Chapter 1

Motivation

Current observational evidence indicates that a significant fraction of stars are born in groups (i.e., clusters or associations) within giant molecular clouds (e.g., Gomez et al. 1993, Lada & Lada 1995, Carpenter 2000, Lada & Lada 2003). As such, understanding young star forming groups plays an important role in advancing our knowledge of the universe. Key questions that can be addressed by studying star-forming groups include the following: (1) What is the timescale of star formation within a single molecular cloud compared to the lifetime of that cloud? Most nearby regions of recent star formation are found to contain only very young stars ($\lesssim$1–2 Myr) whereas molecular clouds, from which those stars are born, are thought to have lifetimes on the order of >10 Myr. We do not yet understand how to reconcile these two seemingly inconsistent results. (2) How and why do molecular clouds contract at particular sites to form stellar clusters and associations? It is suspected that formation of massive stars in one region can trigger star formation in a neighboring region (e.g., Brown 1996). What is not understood is how the processes of triggered vs. independent star formation will affect (if at all) the end result of the star forming group. (3) What determines whether a particular site of star formation will become a sparse T association, an OB association, or a bound cluster? (4) What role, if any, does stellar birth environment have on determining the observed spectrum of stellar masses within a star forming region? The answer to this question requires detailed comparisons of the initial mass function (IMF) across many different star forming regions. Because current stellar theory predicts that the evolution of an individual star is dictated almost entirely by its stellar mass, understanding the IMF and its possible variations is of extreme importance in star formation theory. (5) Does a young star's external environment affect the lifetime of its primordial circumstellar disk? High stellar densities and possible UV excess emission present in large star forming clusters could affect the lifetimes of circumstellar disks and thus, the capability of cluster members to form planetary systems.

Of particular interest for examining the above questions are the low mass populations associated with recent star formation. Studies of low mass ($M \lesssim 1$ $M_\odot$) pre-main sequence (hereafter PMS) stars offer distinct advantages over studies of associated higher mass stars for the primary reason that there are many more low mass stars to examine. An average star forming group containing ∼500 $M_\odot$ worth of stars (Lada & Lada, 2003) will contain ∼1000 stars, only ∼5% of which will have $M > 1$ $M_\odot$. The sheer numbers of low mass stars in these regions allow statistical studies not possible when considering only the high mass populations. Furthermore, we might expect lower mass stars to be more susceptible to environmental influences. Newly formed low mass stars have correspondingly lower mass circumstellar disks (Scholz et al. 2006, Andrews & Williams 2005), which are more easily photoevaporated in the presence of an external radiation field (e.g., Adams et al. 2004). Lower mass stars also are more sensitive to dynamical interactions with surrounding stars than their higher mass neighbors (Adams et al., 2006). Thus, studies of the low mass members within a star forming group will better reflect any effects caused by differences in birth environment than will studies of only the high mass members.

For my thesis, I sought to address some of the aforementioned unanswered questions relating to star formation in clusters and associations. The specific goals of my thesis are fourfold:

1) To identify low mass PMS stars and brown dwarfs in a variety of different star forming environments using a combination of imaging and spectroscopic techniques.

2) To determine the possible existence of a population of intermediate-age PMS stars (∼5–10 Myr) associated with the young (∼1 Myr) Taurus members. My goal in this region is specifically to address the length of time stars have been forming in

Taurus compared to the assumed lifetime of the associated molecular cloud.

3) To examine mass functions for clusters and associations in different environments. I concentrate on the low mass end and attempt to discern if environment plays a substantial role in determination of the IMF.

4) To probe the evolution of circumstellar material around substellar objects during the first 5 million years.

1.1 Star Formation in Clusters and Associations

Our working knowledge of how isolated stars are born is not substantially different from the view put forth by Shu et al. (1987) in their seminal paper "Star Formation in Molecular Clouds: Observations and Theory." In this work Shu et al. (1987) proposed a fourstage process to star formation, shown as a, b, c, and d in figure 1.1. In this picture, star formation begins with slowly rotating cloud cores inside molecular clouds (a) which become unstable, and collapse dynamically forming a protostar with a disk embedded inside the molecular cloud (b). During this stage, the protostar accretes material from the surrounding disk and envelope until it has accumulated enough mass to begin driving a stellar wind which channels itself along the rotational poles (c). In the fourth phase (d) of the Shu et al. (1987) model, the surrounding stellar envelope has dissipated and the system has evolved into a classical T Tauri star with a circumstellar disk.

However, as discussed above, most stars do not form in isolation, they form in clusters and associations that share a common parental molecular cloud. Thus, understanding how stars form in groups, rather than in isolation, is crucial to understanding the formation of a 'typical' star. Unlike formation of a single isolated star, multiple star-forming protostellar cores must undergo significant fragmentations (Lada & Lada, 2003). The physics behind this process is not well understood. Various theoretical models have been proposed (e.g., Myers 1998); however, because protostellar clusters are still deeply embedded in molecular gas and dust, corresponding observational evidence from the earliest stages of stellar group formation is difficult to accrue.

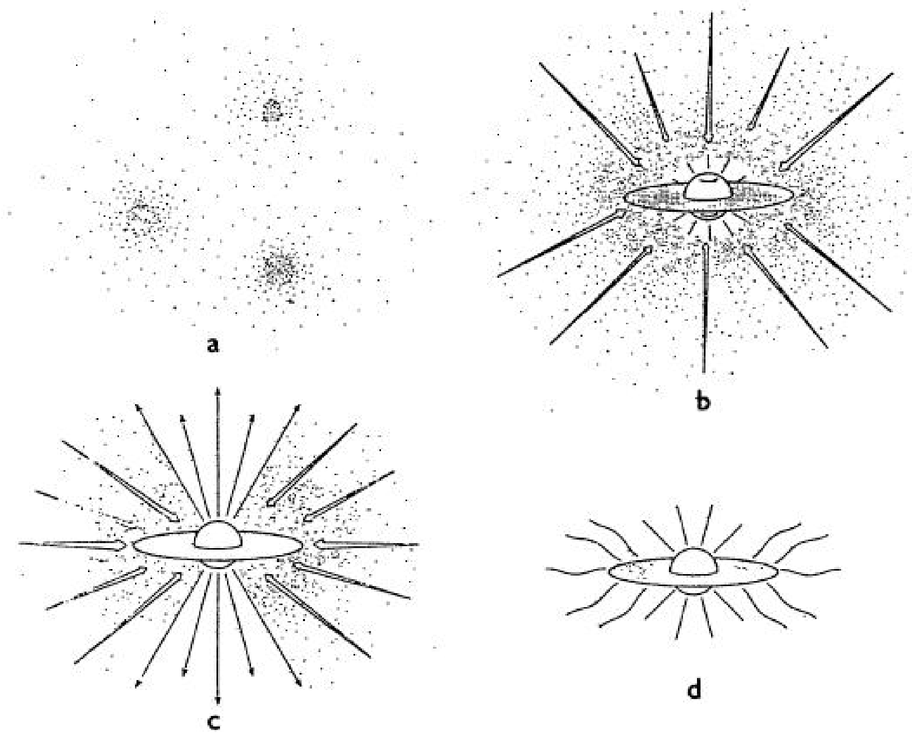

Figure 1.1 Figure 7 of Shu et al. (1987) illustrating the four stages of star formation.

Observations of the end results of these process, i.e., resultant young stellar groups, however, are more readily made using traditional optical and near-infrared observing techniques. In particular, from observations of mass, age and spatial distributions of different regions at different stages of evolution, we can begin to piece together the picture of how stars within those regions formed and what role birth environment may have played in this process.

The first issue that must be addressed in this matter is to understand that not all stellar groups are the same. They come in many different flavors, the most common of which (and those that will be discussed in this work) are described below.

Young stellar clusters. In its most general definition, a star cluster is a group of stars that is gravitationally bound. This fact implies that young clusters either have densities $\rho_* \geq 1$ M$_\odot$ pc^{-3} and thus remain stable against galactic tidal forces (Bok, 1934) and interactions with giant molecular clouds (Spitzer, 1958), or are still deeply embedded in primordial molecular gas and dust that binds them together. I have used the term ‘young stellar cluster’ to differentiate the clusters that will be discussed in this work from globular clusters, which are a fundamentally different type of stellar cluster and not relevant to the discussion at hand. Young star clusters can come in a large variety of shapes and sizes and can range up to densities as high as $\sim 10^4$ stars pc^{-3}. An example of a young stellar cluster is the Orion Nebula Cluster (ONC; figure 1.2, top) which contains $\sim$3500 stars within a radius of $\sim$2.5 pc. The ONC is an example of an embedded cluster in that it still retains much of its surrounding molecular gas and dust, rendering only $\sim$50% of its population observable at visible wavelengths. The ONC is centrally concentrated with the most massive stars found preferentially within $<$0.3 pc from the cluster center (Hillenbrand, 1997).

Stellar associations. Groups of stars formed out of the same molecular cloud which are not gravitationally bound to each other are called stellar associations. Because stellar associations have inherently low stellar densities ($\rho_* \lesssim 1$ M$_\odot$ pc^{-3}), members are often hard to identify among the considerable field star population that lies along the same line of site. The low densities of a stellar association implies that it cannot live more than $\sim$200 Myr before tidal interactions with giant molecular clouds pull the association apart (Spitzer, 1958). In general, associations can contain as few as ten to as many as several hundred members. Stellar associations are further subdivided dependent on their stellar content and spatial distribution. I discuss several specific examples.

OB associations - OB associations are characterized by a substantial fraction of O- and B-type stars. Often, they start out their lives as loosely bound stellar clusters; however, the high mass stars blow out any gas and dust associated with the star forming region within the first few megayears, leaving the stars unbound. OB associations are, by definition, still very young because their massive OB members do not live longer than $\sim$1–10 Myr. An example of an OB association is the Upper Scorpius OB association (figure 1.2, bottom) which contains 120 known Hipparcos members, including 49 B-type stars and the pulsar remnant of a massive O star that exploded as a super novae $\sim$1.5 Myr ago.

T associations - A T association contains a large fraction of low mass T Tauri-type

Figure 1.2 Top: Inner region of the Orion Nebula Cluster imaged in the near infrared (1–5 μm) with the VLT. The central concentration of bright blue high mass stars is clearly visible in the center of the cluster. Bottom: Palomar Sky survey plate of part of the Upper Scorpius OB association. The brightest star visible is π Sco, a B1V-B2V spectroscopic binary member of Upper Sco.

stars and very few, if any, high mass stars. The nearest example is the Taurus-Auriga T association located ~140 pc from the sun. Taurus contains >100 known members, most with M <1 $M_\odot$.

Moving groups - Broadly speaking, all associations are moving groups in that their stellar constituent has a common origin and moves together through space. In a more narrow view, when one speaks of young moving groups, such as TW Hya, Beta Pic or AB dor, she is generally referring to small groups of very nearby (<50 pc) stars. The moving groups that we can observe are thought to be the remnants of small-scale star forming events that produced a few dozen stars which have since drifted apart. Members can be identified by common space motions that can be traced back to a common point of origin. Because moving groups contain so few stars spread over a large area on the sky, we can identify only those that are our close neighbors.

Common properties to all young stellar clusters and associations is that members share a common parental molecular cloud, and hence, a common birth environment. They contain statistically significant samples of stars within a relatively small volume of space, and thus can be used to test theories of stellar evolution.

1.2 Observational Challenges to Observing Nearby Star Forming Regions

Observational studies of nearby young clusters and associations have found, in almost every case, that star formation within a molecular cloud takes place on short timescales (1–2 Myr). For example, Carpenter (2000) carried out a statistical star count survey of the Perseus, Orion A, Orion B, and Mon R2 molecular clouds using the 2 Micron All Sky Survey (2MASS). From this work he found no evidence for a large fraction of stars substantially older than previously known young members in any region. Another example can be found in the study by Palla & Stahler (2000). This work derived ages for nine young star-forming regions by placing known members of each association onto an HR digram. In eight of the nine regions they find only a small fraction of each association is contained in stars older than $\sim$4 Myr, with the dominant component consisting of very young, 1–2 Myr-old stars.

The large numbers of very young stars and apparent lack of more evolved post T-Tauri stars ($\sim$3–10 Myr-old star; hereafter PTTSs) in star forming regions contrasts with ages of a tens of megayears (e.g., Blitz & Shu 1980) inferred for molecular clouds, because it implies that star-formation takes place for only a small fraction of the cloud lifetime. If that were true, and a typical cloud lifetime is $\sim$10 Myr but it is only actively forming stars for $\sim$2 Myr, we would expect to see $>4\times$ more quiescent (i.e., not currently star forming) giant molecular clouds than active star-forming clouds. However, the observed result is that there exist $\sim2\times$ more active than quiescent giant molecular clouds (Ballesteros-Paredes & Hartmann, 2007). This problem has been discussed in the literature for almost three decades, and is commonly known as the 'Post T-Tauri Star Problem' (Herbig, 1978).

One explanation for these results that has received renewed interest in recent years is that the lifetime of molecular clouds is much shorter than previously accepted. Such could be the case if, for example, molecular cloud formation occurs due to large-scale flows in the ISM driven by global stellar winds and supernovae (Hartmann et al., 2001). An alternative explanation for the apparent lack of older stars in molecular clouds is that such objects have been missed in previous surveys. Most techniques (e.g., strong Hα emission or infrared excess detection) to identify pre-main-sequence stars emphasize characteristics associated with optically thick, circumstellar accretion disks that may last for only a few million years (e.g., Briceño et al. 2001). Thus, if one wishes to probe for PTTSs associated with the young, $\sim$1 Myr-old population in Taurus, or to study low mass stars associated with the $\sim$5 Myr-old Upper Scorpius OB association (Preibisch et al., 2002) or the $\sim$11 Myr-old Beta Pic moving group (Ortega et al., 2004), such techniques will not garner a full census of the population.

Observable magnetic activity in young stars will last well beyond disk dissipation timescales up to at least the $\sim$115 Myr age of the Pleiades (Marino et al., 2003). Activity signatures are observable through several means, most notably photometric variability, X-ray emission, and UV excess detection. X-ray emission in particular is known to be particularly strong in pre-main sequence stars from very young ages through >100 Myrs and several authors (e.g., Neuhaeuser et al. 1995, Wichmann et al. 1996) have attempted to identify higher mass (A–G type) PTTSs near the young, 1 Myr-old subclusters in Taurus using the ROSAT All Sky Survey. These observations revealed a population of Lithium-rich (indicating that they are younger than ~100 Myr) stars widely dispersed across the cloud. However, neither X-ray emission nor Li measurements are capable of distinguishing whether a star at these spectral types is 1, 10 or 100 Myr-old and the origin of these stars and their relation to Taurus is still debated (Briceno et al., 1997). Further, due to sensitivity limits of X-ray observations, attempting to search for the existence of a low mass (K- and M-type stars) population of PTTSs in this manner is impractical.

One of the most efficient methods of identifying low mass members of young stellar clusters and associations in an unbiased manner (i.e., regardless of their circumstellar evolutionary state) is through optical and near-infrared imaging surveys. Young, nearby low mass PMS stars still undergoing contraction will be systematically more luminous than older stars of the same mass. When photometric monitoring observations are available, PMS stars can also be identified through photometric variability caused by the presence of large, cool spots produced from magnetic activity. A major challenge faced by studies seeking to use photometry to identify and assess properties of young stellar clusters and associations is that the group must be relatively nearby if one wishes to probe the entire mass range of its population, down to substellar-type members. However, most young stellar groups within ~300 pc are low density associations, and hence occupy a large area on the sky. Limitations in telescope time and instrument fields of view necessitate that most surveys are constrained to small-area observations that often focus only on small subclusters known to contain very young stars. If a more evolved population of low mass stars exists in these associations, in 5–10 Myr it likely would have dispersed away from active star-forming regions and probing stars only within small subclusters does not necessarily reflect properties of the association as a whole. Thus, understanding how stars form within a given molecular cloud and what role, if any, birth environment plays in shaping the resultant stellar group requires large scale, large instrument field of view efforts. For my thesis, I sought to undertake such surveys in two nearby star forming regions.

1.3 Thesis Overview

My thesis utilized the Quest-2 camera on the Palomar 48-inch telescope. The Quest-2 camera offers a strong advantage for studies of young nearby stellar clusters and associations because it has a *very* large field of view ($\sim$15 deg^2). Thus, using the Quest-2 camera I was able to map several hundred square degrees of sky in a single night. The work presented here concentrates on two nearby star-forming regions, Taurus and Upper Scorpius (hereafter USco). Detailed motivations for selecting to survey these two particular associations is given in chapters 4 and 5. Broadly speaking, Taurus and USco are among the nearest star forming regions to the Sun ($\sim$140 pc), and thus we can examine even the faintest and lowest mass members. Taurus ($\sim$1 Myr) is a sparsely populated T association composed predominantly of low mass stars. The more evolved ($\sim$5 Myr) region of Upper Sco is a well-known OB association with >100 high mass Hipparcos members. Specific survey areas were selected to target both known regions of recent star formation and areas well beyond those previously studied. The goal in USco is to better constrain the mass and spatial distributions of low mass association members, and in Taurus is to search for a possible distributed population of intermediate-age ($\sim$5–10 Myr) PMS stars associated with known young ($\sim$1 Myr) subclusters.

The survey presented here consists primarily of data taken at Palomar Observatory, as discussed in chapters 2– 5. Initial photometric observations were made during 12 nights of observing with the Quest-2 camera on the Samuel Oschin Schmidt 48-inch Telescope. The observations encompassed an area of $\sim$250 deg^2 near the Taurus Molecular Clouds in the northern hemisphere, and $\sim$150 deg^2 in the southern OB association of Upper Scorpius. A detailed description of the Quest-2 camera and of spatial areas observed is given in chapter 2, where I also overview photometric data reduction and analysis. In chapter 3, I combine the Quest-2 optical photometry with

2MASS near-infrared magnitudes to select candidate PMS stars. These candidates must then be observed spectroscopically to confirm signatures of youth and measure spectral types. The follow-up spectroscopic program consisted of 20 nights of observations on the Palomar 200-inch telescope using the Double Spectrograph, and 5 nights of observations at the Cerro Tololo Intra-American Observatory using the Hydra multi-fiber spectrograph.

In chapter 4, I describe results from photometric and spectroscopic observations in Taurus. I identify 42 new low mass PMS stars spread over $\sim 35^o$ in and near the Taurus molecular clouds. Based on assessment of the spatial and proper motion distributions for this population, I argue that new PMS stars identified far from the clouds cannot have originated near the known young stellar subclusters, but instead represent a newly-identified region of recent star formation. Chapter 5 is a discussion of similar results from the observations in USco. I identify 145 PMS stars from this work including 56 brown dwarfs. From analysis of all spectroscopically observed PMS candidates compared to those determined to be association members, I conclude that, within the area surveyed, USco's low mass population shares a common spatial distribution with the high mass members, and find no evidence for spatial segregation.

Chapters 6 and 7 present discussions of follow-up analysis from the survey in USco. In chapter 6 I assess the observed age spread for low mass stars and brown dwarfs as derived from an HR diagram. I derive the first spectroscopic mass function for USco that extends into the substellar regime, and compare results in this region to those I derived previously for the ONC, as well as to results from the literature for other young regions. Chapter 7 presents mid-infrared observations taken with the *Spitzer Space Telescope* for 27 substellar members of USco identified in my thesis. In chapter 8, I discuss ongoing and future directions for this work, and in chapter 9, I give a brief summary of all results.