre-main sequence evolutionary tracks of D'Antona and Mazzitelli (1994). By comparing IR photometric extinction estimates with those based on optical spectroscopy and photometry for well-studied T Tauri stars, we conclude that our method for dereddening YSOs gives results within $\Delta A_v = \pm 2^m$ over a wide range of parameters. Based on H-R diagrams constructed for some fraction of our sample via spectroscopic techniques, we can constrain the mass-luminosity relationship for our target cluster. This allows us to: i) define an A_V -limited sample complete down to $0.1M_\odot$ which depends on the flux-limited of the photometric survey and

the evolutionary status of the cluster and ii) define the stellar luminosity corresponding to $1.0 M_{\odot}$ in order to calculate the ratio of intermediate to low mass stars. This ratio can be compared statistically to that found for field stars in the solar neighborhood.

As an example of this analysis, we presents results for the deeply embedded cluster associated with NGC2024. Our infrared photometric survey indicates that many sources have infrared excess emission similar to classical T Tauri stars. Further, the range of observed luminosities suggests that this cluster is forming stars with a range of masses, from at least $0.1\text{--}2.5 M_{\odot}$. We obtained spectra for 22 stars chosen from our photometric survey and, using techniques outlined in Chapter II, we were able to place 19 embedded sources in the H–R diagrams. Using the dereddening method described in Chapter III, we have assembled a stellar luminosity function for an A_V -limited sample of 72 stars. From the distribution of stars in the H–R diagram we adopt $M_J(1.0M_{\odot}) = 1.5 \pm 0.5^m$ as the break-point between stars greater than and less than $1.0M_{\odot}$. Calculating the ratio of high to low mass stars, we find that there are a few more intermediate mass stars than expected from the field star IMF; however, the result is consistent with having been drawn from the field star IMF. Given our complete A_V -limited sample, we can more accurately determine the frequency of stars with IR excess. We find $F_{IREX} = 0.45 \pm 0.08$ which is similar to the frequency found in the Taurus dark cloud. We also find that the frequency of IR excess does not depend on stellar luminosity.

Because comparing results for different embedded clusters with each other is a more sensitive probe of differences in emergent mass distributions than comparisons to the field star IMF, we contrast the results on stellar masses obtained here for NGC2024 with published results for the Ophiuchus cloud cores. From the H–R diagrams for NGC2024 (Chapter IV) and for the embedded

populations of Ophiuchus (Greene and Meyer (1995)), we conclude that these clusters have similar evolutionary status. From near-IR color-color diagrams for NGC2024 (Chapter IV) and for Ophiuchus (Strom, Kepner, and Strom (1995)) constructed for A_V -limited samples, we conclude that both star-forming regions have similar accretion properties. However, the KS test results on the complete A_V -limited luminosity functions suggests that there is only a 4 % chance that these distributions were drawn from the same parent population. Having established that both clusters have the same evolutionary status and accretion properties, we interpret the difference in luminosity functions as a difference in emergent mass distribution: NGC2024 is forming a greater proportion of intermediate mass stars than is Ophiuchus. Calculations of the stellar volume density for both regions indicate that the density is a factor of $\times 3$ higher in NGC2024 compared with the embedded populations associated with the Ophiuchus cloud cores. This suggests some sort of relationship between stellar density and emergent mass distribution.

In order to investigate this further, we combine results presented here for NGC2024 and Ophiuchus with those obtained for other embedded clusters studied using similar techniques. We summarize results for the stellar density enhancements found in the Taurus dark cloud (Kenyon and Hartman, 1995; Strom and Strom, 1994), the aggregate associated with the Herbig Ae/Be star BD+40°4124 (HMSS), the cluster in OMC2 (Jones *et al.*, 1994), and “Coronet” cluster associated with R Cr A (Wilking *et al.*, 1996). According the procedure outlined in Chapter IV for NGC2024 we give the ratio of intermediate to low mass stars with associated uncertainties and estimate the stellar volume densities for each region. Most regions have a ratio of intermediate to low mass stars consistent with that found to characterize field stars in the solar neighborhood. However, there appears to be a weak trend of this ratio with stellar density: regions of higher stellar density appear to be forming a greater proportion of intermediate

mass stars. Yet emergent mass functions that are distinguishable from the field star IMF appear to be rare. From this we conclude that although the physics that generates the low mass end of the mass function appear to be universal, it may be that a high density of protostellar objects is required for the formation of intermediate mass stars.

7.2 Future Work

Future observational work will be required in order to definitively establish the suggested relationship between emergent mass distribution and stellar density. We plan to extend this type of analysis to additional embedded clusters covering a wider range of stellar density than those discussed here. In particular, showing that a number of low density star forming regions are deficient in intermediate mass stars would be particularly strong support for the hypothesis that high stellar densities are required for the formation of intermediate mass stars. However, it will be difficult to assemble the large sample of low mass stars necessary to show this in a statistically significant way. Larger near-IR spectroscopic samples (obtainable with the next generation of 8m telescopes and multi-object spectrographs) would help reduce the uncertainties in our calibrations of the mass-luminosity relationship. Finally, expanded samples of PMS spectroscopic binaries will help us to define the PMS mass-luminosity relationships for different embedded clusters, despite the continuing uncertainties in the accuracy of the theoretical isochrones.

We plan to expand upon the study presented here in order to look in detail at the low mass end of these emergent mass distributions in order to see: i) whether or not there is a definitive turnover near the hydrogen burning limit, and ii) if so, is this turnover the same in different star forming regions. We plan to accomplish these tests through the assembly of stellar luminosity functions for complete samples of embedded cluster members down to sub-stellar masses. Although the

accurate translation of pre-main sequence stellar luminosity to mass will remain a difficult problem, directly comparing luminosity functions constructed in the same fashion for different regions should allow us to address the above questions.

Present evidence suggests that the distribution of stellar masses at the low mass end does not vary greatly from region to region.

A P P E N D I X A

HIGH RESOLUTION INFRARED SPECTROSCOPY

A.1 NICMASS at the KPNO Coudé Feed Telescope

Because the thermal background emission drops significantly at wavelengths below $2.2\ \mu\text{m}$, ambient temperature spectrographs perform only slightly worse than cryogenic systems at these wavelengths. After it came to our attention that Ken Hinkle and colleagues at Kitt Peak National Observatory had made some promising tests using an infrared detector with the Coudé Feed spectrograph, we undertook a program to explore this capability. The spectrograph is a standard Coudé designed to operate at very long focal lengths. It has several gratings that operate with reasonable efficiency in the near-infrared. Normally used for higher resolution spectroscopy at optical wavelengths in second and third orders, the gratings are blazed in first order in the near-infrared resulting in moderate dispersions¹. The telescope consists of a 1.5m flat that re-directs the beam to a 0.9m off-axis paraboloid plus tertiary flat that feeds the spectrograph. Observers have a choice of collimating and camera mirrors as well as a selection of gratings.

We used our near-infrared camera “NICMASS” as the focal plane detector with the Coudé Feed at KPNO during an engineering run in October, 1993 to assess the performance of this system. This infrared camera is described in detail elsewhere (Skrutskie, Meyer, and Coutu; 1996) but its main features are briefly summarized here. Built around a NICMOS3 detector provided by Rockwell

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Typical configurations result in resolving powers from $R = 7,000 - 15,000$. With the echelle grating, resolving powers of $R = 44,000$ can be achieved.

International Science Center, the 256x256 HgCdTe array has 40 μm pixels. Frames are acquired using a double-correlated sampling scheme that consists of a reset-read-integrate-read sequence. This results in a minimum integration time of 0.6 seconds. The read noise of the system operating in this mode is 150e^- and the array has a measured dark current of $1.7\text{ e}^- \text{ sec}^{-1}$ when cooled to liquid nitrogen temperature. Over 99% of the science grade array is cosmetically usable with a cluster of bad pixels in one region. The quantum efficiency varies about 15% across the array and has a mean of about 60% over the 1–2.5 μm region. The full well capacity of the array is $5 \times 10^5\text{ e}^-$; however numerical saturation is set at half this value. The response remains linear within 1 % up to this saturation limit. Filters available include standard broadband J (1.25 μm) and H (1.65 μm) filters, a narrower than usual “special-K” filter (2.17 μm), a 2.299 μm CO bandhead filter with adjacent narrow-band continuum filter, a 2.167 μm Br γ filter, a 1.56 μm FeII filter, and a 1.083 μm He filter. The instrument is controlled through an 80486 PC which can be connected via ethernet to a Sun workstation for data reduction.

We chose the large collimator, grating B, and camera mirror # 5 (see Wilmarth, 1991, for a description of the instrument). Grating B is blazed at 1.2 μm in first order with 316 grooves mm^{-1} . It was necessary to remove the dewar’s internal Lyot stop in order to eliminate vignetting of the $F/3.6$ beam which results from this configuration. We used the broadband H-filter to minimize thermal background and reject unwanted orders. The measured background flux was $270\text{ e}^- \text{ sec}^{-1}$, resulting in counts half-way toward saturation in 10 minute integrations on faint sources. Because of the coarse platescale of the spectrograph at this resolution (2.7 arcsec pixel^{-1}) losses were minimal at the 5.4 arcsec pixel^{-1} slit. The total throughput of the system was measured to be 3 %. This instrumental set-up resulted in a 2-pixel resolving power of $R = 7100$ at a wavelength

of $1.6250\ \mu\text{m}$. We measured background-limited performance of $SNR \sim 10$ per pixel for $H = 7.6^m$ in 10 minutes of on-source integration time.

A.2 Observations and Data Reduction

The spectra were obtained by nodding the source along the slit at five separate locations. Bias-subtracted flat fields were assembled from median-filtered thermal background frames taken of the warm spectrograph slit. The object frames were median filtered to create an image of the thermal background which was then subtracted from each frame. The (object-sky) frames were divided by a normalized flat-field to remove local pixel-to-pixel QE variations and bad pixels were interpolated over. Spectra were extracted using the IRAF-TWODSPEC routine APALL. Residual sky emission was subtracted using a linear interpolation across the source aperture. Wavelength calibration was achieved using fits to the OH airglow emission spectrum taken from the median-filtered sky background frames. These observations produced $R = 7100$ spectra over the wavelength range from $1.61 - 1.64\ \mu\text{m}$. Because of the lack of strong telluric features in this spectral region, no attempt was made to correct for them. The continuum of each spectrum was then normalized to a value of one using a polynomial fitting routine. Equivalent widths were measured from each of the five individual reduced spectra and averaged together for the analysis presented below. Errors were calculated from the dispersions in the measurements. Uncertainties in measuring equivalent widths yielded $SNR \sim 20$ for our faintest sources ($H = 7 - 8^m$) representing five 10 minute exposures.

A.3 Near-Infrared Veiling Measurements for T Tauri Stars

In the optical spectra of T Tauri stars, continuum excess emission associated with accretion related phenomena complicates the derivation of spectral types

from moderate resolution data. Excess emission is also observed in the near-IR spectral energy distributions of young stellar objects. If there are strong gradients in this near-IR continuum emission, or if it is accompanied by strong emission lines, the line ratios identified in Chapter II could give erroneous results when used to infer spectral types. In order to investigate complications that arise due to the PMS nature of sources found in embedded clusters we obtained near-infrared spectra with the Coudé Feed of several well-studied optically-visible young stars along with a grid of spectral standards. We acquired spectra of both weak-lined T Tauri stars (WTTS) which lack evidence of accretion and classical T Tauri stars (CTTS) with a variety of accretion rates.

Comparison of the PMS stellar spectra with our MK standards confirms that spectral types derived from IR spectra agree with those derived in the optical for young stars. In Figure A.1 we show a late-type WTTS spectrum along with dwarf and giant star spectra of similar spectral type. Note the features in the WTTS are very similar to those in the dwarf star; however there are some recognizable “giant-like” characteristics indicating lower surface gravity. We observe this in stars as early as K0 while in earlier-type stars, the giant and dwarf star spectra are not distinguishable.

Figure A.1. High resolution $R=7100$ near-infrared spectra obtained with “NIC-MASS” at the KPNO Coudé Feed telescope/spectrograph: A.) The spectrum of Hubble 4 (K7 WTTS) plotted with a dwarf and a giant star of similar spectral type. The CO band at $1.62 \mu\text{m}$ is prominent in the giant star and the OH features are visible in all spectra. B.) Along with Hubble 4 are plotted two classical T Tauri stars for which veiling estimates were obtained; DF Tau (M0.5) and DR Tau (K7). The Ca I doublet at $1.617 \mu\text{m}$ is visible along with several OH features from $1.63\text{--}1.64 \mu\text{m}$.

Table A.1. Near-IR Veiling Measurements

Source	Sp. Type	Double ¹	$r_{0.6\mu m}$ ²	$r_{1.62\mu m}$
SU Aur	G2	No	0.0*	0.87 ± 0.18
T Tau	K1	Yes	0.0*	0.61 ± 0.16
RY Tau	K1	No	0.1	3.2 ± 0.8
DR Tau	K7	No	9.2	4.0 ± 2.0
DF Tau	M0.5	Yes	0.66	0.59 ± 0.19

¹ The presence or absence of companions within the slit based on the compilation of Simon *et al.* (1995).

² Values are from HEG except those marked “*” which were taken from Basri and Batalha (1990).

We can also use these data to study the infrared excess emission by looking at the continuum “veiling” of photospheric lines. The veiling parameter, r_λ is the ratio of excess emission to pure stellar emission such that:

$$r_\lambda = (EW_{\lambda,unveiled}/EW_{\lambda,veiled}) - 1$$

In Table A.1 we present the veiling measurements from $1.61 - 1.64\mu m$ for five CTTS along with other relevant information. WTTS of similar spectral type were used as comparison stars for the equivalent width analysis; for DF Tau and DR Tau we used Hubble 4 (K7V), for T Tau and RY Tau we used V773 Tau (K2V), and for SU Aur we used HDE283572 (G5IV). Although V773 Tau does have evidence of accretion activity (HEG), it does *not* have a measurable near—infrared excess. The features used in this analysis are visible in Figure A.1.

How do these spectroscopic measurements of continuum excess compare with estimates made from near-IR photometry? As described in Chapter III, the extinction corrected classical T Tauri stars lie along a well-defined locus in the (H-K) vs. (J-H) color-color diagram. The extent of near-infrared excess emission can be assessed by the distance each source lies from the intrinsic colors expected for the its spectral type. The veiling measurements tabulated above are well-matched to the intrinsic IR excesses of the sources labeled in Figure A.2. The

further the displacement of the observed intrinsic color from the expected main sequence color, the larger the observed spectral veiling in the near-IR.

Figure A.2. Near-IR color-color diagram for *dereddened* T Tauri stars in Taurus-Auriga. Note the locus of classical T Tauri stars. The five objects indicated are those for which IR veiling measurements have been obtained.

In summary, we find that; i) spectral types derived from high resolution near-infrared spectra agree with those obtained in the optical; ii) T Tauri stars appear to have surface gravities closer to dwarf stars than giant stars, although they do show some giant-like characteristics; and iii) it is possible to derive the ratio of continuum excess to photospheric emission from high resolution near-infrared spectra.

A targeted program aimed at deriving near-infrared veiling measurements for a large number of YSOs spanning a range of spectral types and accretion properties would be extremely valuable. Such a program would provide crucial constraints on future models for the SEDs of these sources. For example, the $1.62\ \mu\text{m}$ excess emission probes the inner regions of the circumstellar environment where one might expect to find evidence for holes in the disks of T Tauri stars.

A P P E N D I X B

INITIAL IMAGING SURVEY OF NGC2024

B.1 NICMASS at the MDM Observatories

Through special arrangement with the Michigan–Dartmouth–MIT consortium, a near-infrared direct imager was built for use with the 1.3m McGraw–Hill and 2.4m Hiltner telescopes at the MDM Observatories, Kitt Peak, Arizona. The focal plane instrument incorporated was the NICMASS infrared camera discussed in Appendix A. A flat mirror re-directs the beam from the Cassegrain focus through the re-imaging optics and onto the detector. Re-imaging optics consist of a warm ZnSe anti-reflection coated doublet that images the secondary onto an oversized cold stop inside the dewar. At F/13.5 on the 1.3m, the re-imaging optics give a platescale of $0.81 \text{ arcsec pixel}^{-1}$ resulting in a field of view of 3.4 arcmin on a side. The minimum exposure time of 0.6 seconds results in automatic saturation of all stars brighter than $K = 7.0^m$ on the 1.3m under good seeing conditions. Exposures are limited to less than 150 seconds due to saturation of the H-band background flux, and less than 30 seconds at K-band. The J-band exposures of 10 minutes are not prohibited by background flux. Filters include standard broadband J- ($1.25 \mu\text{m}$) and H-band ($1.65 \mu\text{m}$) filters, the K_s -band ($2.2 \mu\text{m}$) filter, as well as the narrow-band filters listed in Appendix A. The 80486 data acquisition computer has an interface to the telescope control system to enable mosaic mapping observations. This computer can also be connected to Sun workstations via ethernet to transfer data for reduction.

B.2 JHK Photometry of NGC2024

An initial infrared survey of the embedded cluster associated with NGC2024 was undertaken during an observing run with NICMASS in March, 1993 at the 1.3m telescope of the MDM Observatories. A 2×2 mosaic pattern was observed at half-array width spacings (1.7 arcmin) in the J-, H-, and K_S-band filters. At each position of the mosaic, four 25 second exposures were obtained dithered by 10.0 arcsec in order to remove numerous bad pixels. This resulted in a total on-source integration time of $4 \times 25 \times 2 = 200$ seconds per position in the central $3.4 \text{ arcmin} \times 3.4 \text{ arcmin}$. Short exposure mosaics were also obtained with integration times of 2 seconds per frame in order to obtain photometry of sources saturated in the longer exposures.

The data were reduced in the following manner. A master bias frame was constructed from the median filter of bias frames taken at the beginning of the night. Flat-fields at H- and K-band were made from bias subtracted median filtered images of low source density regions obtained within 1–2 hours, and scaled to a common mean. Flat-fields constructed in this way typically varied at the 1–3 % level per pixel from night to night. The H- and K-band source frames were bias subtracted and divided by the appropriate flat-field. During this run, it was noticed that the J-band filter suffered from an additional light leak. To correct for this, a background sky-emission frame was constructed for the J-band filter from the median filtered off-cluster frames taken immediately after the NGC2024 observations. These background subtracted images were divided by the H-band flat-field due to complications in constructing a J-band flat as a result of the light leak. The processed source frames were registered, stacked, and combined using the IRAF SQUID package written by K. M. Merrill of KPNO. Bad pixels were masked and a median filter was applied to the stacked frames creating a final mosaic frame in each of the J-, H-, and K_S-bands.

Sources were identified from visual inspection of the images. Aperture photometry was performed on the final mosaicked images using the IRAF digital photometry package APPHOT. An aperture of diameter 6.5 arcsec was used on the mosaicked source frames with a sky annulus of inner diameter of 16.0 arcsec and a width of 2.4 arcsec. The sky conditions were photometric and the seeing was $FWHM = 2.0 - 3.5 \text{ arcsec}$ in all three bands as measured from the mosaicked frames. Photometric calibration was performed by observing Elias (1982) standards as well as stars from the list of faint UKIRT standards (Casali, 1992) transformed into the CIT system in order to match the colors of the Elias stars. An aperture of diameter 16.0 arcsec was used for the standard stars and aperture corrections were applied to the source photometry as measured from bright sources on the mosaic frames. Based on the uncertainties in these calibrations, the minimum errors derived were 0.06^m in the H- and K-bands and 0.15^m in the J-band. The 5σ detection limits above the thermal background for this survey are estimated to be $J = 16.2^m$, $H = 16.3^m$, and $K = 15.2^m$.

Astrometry was performed on the final mosaicked K-band frame using the astrometry software available through the NOAO IRAF programming group. Thirteen optically-visible stars were used as astrometric reference positions. RMS residual errors from the plate solutions were 0.6 arcsec in right ascension and 0.5 arcsec in declination.

This initial survey was used to select sources for the spectroscopic survey described in Chapter II. In addition we report photometry for 14 sources in Table B.1 for which data are unavailable from the follow-up photometric survey described in Chapter IV. Ten of these sources were saturated in at least one of the IRCAM3 J-, H-, or K-band exposures. We compared the highest quality photometry from the NICMASS survey with data for sources not saturated in the IRCAM3 database. In all cases the photometry agreed within $\pm 0.2^m$ in the J-,

H-, and K-bands. Given possible source variability and the errors in the NICMASS calibrations, we consider this agreement satisfactory and did not apply any zero-point or color-corrections to the NICMASS data. Within the errors quoted for the photometry we assumed the NICMASS data to be on the same system as IRCAM3. For the ten sources denoted in Table B.1, we replaced the JHK photometry from IRCAM3 with the NICMASS data for the analysis of Chapter IV. The measured fluxes and colors of young stellar objects are known to vary in time by a few to several tenths of a magnitude, even at near-infrared wavelengths (Skrutskie *et al.*, 1996). Because of this variability, we chose to use the complete JHK photometry for a source lacking a measurement in at least one wavelength with IRCAM3. In addition, four of the sources listed in Table B.1 fell just outside of the IRCAM3 survey area. Although these sources are not included in the flux-limited photometric sample used in Chapter IV to derive the emergent mass distribution for the cluster, they do appear in the H-R diagram for the cluster. Despite their positions outside the survey limits, they contribute to our understanding of the evolutionary status of the cluster.

Table B.1. NICMASS Photometry of Embedded Sources in NGC2024

Source	RA(1950.0) ¹	DC(1950.0) ¹	m _J ²	m _H ²	m _K ²	Note ³
B024	05:39:07.555	-01:55:23.66	12.06	10.16	8.82	ID074
B028	05:39:03.332	-01:56:44.38	99.99	9.84	9.14	
B002	05:39:18.300	-01:55:55.03	10.10	8.47	7.49	
B029	05:39:18.948	-01:54:39.57	9.33	8.63	8.18	
B003	05:39:19.466	-01:56:32.04	12.17	10.28	9.00	
B023	05:39:06.201	-01:55:16.85	10.45	9.07	8.15	ID043
B030	05:39:06.338	-01:56:02.14	7.11	6.78	6.12	ID046
B020	05:39:07.036	-01:54:48.13	10.63	9.28	8.44	ID065
B010	05:39:13.294	-01:55:50.31	13.27	10.46	8.78	ID183
B026			99.99	10.35	8.81	ID017
B031			11.95	9.03	7.11	ID197
B032			10.06	9.26	8.49	ID035

¹ All positions from NICMASS thought to be good to 0.75".

² J-band data is ± 0.15 mag while H- and K-band data is ± 0.06 mag.
99.99 indicates no data available. Photometry quoted in the natural NICMASS system as calibrated with standards in the CIT system.

³ Identifications from Table 4.2 are listed.

A P P E N D I X C

TRANSFORMATION OF PMS TRACKS INTO OBSERVATIONAL PLANES

The theoretical calculations of D’Antona and Mazzitelli (1994) provide tabulations of luminosity and effective temperature for stars of different mass as a function of age. These tracks can be accessed electronically through the World Wide Web (<http://donald.phast.umass.edu>). Given the effective temperature we know the intrinsic colors and bolometric correction appropriate for each point on the grid. Our goal is to translate the luminosity and effective temperature plane into mass–absolute magnitude relationships as a function of time.

C.1 Intrinsic Colors and Bolometric Corrections

We begin by adopting the temperature–bolometric correction scale of Schmidt–Kaler (1982) noting that PMS stars appear to have surface gravities closer to dwarf stars than giants (Schiavon *et al.*, 1995; Basri and Batalha, 1990). Because these bolometric corrections are defined in the V–band at $0.55\ \mu\text{m}$ and we wish to consider near–infrared measurements, we must adopt intrinsic colors in order to calculate J–, H–, and K–band magnitudes. Using the spectral type–temperature relations for dwarf stars of Schmidt–Kaler (1982), we adopt the main sequence intrinsic colors of Bessell and Brett (1988) for $(V - K)$, $(J - H)$, and $(H - K)$ as a function of effective temperature. Note the $(J - H)$ and $(H - K)$ colors were first transformed into the *CIT* photometric system. Polynomial fits to these relationships are given below.

$$BC_v \pm 0.05 = -101.3651 + 8.971698E - 2 \times T_{eff} - 3.290524E - 5 \times T_{eff}^2$$

$$\begin{aligned}
& +6.334656E - 9 \times T_{eff}^3 - 6.714475E - 13 \times T_{eff}^4 \\
& +3.705377E - 17 \times T_{eff}^5 - 8.309852E - 22 \times T_{eff}^6
\end{aligned} \tag{C.1}$$

$$\begin{aligned}
(V - K) \pm 0.05 = & 231.6392 - 0.2627116 \times T_{eff} + 1.32161E - 4 \times T_{eff}^2 \\
& -3.773421E - 8 \times T_{eff}^3 + 6.658074E - 12 \times T_{eff}^4 \\
& -7.432943E - 16 \times T_{eff}^5 + 5.129903E - 20 \times T_{eff}^6 \\
& -2.001820E - 24 \times T_{eff}^7 + 3.381241E - 29 \times T_{eff}^8
\end{aligned} \tag{C.2}$$

$$\begin{aligned}
(J - H) \pm 0.01 = & 2.857311E2 + -4.551107E - 1 \times T_{eff} + 3.134182E - 4 \times T_{eff}^2 \\
& -1.224157E - 7 \times T_{eff}^3 + 2.994256E - 11 \times T_{eff}^4 \\
& -4.764616E - 15 \times T_{eff}^5 + 4.938796E - 19 \times T_{eff}^6 \\
& -3.218916E - 23 \times T_{eff}^7 + 1.197969E - 27 \times T_{eff}^8 \\
& -1.940957E - 32 \times T_{eff}^9
\end{aligned} \tag{C.3}$$

$$\begin{aligned}
(H - K) \pm 0.01 = & 2.788605E0 + -1.731798E - 3 \times T_{eff} + 4.424067E - 7 \times T_{eff}^2 \\
& -5.647841E - 11 \times T_{eff}^3 + 3.559478E - 15 \times T_{eff}^4 \\
& + -8.828952E - 20 \times T_{eff}^5
\end{aligned} \tag{C.4}$$

The errors quoted above are the RMS errors in the polynomial fits.

C.2 Mass–Luminosity Relationships

Now we are ready to directly transform the luminosity and effective temperatures of DM into absolute magnitudes for each mass and age.

$$M_J = 4.725 - 2.5 \times \log(L_*/L_\odot) - BC_{Teff} - (V - J)_{Teff} \quad (C.5)$$

We then define isochrones allowing us to derive mass–absolute magnitude relations for loci of constant age. We present polynomial fits for the following isochrones as illustrated in Figure 3.

$$\begin{aligned} 1 \times 10^5 yr : M_*/M_\odot = & 1.378328E0 - 1.010016E0 \times M_J \\ & + 4.998742E - 1 \times M_J^2 - 1.594059E - 1 \times M_J^3 \\ & + 2.657274E - 2 \times M_J^4 - 1.731412E - 3 \times M_J^5 \quad (C.6) \end{aligned}$$

$$\begin{aligned} 3 \times 10^5 yr : M_*/M_\odot = & 2.956331E0 - 1.898651E0 \times M_J \\ & + 4.466148E - 1 \times M_J^2 - 3.579509E - 2 \times M_J^3 \quad (C.7) \end{aligned}$$

$$\begin{aligned} 1 \times 10^6 yr : M_*/M_\odot = & 1.166553E0 + 5.477412E0 \times M_J \\ & - 6.359022E0 \times M_J^2 + 2.877382E0 \times M_J^3 \\ & - 6.492118E - 1 \times M_J^4 + 7.231138E - 2 \times M_J^5 \\ & - 3.158436E - 3 \times M_J^6 \quad (C.8) \end{aligned}$$

$$\begin{aligned} 3 \times 10^6 yr : M_*/M_\odot = & 2.560103E0 - 3.990461E - 1 \times M_J \\ & + 6.856878E - 1 \times M_J^2 + 1.777226E - 1 \times M_J^3 \\ & + 1.777226E - 1 \times M_J^4 - 2.315075E - 2 \times M_J^5 \\ & + 1.111853E - 3 \times M_J^6 \quad (C.9) \end{aligned}$$

These fits provide smooth interpolations between data points derived from the DM calculations and in all cases give RMS errors less than $0.03M_\odot$.

C.3 Color–Magnitude Relationships

In a similar fashion we fit relationships in color–magnitude space for each isochrone.

$$\begin{aligned}
 1 \times 10^5 yr : (J - H) = & 4.867641E - 1 + 4.002055E - 2 \times M_J \\
 & -1.720163E - 4 \times M_J^2 + 1.546403E - 2 \times M_J^3 \\
 & -7.860252E - 3 \times M_J^4 \\
 & +9.126259E - 4 \times M_J^5
 \end{aligned} \tag{C.10}$$

$$\begin{aligned}
 3 \times 10^5 yr : (J - H) = & 3.858318E - 1 + 1.791020E - 1 \times M_J \\
 & -2.611584E - 1 \times M_J^2 + 2.102829E - 1 \times M_J^3 \\
 & -7.047245E - 2 \times M_J^4 + 1.011021E - 2 \times M_J^5 \\
 & -5.160369E - 4 \times M_J^6
 \end{aligned} \tag{C.11}$$

$$\begin{aligned}
 1 \times 10^1 yr : (J - H) = & 1.042253E - 1 + 6.490169E - 1 \times M_J - 5.763968E - 1 \\
 & \times M_J^2 + 2.515031E - 1 \times M_J^3 - 4.809286E - 2 \\
 & \times M_J^4 + 3.271405E - 3 \times M_J^5
 \end{aligned} \tag{C.12}$$

$$\begin{aligned}
 3 \times 10^6 yr : (J - H) = & 2.286919E - 2 + 5.195482E - 1 \times M_J - 3.795429E - 1 \\
 & \times M_J^2 + 1.439499E - 1 \times M_J^3 - 2.362021E - 2 \\
 & \times M_J^4 + 1.363070E - 3 \times M_J^5
 \end{aligned} \tag{C.13}$$

The RMS errors in these fits are less than ± 0.01 in all cases. As discussed in Section 3.2 we determined a “mean isochrone” from the envelope of points in

color-magnitude space defined by the four isochrones listed above. This mean isochrone consists of three line segments covering different portions of the color-magnitude diagram.

$$\begin{aligned}
 2.37 > M_J > -0.76 : (J - H) &= 4.599308E - 1 \\
 &+ 1.486422E - 2 \times M_J \quad (C.14)
 \end{aligned}$$

$$\begin{aligned}
 4.02 > M_J > 2.37 : (J - H) &= 3.558802E - 1 \\
 &+ 5.888167E - 2 \times M_J \quad (C.15)
 \end{aligned}$$

$$\begin{aligned}
 6.58 > M_J > 4.02 : (J - H) &= 6.650516E - 1 \\
 &- 1.794414E - 2 \times M_J \quad (C.16)
 \end{aligned}$$

Here we have defined a locus of points that minimizes the distance projected in A_v across the envelope spanned by the four isochrones discussed above and plotted in Figure 4.10. When using the mean isochrone for dereddening instead of an individual isochrone, the errors in A_v are always less than $\pm 1.25 A_v$. Again the RMS errors in the fit with respect to these data points are less than ± 0.01 in each case.

A P P E N D I X D

PREVIOUS STUDIES OF THE NGC2024 REGION

In the past few years, NGC2024 has been the subject of several investigations aimed at probing the interstellar medium surrounding the H II region. However comparable studies aimed at characterizing the stellar population have not been available. Radio continuum studies of the ionizing flux suggest the presence of an O9.5 or B0 star (e.g. Thompson *et al.*, 1981) though a single exciting source have never been identified. Infrared studies of the embedded sources IRS#1 and IRS#2 led Grasdalen (1974) to suggest that IRS#2 was the exciting source for the region. However, far-infrared measurements by Thronson *et al.* (1984) indicate that while both IRS#1 and IRS#2 contribute to the far-infrared luminosity, they cannot be responsible for the entire H II region. This summary is not intended to be an exhaustive literature review, but to highlight some recent work which will help place our near-infrared study in context.

D.1 Gas and Dust in the Cloud Core

Pioneering surveys by Maddelana *et al.* (1986; ^{12}CO) and Bally *et al.* (1987; ^{13}CO) helped to define the extent of the molecular material associated with the Lynds 1630 dark cloud. Recently Kramer, Stutzki, and Winnewisser (1995) have performed a multi-line CO study of the region and derive a mass of $211 M_{\odot}$ within a radius of 0.4 pc for the central core from ^{13}CO data assuming LTE. Lada *et al.* (1991b) performed an unbiased survey for dense cores using CS as a tracer and found a mass of $430 M_{\odot}$ for the core associated with the H II region NGC2024 with a radius of 0.4 pc. Based on OH absorption measurements made toward the H II region, Barnes *et al.* (1989) established that the core actually consists of two

regions; one filament foreground to the H II region and a background cloud core. This picture was supported by Graf *et al.* (1993) who draw the same conclusion from their multi-line molecular study of the region. The geometry of the region, shown in Figure 10 of Barnes *et al.* (1989), is such that the dark lane foreground to the H II region joins the background cloud core just south of the ionization front observed in the radio continuum as well as thermal infrared. The H II region has apparently carved out a pocket in the molecular material. This is consistent with our near-infrared survey data where we see relatively few sources with extinction less than 5.0^m and values as high as $A_V = 40^m$ near the limit of our survey (see Figure 4.2). Perhaps the embedded cluster is contained within this pocket of molecular material.

Concerning the dust emission in the region, Mezger *et al.* (1988; 1992) have identified seven compact sources of millimeter continuum emission. They suggest that these are cold ($< 20K$), dense ($n_H \sim 10^8 cm^{-3}$), massive ($M \sim 5 - 10M_\odot$) clumps discovered just in the beginning stages of protostellar collapse. Ho *et al.* (1993) used the VLA to study the NH_3 emission at spatial resolution comparable to the 1.3 mm continuum observations ($\sim 10''$). They find that ammonia emission associated with FIR 5-7 has a kinetic temperature of $\sim 40K$ suggesting that perhaps these objects have an internal source of energy such as an embedded protostar. One of these sources, FIR4, has been identified with an embedded infrared source (Moore and Chandler, 1989; Moore and Yamashita, 1995). Two others, FIR5 and FIR6, have been associated with molecular outflows in the southern portion of the cloud core (Richer *et al.*, 1992; Richer, 1990). However Chernin (1995) has recently completed a high spatial resolution study ($\sim 4''$) of the outflows originally reported by Richer and collaborators. He finds evidence for at least three outflows in the region and rule out the FIR5 position as the driving source for any of them. FIR6 appears to be associated with at least one of the

outflows. Because of the position angle different between the two outflows near FIR6 Chernin (1995) suggests that there may be an additional source driving one of them. We find a faint red source, IRC018, in the vicinity of the NS1 outflow which appears to exhibit an infrared excess. K-bands Wilson *et al.* (1995) also present high spatial resolution observations of NGC2024 ($\sim 8''$) in C180 and 2.7 mm continuum. They detect FIR 3, FIR5, FIR 6, as well as IRS#2 at 2.7 mm and derive spectral indices of $\alpha = 4 - 5$ for the FIR sources as expected from thermal dust emission. The distribution of the C^{18}O emission appears to be *anticorrelated* with the most intense millimeter continuum emission. In fact, Chernin (1995) proposed that driving sources of the outflows observed may lie within the peaks of the C^{18}O emission reported by Wilson *et al.* (1995) and not the FIR sources. In our near-infrared survey data, we find no point sources coincident with FIR 5–7 down to our completeness limit of $K < 16^m$. We confirm the positional coincidence of an extended infrared source with FIR 4 observed in the H- and K-bands (IRC071; see Table 4.2). With our improved astrometry, we also tentatively associate the FIR sources 1 and 2 with near-infrared sources first detected by Moore and Chandler (1989). FIR1 lies close to our position for IRC151 and FIR2 appears to be associated with IRC124. We will explore further the associations between the $2.2\mu\text{m}$ sources and the FIR sources and outflows in a forthcoming paper.

D.2 Previous Characterizations of the Stellar Populations

Finally, we briefly summarize previous studies aimed at characterizing the stellar component of the star-forming cloud core. With the discovery of IRS#1 by Johnson and Mendoza (1964) and IRS#2 by Grasdalen (1974), two massive stars ($M_\star \sim 10 - 15 M_\odot$) were known to be associated with the H II region. IRS#2 has been the subject of several infrared spectroscopic studies. This unusual object

displays large photometric and spectroscopic variations (Nisini *et al.*, 1994) and shows CO bandhead emission which can be attributed to a circumstellar disk (Chandler *et al.*, 1995). Barnes *et al.* (1989) report a near-infrared survey of the region undertaken with a mapping photometer at the AAT. This survey detected 31 sources within a 5×5 arcminute field with a resolution of $3-4''$. Based on analysis of the available infrared and radio data, Barnes *et al.* concluded that the most likely source for the observed H II region was the combined luminosity of several embedded objects. Our observations suggest the presence of 14 PMS stars with masses greater than $1 M_{\odot}$ within a sample restricted to $A_V < 19^m$ (see Chapter IV). If we consider sources buried even more deeply into the cloud core, Figure 4.2 indicates that there are at least 8 sources which could have masses greater than $2.5 M_{\odot}$. As discussed above, Moore and Chandler (1989) also conducted an IR imaging survey in the region with the goal of detecting $2 \mu\text{m}$ counterparts to the FIR sources discovered by Mezger *et al.* (1988). They detected 26 sources within a 1×1 arcminute field with a resolution of $2.0''$.

Lada *et al.* (1991a) conducted the first comprehensive survey of the L1630 region in the K-band. They discovered a dense cluster of $2 \mu\text{m}$ sources associated with the H II region NGC2024. Within the boundaries defined for the cluster (0.88 pc) they detected 309 sources $K < 14.0^m$. Based on the K-band source counts they estimated the stellar volume density of the cluster to be on the order of $4000 \text{ stars pc}^{-3}$, in agreement with our estimate described in Chapter V. Another important result from their survey was the discovery that the brighter $2 \mu\text{m}$ sources are observed to be more centrally condensed than the fainter sources. Whether this is due to radial gradient in age, accretion properties, or stellar mass distributions remains unclear. However, based on our analysis presented in Chapter V, we favor the latter explanation. The authors note the possible existence of a turnover in the apparent K-band luminosity function at $K = 12^m$.

Hodapp (1994) confirms this turnover in a survey complete down to $K = 16^m$ over a field of view $8' \times 3'$, as do we from our observations of the central cluster region. The only other published survey of the stellar population associated with NGC2024 available at this writing is that of Freyberg and Schmitt (1995) who present a study of the ROSAT observations in this region. It appears that many of the x-ray sources are coincident with the near-infrared point sources.

In a future contribution, we plan to combine optical and infrared photometry with additional spectroscopy in order to study the properties of the embedded cluster associated with NGC2024 over a range of spatial scales (from $r < 0.5$ pc to $r \sim 5$ pc).

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