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THE INITIAL STELLAR POPULATION

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Invited Review

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THE INITIAL STELLAR POPULATION

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The collections of young stars with ages of 10^7 years or less found in association with molecular clouds are referred to as the initial stellar population. The majority of this population is comprised of low mass ($<3\,M_\odot$) objects with long timescales for thermal contraction to hydrogen burning stars. As a result, they can display a wide variety of evolutionary states ranging from deeply embedded infrared sources to optically visible stars with enhanced magnetic surface activity. Hence, the study of the initial stellar population requires observational techniques spanning the entire electromagnetic spectrum. Two recent advances in infrared astronomy, the Infrared Astronomical Satellite all-sky survey, and the growing availability of infrared array detectors, have dramatically improved our sensitivity to heavily obscured solar and sub-solar mass objects, and greatly enhanced our ability to sample completely the young stellar population over an entire cloud. We begin this chapter with a brief discussion of current theories for the origin of stellar masses and the Initial Mass Function, focusing on the formation of stars in clusters, and the possibility that several different formation mechanisms are at work in the Galaxy. Motivated by recent infrared camera observations of obscured clusters, models are presented for the evolution of the 2.2 μm pre-main sequence luminosity function of a young coeval star cluster, with a discussion of the implications the results have for the conversion of an observed luminosity function into the underlying mass function. A description of theories which allow spectral energy distributions of young stellar objects to be used as diagnostics of their evolutionary states is given. The observational section of this chapter begins with a discussion of techniques employed to study the initial stellar population. Observations of young stellar populations over a wide range of distances from the Sun are reviewed, beginning with low mass aggregates in nearby dark clouds and ending with clusters surrounding massive stars in distant giant molecular clouds. Particular attention is paid to populations within 500 pc of the Sun, including those associated with the ρ Ophiuchi, Taurus-Auriga, and Orion molecular clouds, where a significant number of solar and sub-solar mass objects are observed. The question of the existence of sub-stellar objects (brown dwarfs) in nearby young clusters and regions of star formation is addressed. Finally, we briefly discuss current problems and future directions for studies of the initial stellar population.

I. DEFINITION, MOTIVATION, AND SCOPE

The term 'initial stellar population' has been coined to describe the ensembles of young stellar objects (YSOs) with typical ages of 10^6–10^7 years or younger, found associated with molecular clouds. Since the objects cannot have moved far from their birthplaces, studying the distribution of their masses gives us insight into the origin of the stellar mass function at birth, *i.e.*, the Initial Mass Function (IMF), averaged over a molecular cloud. We may hope to find out whether or not the IMF is different in different types of molecular clouds, or in regions where star formation appears to be spontaneous rather than externally triggered. By studying the youngest observable populations in star-forming molecular clouds, we may ultimately be able to tackle some of the following questions:

• Are there significant variations in the stellar mass spectrum from cloud to cloud? Is there a difference in the low mass stellar content between regions that have or have not formed massive stars?

• Is there mass segregation in a young cluster? Do massive stars tend to form near the cluster centre? Are there 'halos' of low mass stars around the clusters?

• Is the most massive star that can form related to the depth of the gravitational potential of the protocluster?

• Is there a cut-off at some characteristic low mass or are there many brown dwarfs forming in clouds?

• Do all stars in a cluster form at the same time? If not, what governs the age spread in a very young cluster? Do low mass stars form first? Do stars form sequentially in mass?

If we can answer these questions, we will go a long way towards understanding the details of the star formation process. We may be able to determine the 'rules of star formation', if any. By trying to observe collections of young stars as early as possible, we can hope to identify temporal and spatial correlations between stars of different masses (*e.g.*, initial mass segregation and/or hierarchical stellar groupings) before they are erased by averaging over the field.

Studies of the initial stellar populations in molecular clouds face two problems—one is theoretical, the other observational. The theoretical problem is that it is not trivial to relate the luminosity of most YSOs to their mass. Only massive stars are born almost directly as hydrogen-burning main sequence objects. Lower mass objects exhibit luminosity evolution along pre-main sequence (PMS) tracks, taking progressively longer times to reach the main sequence, *e.g.*, a few $\times 10^7$ years for a 1 $M_\odot$ star. Thus the conversion of an observed luminosity function into a mass function by virtue of a time independent main sequence mass-luminosity relation is not possible: this step requires a theory that describes changes in the bolometric luminosity or absolute infrared brightness of PMS objects as a function of age and mass.

The observational problem is that the photospheres of YSOs are partially or totally obscured by dust at optical wavelengths. This dust can absorb much of the YSO luminosity and reprocess it to infrared wavelengths from 1–100 μm, depending on the proximity of the dust to the YSO. In addition, in clouds where massive stars have formed, the accompanying H II region nebulosity is often bright and can present a serious contrast problem in the optical. Therefore, in general, the earliest phases in the life of a YSO are best studied in the infrared, where YSOs are most luminous, where dust obscuration is vastly reduced, and where contrast against any nebular background is increased. Until recently however, only single-element infrared detectors were available, making it impossible to carry out sensitive studies of large ensembles of sources. Instead, most studies concentrated on low sensitivity, low resolution surveys, or detailed studies of individual or small groups of objects. In addition, ground based studies at thermal infrared wavelengths were severely hampered by the enormous background flux from the warm telescope and lower atmosphere.

With the introduction of infrared array detectors in the past five years, it is now possible to obtain high-resolution ($\sim$1 arcsecond), high-sensitivity near-infrared (1–5 μm) images over relatively large areas of the sky. The same period saw detailed analyses of data from the Infrared Astronomical Satellite (*IRAS*) mid- and far-infrared (12–100 μm) all-sky survey. These two factors have led to a flood of new information about the embedded stellar populations of galactic star-forming regions. In this chapter we review both the observational and theoretical progress in studying the initial stellar population since the *Protostars and Planets II* conference in 1984. For a clear picture of our prior state of knowledge regarding fragmentation, star formation (including that in OB associations and young clusters), and the IMF, we refer the reader to reviews from the previous books in this series (*e.g.*, C. Lada *et al.* 1978; Scalo 1978; Silk 1978; Klein *et al.* 1985; Evans 1985; Scalo 1985; S. Strom 1985; Wilking and C. Lada 1985).

II. THEORETICAL CONCEPTS

We begin this section with some basic ideas regarding the origin of stellar masses and the IMF, as one of our prime goals is to understand which types of stars are born in the various kinds of molecular cloud. We continue with a simplified analysis of the time dependence of the mass-luminosity relation for low mass PMS stars. Combining this relation with a given mass function, we examine the time dependent behaviour of the corresponding luminosity function. The model predictions suggest a new technique that may prove very useful for the interpretation of empirical 2.2 μm luminosity functions of embedded clusters, surely a very topical subject in the next few years. Finally, we discuss some of the more realistic aspects of YSOs, in particular the interpretation of the spectral energy distributions (SEDs) in terms of the evolution of YSOs and their circumstellar material. These considerations lead to a better delineation of the components of a YSO (star + disk + halo) that must be included in radiative transfer calculations to allow fits in observable parameter space.

A. The origin of stellar masses and the IMF

An increasing body of observational data leads to a picture of star formation in which stars are born in individual dense clumps or protostellar fragments that appear to be more massive than the stars that eventually form from them (see Myers 1991, and references therein). This fact suggests that the origin of stellar masses and the IMF are inextricably linked to the mass distribution of dense clumps and the efficiency with which an individual dense clump forms a star or a group of stars. Through spatially- and velocity-resolved molecular line observations, it has recently become possible to identify dense clumps in molecular clouds and establish their mass distribution over a wide range of spatial and density scales (Blitz 1987; Stutzki and Güsten 1990; E. Lada *et al.* 1991*a*; Blitz, this volume). The mass distribution (dN/dM) appears to be very similar in each cloud studied so far and may be fairly universal: it scales as the clump mass M to roughly the -1.5 power. In order to obtain the IMF of stars born in these clumps, we require an 'initial-final mass relation' to translate the (initial) mass distribution of the clumps into a (final) mass distribution of stars (Zinnecker 1989, 1990). If the final stellar mass m scales with the initial clump mass M as $m \propto M^p$ (with $p < 1$, *cf.* the observations of Stacey *et al.* 1988), one can easily show that the stellar mass spectrum is a power-law with index $x = -(0.5 + p)/p$. For example, to produce the index of the Salpeter IMF ($dN/dm \propto m^x$, $x = -2.35$; Salpeter 1955) requires $p \sim 0.4$. The observed mass distribution of dense clumps may be a result of collisional fragmentation (see, *e.g.*, Nozakura 1990, and references therein) and/or the hierarchical structure of interstellar clouds (see, *e.g.*, B. Elmegreen's 1985 model; see also Zinnecker 1985). The physical justification for the power p in the initial-final mass relation may come from the theory of protostellar winds dispersing the parent clumps (for low mass stars: see Shu *et al.* 1991) and the theory of radiation pressure acting on dust grains in protostellar envelopes to reverse their infall (for high mass stars: see Yorke 1980; Wolfire and Cassinelli 1986). In addition, it would seem that magnetic field tension can help prevent complete accretion of the envelope mass, especially for low mass stars (Nakano 1984; Lizano and Shu 1989; Mouschovias 1991). All these ideas are still rather crude and the details have yet to be worked out, but the suggestion is that it will be progressively harder for the more massive clumps to accrete a substantial fraction of the original clump mass, while for the lower mass clumps relatively more dense gas ends up in the star. This theory therefore suggests splitting any understanding of the IMF into two parts, namely the clump mass distribution and an initial-final mass relation. The advantage is that, at least in principle, each part can be tested separately by observations.

The theory as outlined above neglects various details of the star-forming process. For example, is there a characteristic mass for the clumps (con: Shu *et al.* 1987; pro: Mouschovias 1991)? Does every clump form a star (Larson 1991)? Do larger clumps subfragment into several yet denser clumps (Zinnecker 1990)? Current theory suggests that indeed there *is* a characteristic clump mass ($\sim 1\, M_\odot$), selected and preserved by self-gravity in a dense, turbulent, and magnetic interstellar medium (Mouschovias 1991; Larson 1991). It is suspected that every clump above some critical density *does* form a star, and that subfragmentation *does* become increasingly important for progressively larger clump masses (Larson 1978; Larson 1991). Indeed, if the probability of subfragmentation increases with clump mass, this will steepen the slope of the original clump mass spectrum, as required to explain the observed IMF. Furthermore, this process can produce an IMF which does not have a single power-law slope, but a slope whose index changes gradually with mass, much like the Miller-Scalo IMF (Miller and Scalo 1979)—in this case, the variable p would have to be a function of the clump mass.

Implicit in these considerations is the route by which the IMF arises in a *system of stars,* such as a protocluster (*cf.* Scalo 1986; Zinnecker 1986*a*). Larson (1990) and Myers (1991) have discussed the possible evolution of protoclusters, with emphasis on dissipational processes. Larson (1991) further elaborated on the origin of the slope of the upper IMF in a protocluster, suggesting that the power-law extension of the IMF toward higher masses may result from accretional growth of some stars to much larger masses. However, there must be a limit to accretion on each star, and a key question on the way to a full understanding of the origin of the IMF is the process by which accretion is cut off. Does the protostar terminate the mass inflow by switching on a protostellar wind, thereby defining its own mass ('self-limited accretion', Shu *et al.* 1987)? Is the reservoir for accretion limited by the other stars competing for material ('competitive accretion', Zinnecker 1982)? Or is the amount of accretable material mostly dictated by the initial conditions (*e.g.*, 'angular momentum limited accretion', Larson 1978)? Hopefully, detailed observations will provide us with some clues.

Finally, in any discussion of the IMF, we cannot ignore the fact that most stars are binaries. In particular, with regards the observational determinations of stellar luminosity and mass functions presented later in this

chapter, the effect of unresolved binaries may be quite important, and has recently been discussed in some detail (Kroupa *et al.* 1991; Piskunov and Malkov 1991; Reid 1991). However, these analyses, along with the origin of binary stars and the origin of their mass ratios, are beyond the scope of this chapter, and the reader is referred to the chapter by Bodenheimer *et al.* for more information.

1. Isolated versus collective star formation

There are several distinct effects that come into play regarding collective as opposed to isolated star formation, including tidal forces, mass segregation, and radiative implosion. These effects imply qualitatively observable consequences.

First we consider tidal effects. Accretion may be inhibited by the tidal forces generated by a star on the disk or protostellar envelope of a neighbouring stellar core, or perhaps more importantly, by a protocluster cloud on smaller extended fragments that are randomly positioned off-centre within it. Both effects limit the reservoir for accretion, unlike the single star case considered by Shu *et al.* (1987) where only the star itself (*i.e.*, via its wind) can limit the accretion. At the same time that tidal forces limit the reservoir for accretion, they may also increase the *rate* at which the remaining material is accreted, due to the tidal torques that are present. Thus overall, young stars in a protocluster may have less massive but more rapidly evolving circumstellar disks than isolated objects of the same age.

A second important effect in a protocluster is mass segregation. Are the more massive stars born in the denser, more central regions of the cloud? A naïve application of the Jeans criterion for a centrally condensed isothermal cloud would predict the opposite outcome, with low mass stars in the centre and high mass stars at the periphery. However, in the centre the clump-clump collision timescale is shorter than the collapse timescale of an individual clump. This effect, along with accretion of residual gas sinking towards the centre due to dissipational processes, leads to a prediction that the more massive stars will indeed form near the cloud centre. More specifically, we predict that the mass of the most massive star should scale with the depth of the gravitational potential well at the cloud centre, since the deeper the well, the more difficult it is for gas to escape. Clumps further from the centre will avoid collisions more readily and will remain small, forming lower mass stars.

A third effect concerns star formation triggered by the radiative implosion of clumps, initiated by ionisation shock fronts from newly formed OB stars in the cluster (Klein *et al.* 1980). Close to the massive stars the clumps should be completely obliterated, creating a 'zone of avoidance' (R. Klein, personal communication), while at greater distances, dense enough clumps will survive to form other high mass or intermediate mass stars. Infrared imaging observations might be able to reveal evidence for 'gaps' around the most massive members of a cluster.

In summary, the conditions that arise only in a cluster environment could play a dominant role in producing the wide range of masses observed in the stellar mass spectrum. In particular, perhaps massive stars can only form in a cluster. Furthermore and equally important, the majority of field stars may be former members of clusters and OB associations (see the chapter by E. Lada *et al.*), and therefore the form of the *field star* IMF may be determined more by the effects of the cluster environment than any other factor.

2. Bimodal star formation

The concept of a 'decoupling' of low and high mass star formation originated with Herbig (1962*b*). In his picture, low mass stars form continuously over a long period, only to be interrupted by the relatively rapid formation of high mass stars, the violence of which leads to dissipation of the remaining molecular material. This idea of temporal variations in the star formation process with respect to stellar mass was further codified to refer to separate formation mechanisms for high and low mass stars, perhaps leading to distinct formation sites for OB stars and low mass stars. This is the basis for so-called 'bimodal star formation' (see, *e.g.*, Eggen 1976; Mezger and Smith 1977; Güsten and Mezger 1982). However, as noted by Herbig (1962*b*), OB associations commonly have related associations of low mass T Tauri stars, whereas the converse is not always true. Therefore, one continuous process could be at work, with an upper mass limit in regions of low mass stars formation set by, say, the initial reservoir of cloud material. The proof for separate mechanisms for high and low mass stars would be a region that has formed high mass stars exclusively, implying a process that either prevented or biased against low mass star formation.

Perhaps the strongest evidence for bimodal star formation has come from the study of starburst galaxies where low M/L ratios are best explained by the formation of predominantly high mass stars in the nuclear regions (*cf.* Larson 1986, and references therein). Whether or not there are individual H II regions in our Galaxy whose exciting stars are *not* accompanied by low mass stars is a very important question, with many

implications for the origin of the IMF, both within a given cloud and throughout the field. However until recently, finding observational evidence for this has been hindered by the difficulties encountered in detecting low mass stars in regions where more massive stars are known to have formed.

In the spirit of bimodal star formation, Shu *et al.* (1987) and Lizano and Shu (1989), following ideas by Mestel (1985), proposed a model whereby two distinct star-forming mechanisms can operate depending upon the ratio of magnetic support to cloud self-gravity. A small cloud dominated by magnetic support evolves slowly via ambipolar diffusion to form a low mass core, and subsequently a low mass star. Conversely, if enough of these smaller clumps can agglomerate into larger clumps, for example in a GMC via some external trigger, gravity can overcome the magnetic support, and these clumps will collapse rapidly, forming high mass stars. In the latter scenario, fragmentation can also take place, perhaps forming low mass stars. This model also explains the low star formation efficiency seen in complexes with only low mass cores and stars. The long timescale for low mass core evolution leads to an incoherence across the cloud complex, and the collapse of some cores may be disrupted by the stellar winds of nearby newly formed stars.

Mouschovias (1987) took another perspective on the difference between low and high mass star formation. In his scenario, low and intermediate mass stars form in quiescent clouds collapsing at sub-Alfvénic speeds, while a cloud initially supported by magnetic fields then imploded by an external trigger may collapse rapidly at Alfvénic or super-Alfvénic speeds, forming more massive stars.

It is important to note that neither of these models seems to preclude the formation of low mass stars alongside the high mass stars. Indeed, if the high mass stars form first, they may trigger low mass star formation in the clumpy medium by radiative implosion (Klein *et al.* 1980, 1983; La Rosa 1983).

As our sensitivity to low mass stars in the more distant massive star-forming regions improves, our ideas of bimodal star formation will become better developed. A possible example of bimodal star formation in our galaxy, in the star-forming region S 255/257, is described below in Section III.C.2.

B. Evolution of a model PMS infrared luminosity function

From an observational standpoint, the near-infrared (1–2.5 μm) is perhaps the best wavelength range over which to find young low mass stars in clusters. Using array detectors, it is now easy to detect and measure the near-infrared fluxes of large numbers of stars in such clusters, as we shall see in Section III. Unfortunately, it remains hard to make immediate astrophysical sense of these raw measurements. Because the stars are heavily reddened and may have large infrared excesses, it is not easy to determine the total stellar luminosity. Because the stars are young, a time-independent main sequence mass-luminosity relation cannot be used to determine the stellar mass, and a time-dependent PMS relation must be used: for example, an empirical fit to the models presented below shows the near-infrared (K) luminosity for low mass stars evolving down their Hayashi tracks changing as $L_K \propto M^{1.6} \times t^{-2/3}$.

The classical approach to these problems for PMS stars is to measure the underlying spectral type of each star and thence the reddening towards it. The luminosity is determined by integrating under the spectral energy distribution, and by combining this with the effective temperature, the age and mass of each star can be found by comparison with PMS evolutionary tracks in an HR diagram (Cohen and Kuhi 1979). However, it is difficult to obtain spectral types and reddening for all the members of a dense, heavily obscured PMS cluster, and some assumptions have to be made. For example, in their study of the Trapezium Cluster, Herbig and Terndrup (1986) measured a few stars spectroscopically and then used the mean derived extinction to deredden the rest of the cluster members. As an alternative, Straw *et al.* (1989) assumed all the stars they measured in NGC 6334 were on the ZAMS, and moved them parallel to the reddening vector in the HR diagram until they intercepted the ZAMS locus. In the former case, it is highly unlikely that all stars in an embedded cluster have the same extinction. In the latter case, assuming the stars to be on the ZAMS when they are more likely to be PMS will overestimate their mass. However, if there was some other way of estimating the age of a PMS star or even a whole cluster, it should be possible to deredden the stars in the HR diagram until they intercept the appropriate PMS isochrone, thus determining their masses. The possibility of infrared excesses will complicate such simple approaches, but to some extent that can be dealt with by looking at a star's location in a near-infrared colour-colour diagram. In these diagrams, the reddening vector, isochrones, and isomass tracks all form a roughly parallel locus, whereas stars with infrared excesses fall below this line.

With this problem in mind, and as part of an on-going study of young clusters and how observations may be converted into physically useful parameters, we have performed some simple modeling which allows us to explore the phase space covered by young low mass stars in near-infrared coordinates. One particular

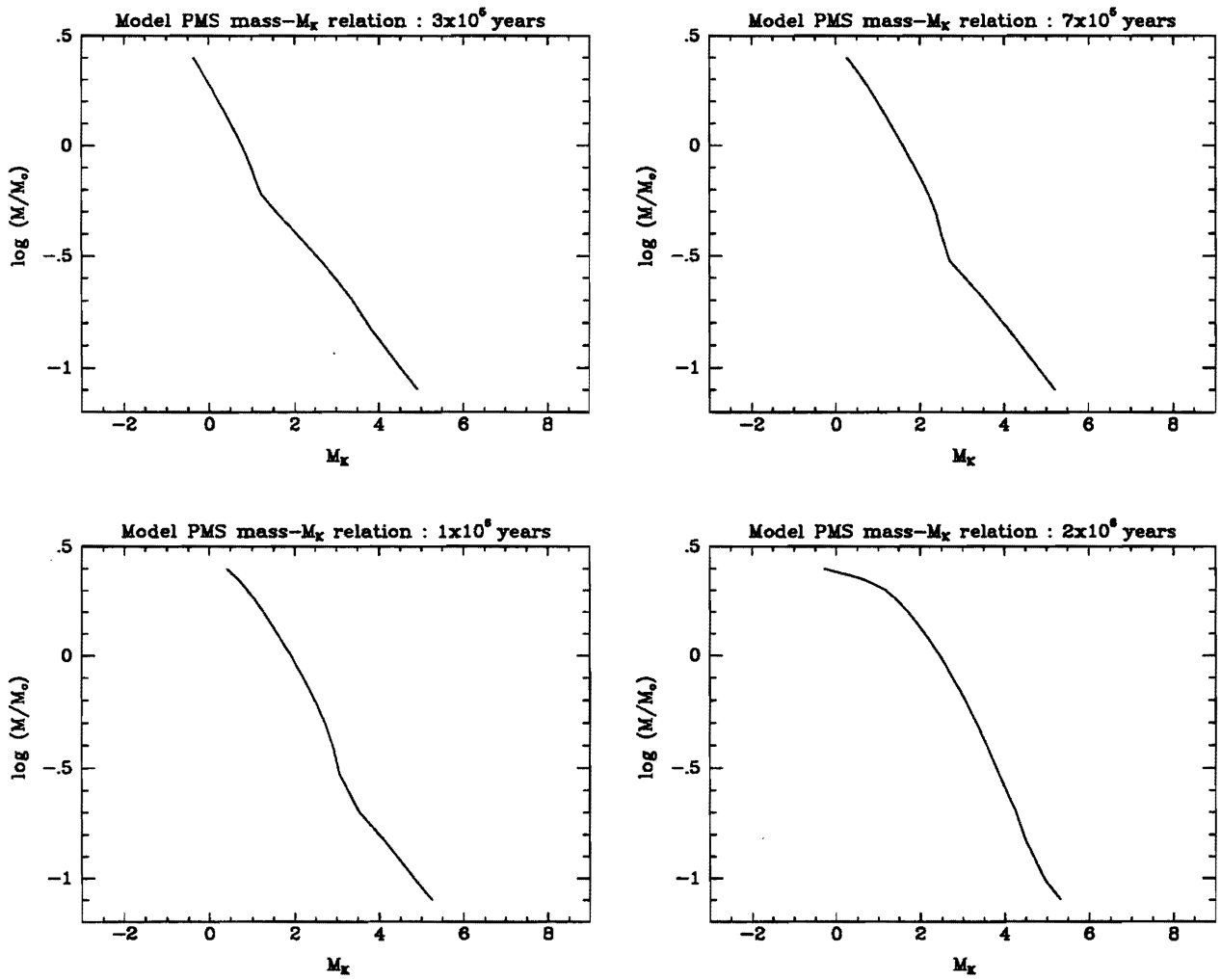


Figure 1*a,b,c,d* Time dependent mass–M_K luminosity relations, as derived from homogeneous tracks of pre-main sequence evolution calculated and kindly provided by I. Mazzitelli. Four ages are shown: 3×10^5, 7×10^5, 10^6, and 2×10^6 years.

point of interest is the predicted PMS evolution of the near-infrared luminosity function. Some qualitative results relating to this are given here, and a more rigorous discussion will be presented elsewhere.

1. Modeling

We have taken a homogeneous grid of PMS tracks (10^5–10^7 yrs) for low mass (0.08–2.5 $M_\odot$) stars, kindly provided to us by Dr I. Mazzitelli, and converted them from $T_{\rm eff}$, $R/R_\odot$ coordinates into near-infrared magnitudes assuming the stars to be blackbodies, and using the Sun as a zero-point, also assumed to be a blackbody. Since the Sun is *not* accurately represented by a blackbody, and low mass PMS stars even less so, this work must be repeated using synthetic spectra. However for illustrative purposes here, the results obtained using blackbodies give a qualitative if not quantitative picture.

Normally an observed luminosity function is converted to a mass function via some empirical or model mass-luminosity relation. Here we reverse the procedure. To derive a near-infrared 2.2 μm (K) luminosity function (*i.e.*, dN/dK) we begin by assuming a given mass function (*i.e.*, $dN/d\log M$) and then evaluate the following equation:

$$\frac{dN}{dK} = \frac{dN}{d\log M} \times \frac{d\log M}{dK}$$

where $d\log M/dK$ is the slope of mass–K luminosity relation, and $K = -2.5\log(L_K/L_{\odot K})$. For these models, we used the half-gaussian form of the Miller-Scalo IMF (Miller and Scalo 1979) and the slope of the mass–K

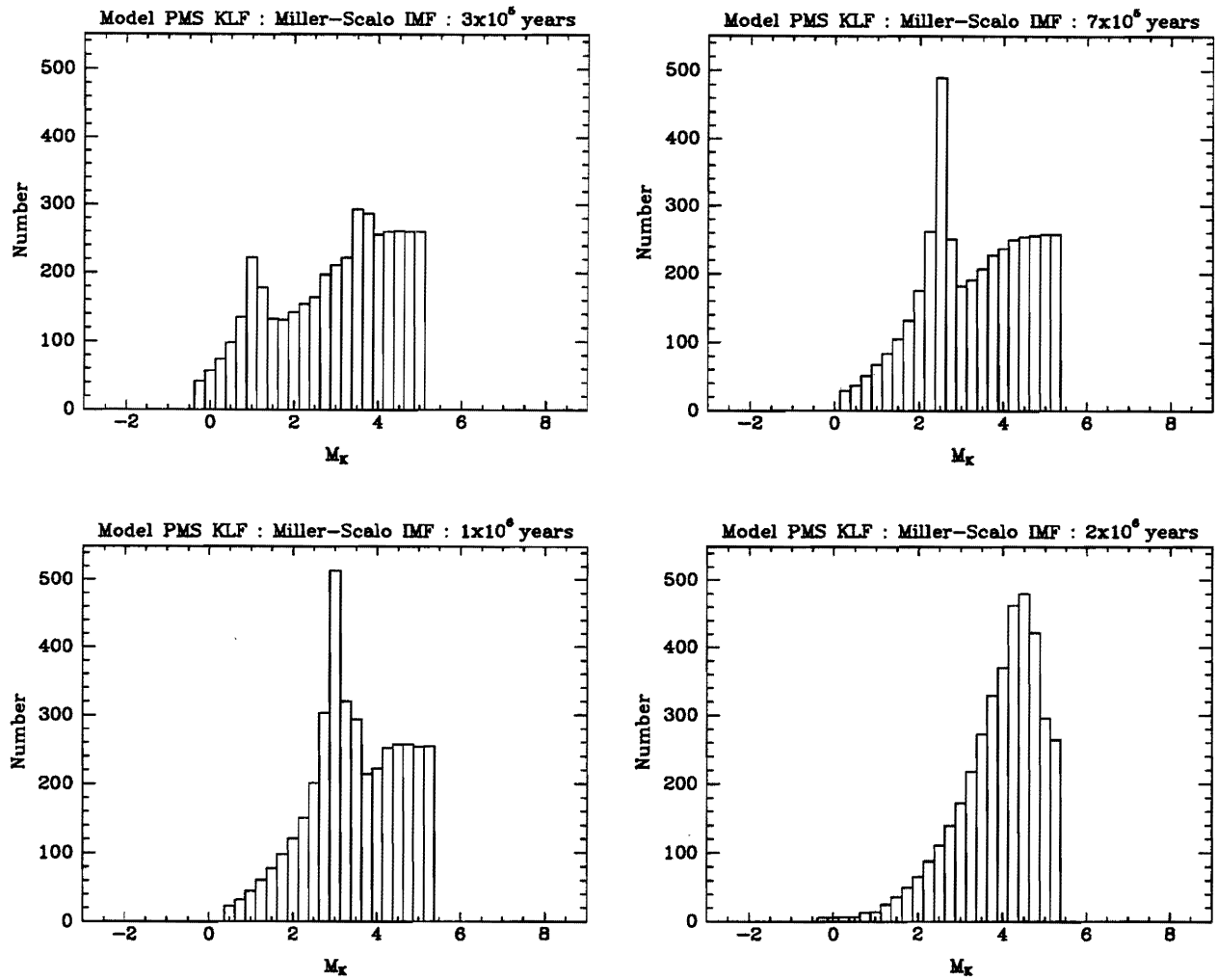


Figure 2*a,b,c,d* Model 2.2 μm (M_K) luminosity functions for a coeval clusters of low mass stars at the same four ages shown in Fig. 1. The luminosity functions were calculated by convolving the mass–M_K relations with a Miller-Scalo IMF. Note the strong peak due to deuterium burning in the last three luminosity functions.

luminosity relation as derived from the transformed PMS tracks at each age and mass. It has been pointed out many times (see, *e.g.*, D'Antona 1986; Bahcall 1986; Kroupa *et al.* 1990) that it is the *slope* of the mass-luminosity relation that is involved here, and that simple inflections in that relation can lead to significant features in the luminosity function, as we shall see below.

2. Results

Figures 1*a,b,c,d* show the model mass-K luminosity relations at four different ages (3×10^5, 7×10^5, 10^6, and 2×10^6 years), while Fig. 2*a,b,c,d* show the corresponding model K luminosity functions (KLFs) for a coeval cluster of low mass stars at the same four ages. Note that the distance to the cluster is assumed to be 10 pc, *i.e.*, in these figures $K \equiv M_K$. For reference, Fig. 3 shows an empirical mass–M_K relation and corresponding spectral types for main sequence stars. Also note that $0.3\,M_\odot$ corresponds to $\log M = -0.5$ in these diagrams.

At 10^5 years (not shown), the shape of the KLF largely reflects the shape of the Miller-Scalo IMF, *i.e.*, turning down and flattening towards the lower masses, corresponding to the almost straight mass–K luminosity relation at this age. Whether or not such a KLF would ever be seen in practice is debatable however, as stars this young would still be deeply embedded in their protostellar cocoons, making it unlikely that the 'naked' PMS stars would be seen at this stage. By 3×10^5 years, features become apparent in the KLF, and by 7×10^5 years, there is a sharp peak in the KLF which can be traced to a sharp inflection at the corresponding point in the mass–K luminosity relation. This point of inflection is seen to move towards

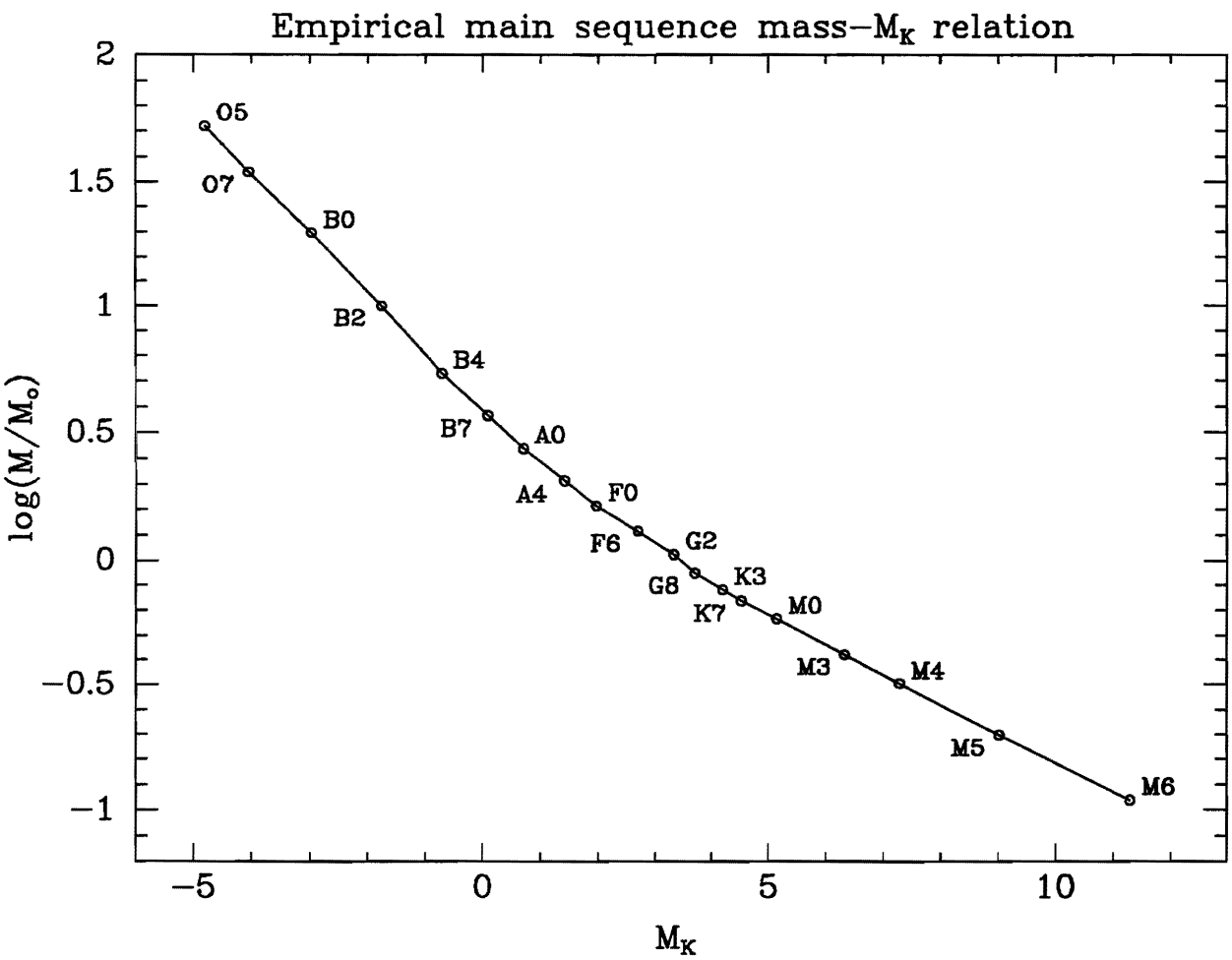


Figure 3 An empirical mass–M_K luminosity relation for main sequence stars, derived from the data of Miller and Scalo (1979), and Koornneef (1983), following Straw *et al.* (1989). Corresponding spectral types are also marked. It should be noted that there is considerable uncertainty in this relation for spectral types K0 and later, as seen when compared to other empirical determinations (M. Simon, personal communication; Henry 1991).

lower masses with time, and by 2×10^6 years the peak in the KLF has moved down close to our chosen mass cut-off at $0.08\,M_\odot$. By 10^7 years (not shown), the peak is long gone.

The inflection in the mass–K luminosity relation is a feature caused by deuterium burning in contracting PMS stars. D-burning occurs when the Kelvin-Helmholtz contraction has proceeded far enough to raise the central temperature to $\sim10^6$ K. For a $0.3\,M_\odot$ PMS star, D-burning occurs at an age of $\sim10^6$ years and lasts for $\sim10^6$ years, until most of the central deuterium is consumed. These timescales are fairly independent of the precise value of the initial deuterium abundance, although for reference, the Mazzitelli models were calculated using a deuterium abundance of 2×10^{-5} by mass, as derived for the solar neighbourhood (York and Rogerson 1976). While deuterium is burning, the corresponding nuclear energy generation provides substantial support against continuing PMS contraction, *i.e.*, for a while the star's radius and luminosity remain almost constant (see Fig. 2 of Mazzitelli and Moretti 1980). While the deuterium is burning strongly in stars of a given mass, D-burning is ending in slightly higher mass stars, and has yet to begin in lower mass stars. Thus, at the mass where peak D-burning is occurring (*i.e.*, the mass whose timescale for the onset of strong D-burning is equal to the present age of the coeval cluster in question), there is a kink in the mass-luminosity relation. This leads to an increase in the value of $d\log M/dK$, and a boost in the luminosity function at the corresponding K magnitude, creating a peak and the subsequent turnover. A physical interpretation is that as the cluster members are decreasing in luminosity, evolving down their Hayashi tracks, stars in a certain mass range temporarily decrease less, and pile up in a slightly brighter than expected magnitude bin. It is however important to note that at no point in our completely coeval

model cluster does a star of mass M appear more luminous than a star of mass $M + \delta M$, as the D-burning never completely halts the PMS contraction.

It is a general feature that the duration of the D-burning phase for a given star is roughly equal to its age at the onset of D-burning, *cf.* Mazzitelli and Moretti (1980). For example, D-burning starts in a PMS star of 1 $M_\odot$ at about 10^5 years and lasts approximately 10^5 years. These timescales are in accordance with the location of Stahler's (1983) 'birthline' in the HR diagram, the location below which optical T Tauri stars seem to appear for the first time, thought to be set by the D-burning 'quasi-main sequence'.

So we can see that for young clusters, features such as peaks and turnovers in the K luminosity function cannot be *assumed* to imply corresponding features in the IMF; rather, they may often reflect the complex process of PMS evolution. Therefore we caution against overly simplistic analyses of near-infrared luminosity functions and inferences for the IMF. On the other hand, such features might still be used to our advantage, namely as a possible age indicator. This somewhat surprising result might even hold when our simplifying assumptions are replaced in more realistic models, *e.g.,* allowing for age spreads and infrared excesses due to circumstellar disks. We will also have to include intermediate mass stars in this procedure, which we have omitted here. The PMS evolution of these stars is currently under investigation (Palla and Stahler 1990, 1991; see also Walter and Stahler, this volume).

C. Spectral energy distributions

The previous discussion was idealised by considering only 'naked' PMS stars without any circumstellar material. But it is known from observations of infrared excesses and sub-millimetre continuum emission that YSOs can possess substantial amounts of circumstellar dust. The distribution and quantity of this dust determines the shape of the emergent energy distribution from the YSO. Low mass YSOs gradually dissipate their circumstellar dust as they approach the main sequence and over their extended evolutionary timescales, the shapes of their spectral energy distributions (SEDs) change dramatically. Therefore, by constructing the energy distribution of a YSO over the 1–100 μm spectral region, the evolutionary state can be inferred. Empirically, sources can be classified according to the slope of their 2–25 μm SED in a $\log \lambda F_\lambda$ vs. $\log \lambda$ plot (see, *e.g.,* C. Lada 1987). The most heavily obscured and presumably youngest YSOs are optically invisible and have SEDs which rise into the far-infrared with a slope greater than zero: these are Class I sources. Visible but reddened YSOs with strong mid-infrared excesses have SEDs with slopes between 0 and -2 and are classified as Class II sources—these objects are usually associated with classical T Tauri stars. Finally, YSOs which have weak or no infrared excesses have SEDs resembling reddened blackbodies (slope ~ -3). These objects, associated with weak emission T Tauri stars, are the Class III sources.

It has been suggested that the variations of shape in the SEDs observed for YSOs represent a quasi-continuous evolutionary sequence from protostars (Class I) to weak-emission T Tauri stars (Class III) (see, *e.g.,* Adams and Shu 1986; Adams *et al.* 1987, 1988; Myers *et al.* 1987; Rucinski 1985). As shown schematically in Fig. 4, Class I SEDs can be successfully modeled as accreting protostars comprised of three components (stellar core, circumstellar disk, and a quasi-spherical envelope or halo), with the far-infrared emission arising from the infalling envelope and the mid-infrared emission from the spatially thin disk. A stellar wind soon develops which breaks out at the rotational poles of the envelope, thereby reducing the extinction to the central YSO. Emission from the central object can now be observed at near-infrared wavelengths, producing a double-peaked, or Class IID, SED. As the wind dissipates the residual envelope, the central YSO plus disk are fully revealed resulting in either a flat spectrum SED, indicative of $r^{-1/2}$ disk temperature gradient, or a Class II SED whose slope approaches $-4/3$, characteristic of a disk with an $r^{-3/4}$ temperature gradient. Finally, as the disk is dissipated, a Class III SED is observed. The time a given YSO spends in each of the Class I, II, and III phases is believed to be longer for the later stages; *e.g.,* for a 1 $M_\odot$ star, 1–2$\times 10^5$ years, 10^6 years, and 10^7 years, respectively. These are only rough estimates, and we should keep in mind that the discrete classes are just an approximation of a continuous evolution.

To characterise further the evolutionary state of a protostellar Class I (or IID) object, it is possible to to use its total luminosity L and the visual extinction to the stellar surface, A_V. Evolutionary L–A_V diagrams have recently been calculated from models of rotating low mass YSOs in an attempt to provide the equivalent of an HR diagram for protostars (Adams 1990; see chapter by Adams and Lin). As accretion proceeds for a given rotation rate, objects increase in luminosity while the visual extinction through the infalling envelope drops. This work extends that of Yorke and Shustov (1981) who had originally suggested the use of such diagrams for young massive stars embedded in spherical dust cocoons. Observationally, the total luminosity can be determined by integrating the SED; A_V is more difficult to determine but can be estimated from the depth of the 10 μm silicate absorption features (Rieke and Lebofsky 1985), from a comparison of the

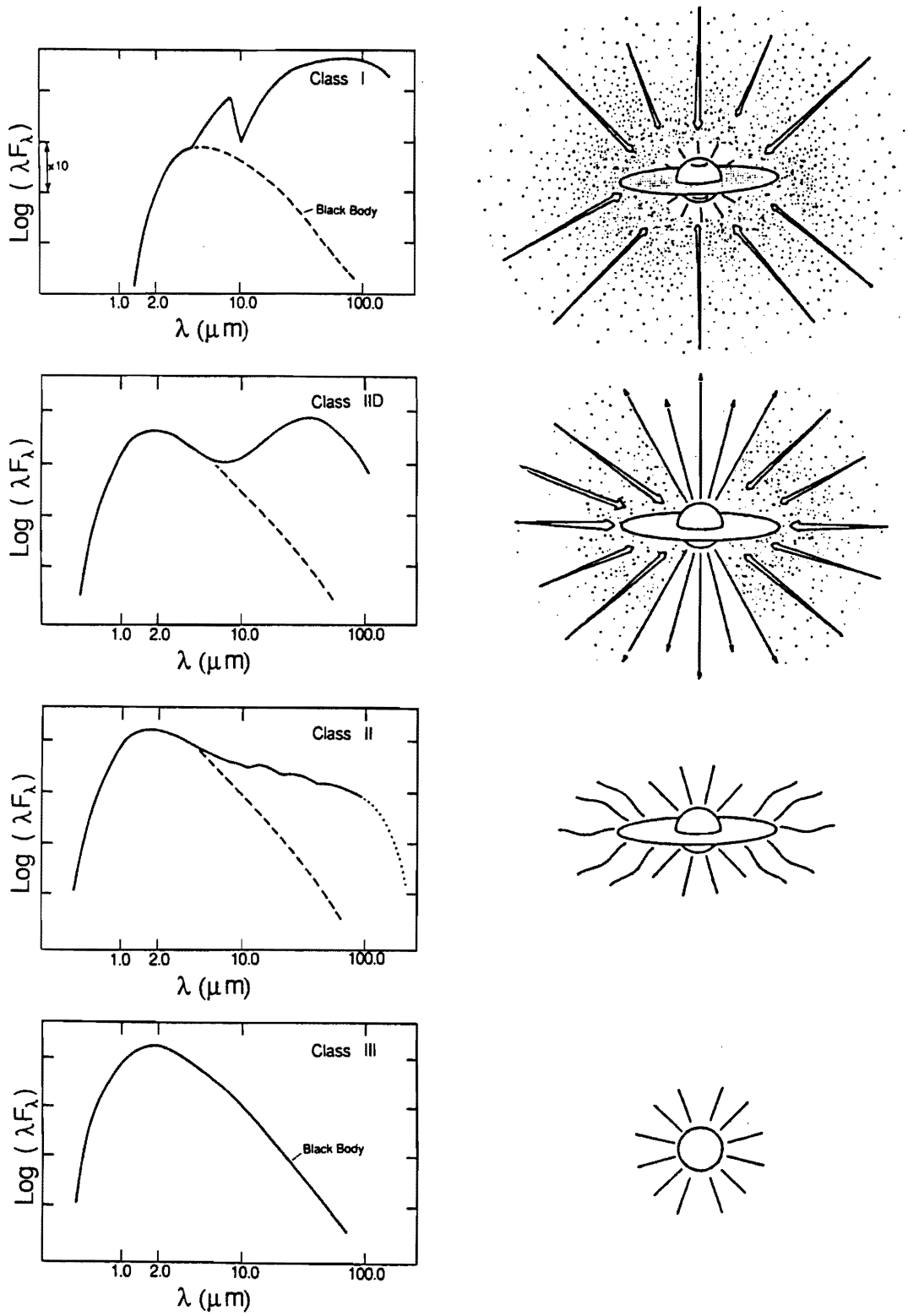


Figure 4 A schematic of the sequence of protostellar evolution, along with the accompanying evolution of the spectral energy distribution (SED). This figure, taken from Wilking (1989), illustrates the ideas described by C. Lada (1987) and in the review article by Shu *et al.* (1987). Reproduction of this figure is by courtesy of the Publications of the Astronomical Society of the Pacific.

intrinsic and the observed ratio of near-infrared hydrogen recombination lines (*e.g.*, Alonso-Costa and Kwan 1989; Evans *et al.* 1987), or from near-infrared colour indices which are free of excess emission (Myers *et al.* 1987). However, for very high extinctions ($A_V \gg 100^m$) none of these methods work, and even for lower extinctions each method suffers from specific problems, *e.g.*, how to separate the intrinsic object extinction from foreground cloud extinction.

While Class I objects cannot be placed on a conventional HR diagram, Class II and III sources usually can. It must be noted however, that only the stellar luminosity should be used in placing the YSO on PMS tracks, not the total luminosity, which often also includes a significant contribution from an active or even passive disk (Bertout *et al.* 1988; Kenyon and Hartmann 1987). K. Strom *et al.* (1989*d*) and Cohen *et al.* (1989) have discussed methods for splitting the stellar and circumstellar contributions to the luminosities of T Tauri stars with disks, but the problem is far from trivial. Recently, Kenyon and Hartmann (1990) have investigated how a random distribution of disk inclination angles, coupled with a plausible range of accretion rates, can introduce a significant scatter in apparent luminosities for intrinsically identical stars. Age determinations for many PMS stars may therefore be uncertain by as much as factors of 2–3. Ultimately, PMS tracks need to be calculated where the luminosity arises not only from Kelvin-Helmholtz contraction, but also in part from disk accretion (see, *e.g.*, Stringfellow 1989).

In summary, the current theory of YSO SEDs suggests that Class I objects consist of three distinct components, Class II of two, and Class III essentially of only one, *i.e.*, the 'naked' young star. However, this theory may be too simple. For example, Class I models may *not* require much of a disk (F. Adams, personal communication; Butner *et al.* 1991), while Class III models could include a disk with a large central hole (Beckwith *et al.* 1990). Also the time dependent and possibly episodic nature of disk accretion should be considered in future models. For example, recent observations of YSOs in ρ Oph indicate a poor correlation between the mass of circumstellar material and the strength of the infrared excess (André *et al.* 1990*b*), suggesting variations in the 'compactness' of disk material within SED classes. The origin of the $r^{-1/2}$ disk temperature gradient in flat-spectrum sources poses a particular problem, and suggests that future YSO evolutionary models should consider active as well as passive disks. Finally, the likelihood of binary and multiple YSOs sharing circumstellar material needs to be accounted for in analysing SEDs.

III. OBSERVATIONS OF INITIAL STELLAR POPULATIONS

In this section, we will review the various observational techniques, from radio to X-rays, employed to study YSOs over the full range of evolutionary states from protostar to weak-emission T Tauri star. The observational picture has changed dramatically since 1984 due to the success of *IRAS* and the growing availability of infrared array cameras. Examples of studies of the initial stellar population are given for diverse molecular environments ranging from nearby dark clouds, through giant molecular clouds, to regions of star formation in the Magellanic Clouds.

A. Techniques and their selection effects

In order to find and study low mass YSOs in all phases of PMS evolution, it is necessary to use a wide variety of observational techniques spanning the entire electromagnetic spectrum. At the same time, no single technique is likely to produce a complete sample of YSOs in any given star formation region. The following are some of the techniques that have been used to reveal the whole range of YSOs, from Class I to Class III:

- Far-infrared surveys (*e.g.*, the *IRAS* all-sky 12–100 μm survey)
- Near-infrared surveys (*e.g.*, 1–2.5 μm)
- 2.6 mm CO line surveys
- 6 cm radio continuum surveys (*e.g.*, with the *VLA*)
- Optical objective prism surveys
- X-ray surveys (*e.g.*, with the *EINSTEIN* Observatory)
- Optical proper motion surveys

Next, we shall discuss these techniques in more detail, paying particular attention to the inevitable selection effects and other shortcomings associated with each of them.

Since 1974, the Kuiper Airborne Observatory (*KAO*) has carried out studies of both massive and low mass embedded YSOs at far-infrared wavelengths (see Thronson and Erickson 1984 for a review). Angular resolutions are typically 50 arcseconds at 50 and 100 μm; for strong sources, diffraction limited resolution is

possible, *e.g.*, ~23 arcseconds at 100 μm (Lester *et al.* 1986). The *KAO* is somewhat limited in its spatial coverage and sensitivity, and therefore a major step forward was taken in 1983 when the cryogenically cooled *IRAS* carried out an all-sky survey at four mid- to far-infrared wavelengths (12, 25, 60, 100 μm) with a resolution of 0.75, 0.75, 1.4, and 3 arcminutes respectively. In addition to finding a number of deeply embedded YSOs (Beichman *et al.* 1986; Beichman 1987), *IRAS* was also sensitive to many of the previously known emission-line objects and objects associated with optical nebulosity. Thus *IRAS* detected several classes of YSOs and would have been superior to optical and near-infrared surveys were it not for a lack of sensitivity to low luminosity objects (*e.g.*, faint T Tauri stars in nearby dark clouds) and the low spatial resolution. Combined, these shortcomings implied that at the distance of Orion, *IRAS* was not only sensitivity limited but also confusion limited. In some cases, high resolution pointed *IRAS* observations have overcome the source confusion problem in *nearby* dark clouds (*e.g.*, in ρ Oph—Young *et al.* 1986; in Cha I—Prusti *et al.* 1991*a*), as have follow-up *KAO* observations. However, at the distance of even the nearest H II regions, the *IRAS* and *KAO* views are blurred.

Ground-based mid-infrared observations on larger telescopes can deliver higher spatial resolution, but at a great expense in sensitivity, due to the enormous thermal background encountered at 10–20 μm. In contrast, the thermal background is negligible shortward of 2.5 μm, and near-infrared observations at 1–2.5 μm can result in high spatial resolution *and* high sensitivity. The advantages of near-infrared observations are that Class II and III YSOs emit most of their luminosity in that wavelength range; extinction due to foreground dust is greatly reduced compared to optical wavelengths; and competition from the bright ionised nebulosity associated with H II regions is considerably reduced. In general, only the very youngest and coolest, and/or most deeply embedded YSOs will escape detection at near-infrared wavelengths, thus requiring far-infrared and sub-millimetre observations. In the past, near-infrared surveys were limited by the need to scan a single detector over a region of star formation, resulting in a serious compromise between sensitivity, resolution, and areal coverage. Employing sensitive two-dimensional infrared array detectors (with $\sim 64\times64$ to 256×256 pixels), near-infrared cameras are now being used to image large areas of star-forming regions. These observations result in simultaneous high spatial resolution (seeing limited, ~1 arcsecond FWHM) and sensitivity (point sources as faint as $K\sim17^m$ are visible in about one minute on a 2 metre class telescope). It is important to note that for the majority of massive star-forming regions in the Galaxy (1–3 kpc), simultaneous high resolution and sensitivity are required to prevent a bias against detection of the lowest mass stars, which would otherwise be lost in the 'glare' of the ionising massive stars. As we shall see below, the power of near-infrared cameras to reveal large clusters of low mass stars associated with H II regions is proving to be a major step forward in YSO surveys. Perhaps the major complaint against these near-infrared surveys is that they can be *too* effective: in addition to revealing almost the entire YSO population associated with a star-forming region, these surveys can also detect large numbers of stars along the line of sight to and beyond the region, due to the effectiveness with which near-infrared photons can penetrate dust, and the general preponderance of the galactic field star population towards low mass, red objects. Surveys of this kind must employ reasonably sophisticated sorting criteria and/or statistical techniques to winnow out the field population, particularly in the more distant regions close to the galactic plane and within the inner Galaxy.

Mid-infrared (10 and 20 μm) cameras are also being built and starting to become operational. They will complement observations at near- and far-infrared wavelengths and will serve as a high resolution probe of deeply embedded YSOs, although again, the extremely high thermal background seen from the ground will limit them to objects that are sufficiently bright, on the order of a few hundred mJy at 10 μm.

Deeply embedded YSOs, as well as some Class II objects, are associated with energetic mass loss revealed as high velocity molecular gas, Herbig-Haro objects, and/or free-free emission. Unbiased surveys for CO outflows in whole clouds such as NGC 2264 and the L 1641 cloud in Orion have revealed the crude positions of the sources that drive these outflows (Margulis and C. Lada 1988; Fukui *et al.* 1989; Fukui 1990). Sensitivity and resolution problems also plague this technique, and primarily higher luminosity sources have been found. If a source is close to the cloud surface, optical Herbig-Haro objects and jets may result, and infrared searches around them can be used to locate their obscured driving sources (Cohen and Schwartz 1983; Reipurth 1990). There must be many cases however, where the HH objects and jets are themselves deeply embedded in the molecular clouds, avoiding detection in the optical: few optical HH objects are seen near the ρ Oph cloud for example. Infrared cameras offer the potential for revealing HH objects and jets even in highly obscured regions: a recently discovered highly collimated structure in a dense core near IC 348 (Fig. 5) is invisible at

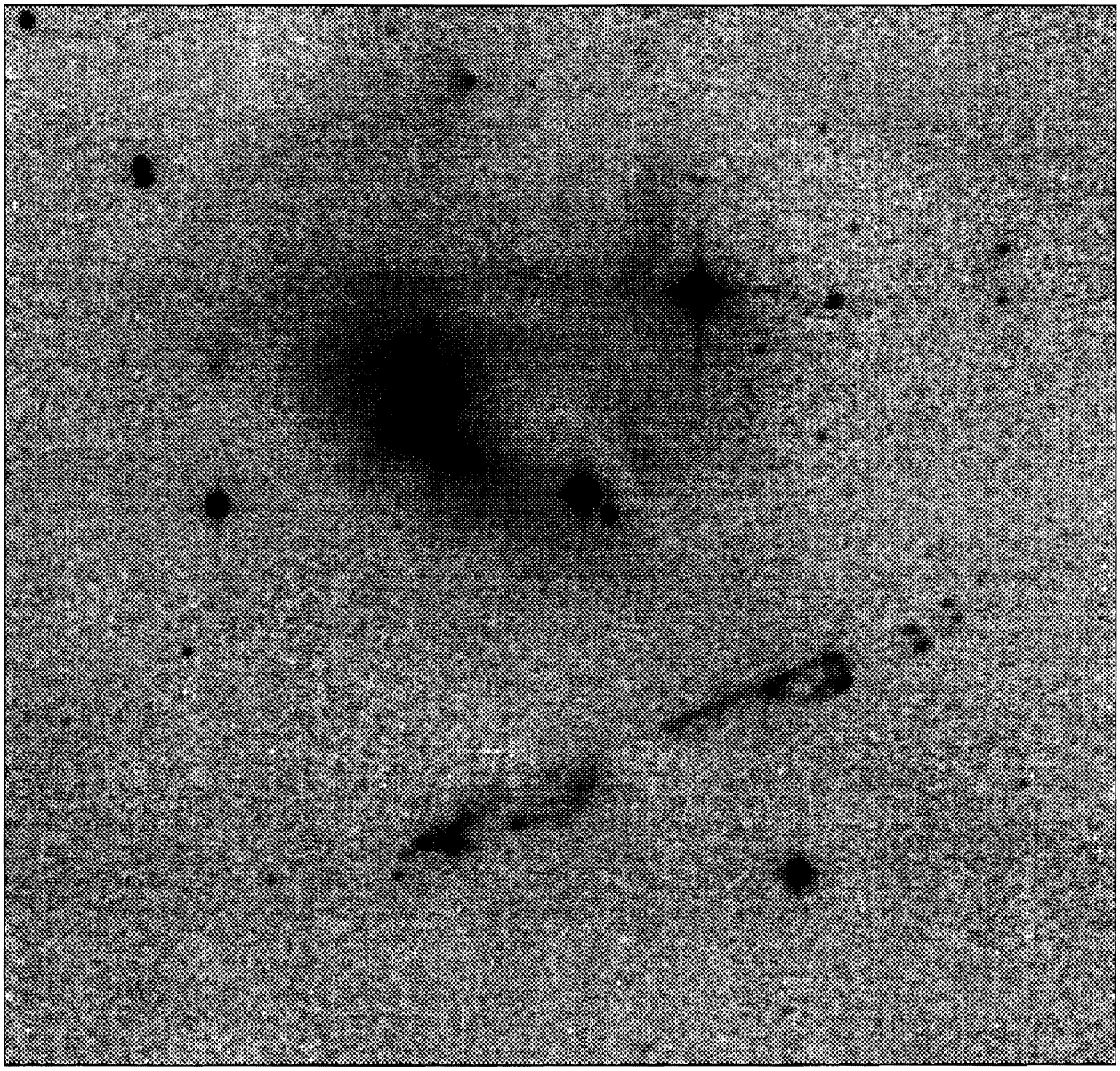


Figure 5 A K (2.2 μm) image of the IC 348-IR region, covering ~3.2×3.2 arcminutes (~0.3×0.3 pc at 300 pc). A previously unknown jet-like feature is revealed, possibly a Herbig-Haro object. The associated driving source, which must be a very young and highly obscured star, has not yet been identified. The data were obtained using a 256×256 pixel HgCdTe array on the University of Hawaii 2.2 m telescope.

wavelengths less than 1 μm, and may be a HH-like object, perhaps radiating strongly in the near-infrared lines of shocked molecular hydrogen and [Fe II].

Potentially promising for uncovering deeply embedded low luminosity YSOs, as well as Class III objects, are large scale radio continuum surveys carried out at the *VLA* (20 cm and 6 cm wavelengths). Typical maps can cover a few square degrees with synthesised beams of order 10–20 arcseconds and source positions better than 5 arcseconds. This technique is very sensitive to small amounts of ionised gas arising from stellar winds (Class I sources) or magnetic surface activity (Class III sources). However, it turns out that most low mass YSOs have only low levels of radio continuum emission. For example, André *et al.* (1987) and Stine *et al.* (1988) conducted a *VLA* survey of 4 square degrees in the ρ Oph cloud. Only a few of the known YSOs were detected and none of the optical T Tauri stars: 90% of the YSOs remained undetected down to a limit of 1 mJy. The bulk of the sources detected at 20 cm at the *VLA* are unrelated to known YSOs, which calls for

tedious identification procedures involving the determination of radio continuum spectral indices and thus multi-wavelength data. However, the radio continuum observations did discover a few new, very interesting embedded young sources which would otherwise have been overlooked, *e.g.*, VLA 1 in the HL/XZ Tau region (Brown *et al.* 1985) and recently VLA 1623 in ρ Oph near GSS 30 (André *et al.* 1990*a*).

Objective prism surveys (Hα) have been very powerful in revealing classical T Tauri stars characterised by strong emission lines at visible wavelengths (see, *e.g.*, Herbig and Bell 1988). Also, surveys for Ca emission have been undertaken to search for weak-emission T Tauri stars, but have discovered few, adding only about 20 emission line stars in Taurus for example (Herbig *et al.* 1986). One caveat in using Hα surveys is that the line strength could be highly variable. For example, emission line objects found on prism plates taken at one epoch have shown less than 50% overlap with those found on plates taken just a decade or so later: *e.g.*, compare Dolidze and Arakelyan (1959) with Wilking *et al.* (1987) who surveyed the same area in the ρ Ophiuchi dark cloud. This variability is worrisome, undermining the usefulness of single epoch Hα surveys to assess the number of young low mass stars in even lightly obscured star-forming regions.

X-ray surveys pick out young stars with magnetic surface activity and have uncovered a population of YSOs which have no or only weak Hα emission and thus were missed in the classical Hα surveys (Feigelson and de Campli 1981; Montmerle *et al.* 1983; Walter 1986; Walter *et al.* 1988; Feigelson and Kriss 1989). Apparently, these weak-emission T Tauri stars have dissipated most of their inner circumstellar gas and dust: however, they still may have *outer* dust disks detectable at millimetre continuum wavelengths (*cf.* Beckwith *et al.* 1990). Because of the limited nature of X-ray surveys with the *EINSTEIN* Observatory and the highly variable nature of the emission, we cannot say at present how many of these Class III objects have been missed. With the *ROSAT* X-ray satellite, launched in June 1990, we should be able to address this problem in the near future. However, even moderately embedded Class III objects can escape detection due to the absorption of soft X-rays by small amounts of cloud material; an optical extinction of $A_V \sim 5$ ($\tau_{1.5\,\mathrm{keV}} \sim 1$) may suffice to lose these young stars.

One of the most unbiased techniques used to identify lightly obscured YSOs in nearby star-forming regions is an optical proper motion survey. For the Taurus clouds, the pioneering work of Jones and Herbig (1979) was recently extended by Hartmann *et al.* (1991), who covered ~9 square degrees to an estimated completeness limit of $V=15^m$. Optical spectra were obtained for the subset of stars with proper motions consistent with Taurus membership, leading to an increase of about 20% in the number of PMS objects in the main survey region, essentially the value predicted by Jones and Herbig (1979). The newly discovered PMS stars have ages around 10^6 yrs, even though much older stars could have been detected. Thus the problem "where are all the post T Tauri stars?" (Herbig *et al.* 1986; Walter *et al.* 1988) remains: they do not seem to be there. It is unlikely that a large population of Class III objects has been missed due to selection effects: the only apparent biasing effect is caused by the movement of the photocentre of binaries due to their mutual orbital motion rather than proper motion.

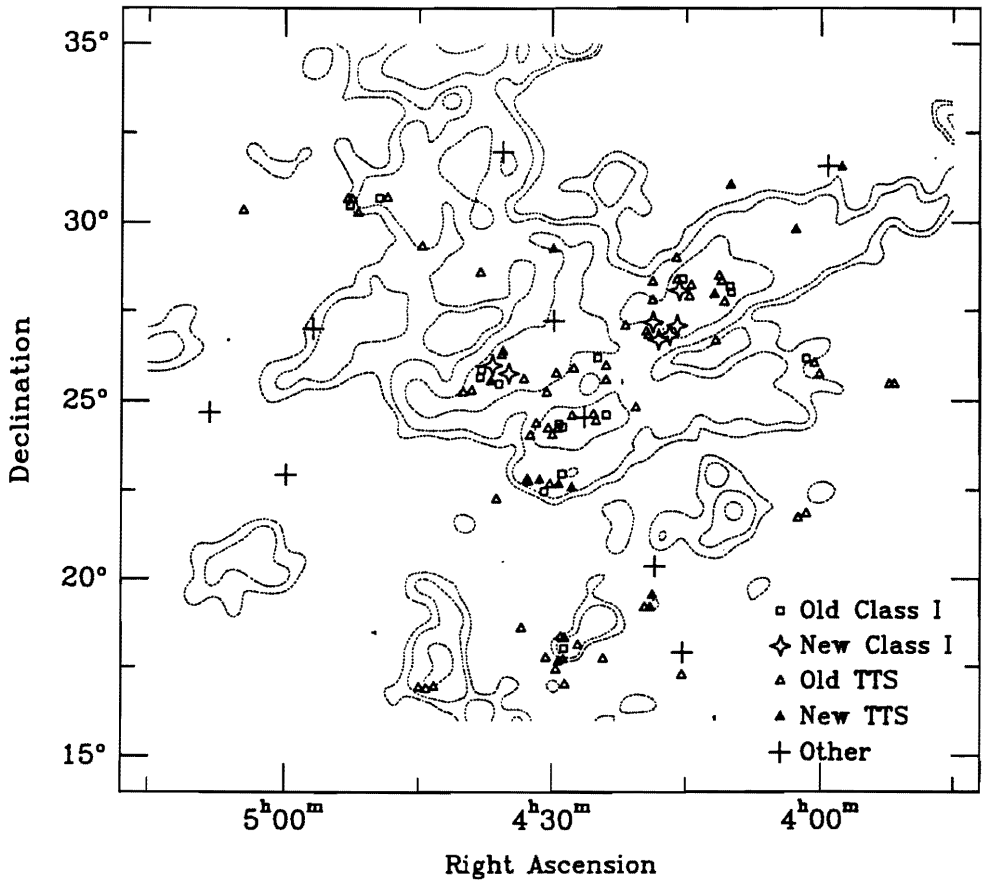
Proper motion surveys for other regions are badly needed, but the effort is huge, and only a few other populations have been examined, *e.g.*, the Orion region centred on the Trapezium Cluster (Parenago 1954; Jones and Walker 1988; van Altena *et al.* 1988; McNamara *et al.* 1989). As many members of these populations remain embedded in molecular cloud material, ultimately we will need proper motion surveys in the near-infrared.

B. Young stars associated with dark clouds

Low mass star formation is best studied in the nearby (< 200 pc) dark cloud complexes. There one can apply the greatest variety of observational techniques with maximum sensitivity to low luminosity YSOs and with the highest linear spatial resolution. Additionally, most of these dark clouds lie well outside of the plane of the Galaxy, so that confusion from background stars is minimised.

1. Taurus-Auriga and ρ Ophiuchi

Among the most intensively studied star-forming regions are the Taurus-Auriga and ρ Ophiuchi dark cloud complexes (Fig. 6*a*,*b*). These are intermediate mass molecular complexes ($\sim 10^4\,M_\odot$) which lie close to the Sun, at distances of about 140 pc and 160 pc respectively. At these distances, their sub-solar mass populations of YSOs are easily accessible to ground-based observers even at mid-infrared wavelengths. Indeed, of the ~100 YSOs identified with each cloud, almost all are low luminosity ($<5\,L_\odot$) objects. These YSOs cover the full range of expected evolutionary states, from heavily obscured Class I sources to optically visible weak emission Class III stars. HR diagrams of the T Tauri populations in these clouds coupled with theoretical PMS tracks suggest that star formation has been going on for at least the past few million years (Cohen and



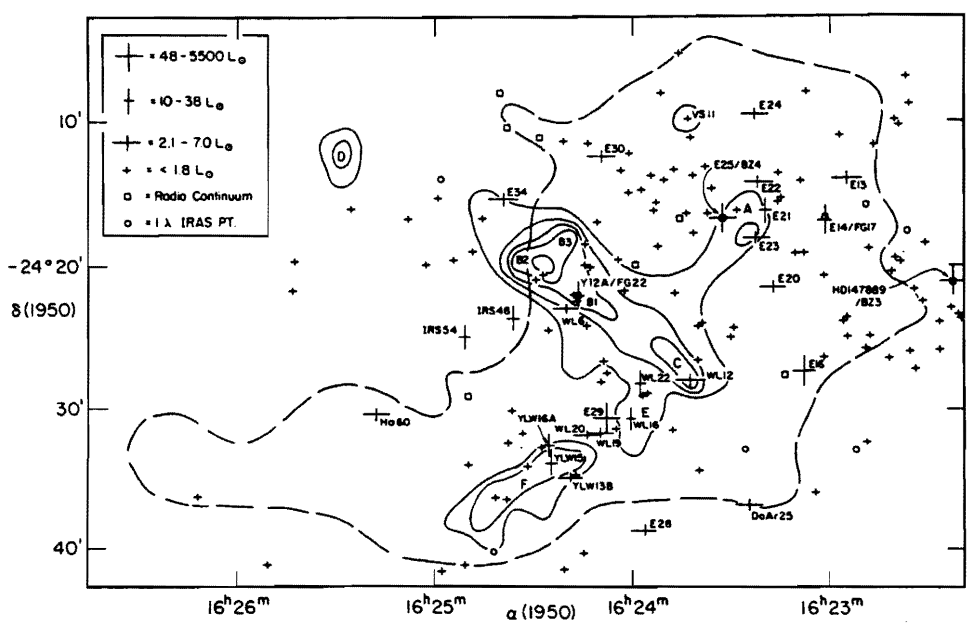


Figure 6*a,b* The spatial distribution of YSOs in the Taurus-Auriga dark cloud complex (covering ~2400 pc^2) from Kenyon *et al.* (1990), and the spatial distribution of YSOs in the ρ Ophiuchi dark cloud core (covering ~4 pc^2) from Loren *et al.* (1990).

Kuhi 1979; Stahler 1983); yet as we discuss below, current evidence suggests that the mechanism for star formation may have been different in the two clouds.

While these molecular cloud complexes have similar masses and are formation sites for comparable numbers of low mass stars, there are important differences between their young stellar populations. Some, if not all, of these differences can be traced to the different interstellar and molecular environments in which the stars have formed. Firstly, the interstellar radiation field is less intense in Taurus-Auriga than in ρ Oph. In the Taurus complex, there are only 8 associated B stars within a 12 pc projected radius of the cloud centre (Elias 1978*b*; Walter and Boyd 1991). In contrast, the ρ Oph cloud lies in the Upper Scorpius sub-group of the Sco-Cen OB association, and has about 20 B or A0 stars within a four times smaller area (radius ~6 pc), with the B2 V star (HD147889) and a B3-B5 V star (Source 1) embedded in the western edge of the complex (Elias 1978*a*; de Geus *et al.* 1989). As a result, warmer dust and gas temperatures are observed in ρ Oph relative to Taurus-Auriga (see, *e.g.*, Greene and Young 1989; Jarrett *et al.* 1989; Snell *et al.* 1989).

A second important difference between these young stellar populations relates to their distributions. Most of the YSOs in the Taurus-Auriga cloud are found in the vicinity of molecular cores with typical masses of $1\,M_\odot$, densities of 10^4–10^5 cm^{-3}, temperatures ~10 K, and visual extinctions of 5^m–10^m (Myers 1985 and references therein; Myers *et al.* 1987). The cores, and hence the YSOs, are distributed throughout a low-extinction, filamentary molecular complex covering about 2400 pc^2 (Ungerechts and Thaddeus 1987). On the other hand, most YSOs in ρ Oph are concentrated toward a 1×2 pc ridge of high column density gas at the western edge of the complex, containing about $550\,M_\odot$ of molecular gas (Vrba *et al.* 1975; Elias 1978*a*; Wilking and C. Lada 1983; Loren 1989*a*,*b*). Characteristic visual extinctions in this region are 50^m–100^m. High density molecular cores are found within the ridge, displaying higher masses and temperatures than their Taurus-Auriga counterparts (Loren *et al.* 1990). A lower density of YSOs is found in the filamentary streamers of Ophiuchus, forming in the vicinity of molecular cores in the manner observed in Taurus-Auriga.

The stellar density within the high column density ρ Oph cloud core is about 150 stars pc^{-3}, and the star formation efficiency (SFE) is roughly 22% (Wilking *et al.* 1989). Thus it has been suggested that given the time-dependent nature of the SFE and the slow release of gas from the cloud, a gravitationally-bound stellar cluster of order 100 stars will ultimately emerge from the core (Wilking and C. Lada 1985). While it is true that the SFE in Taurus-Auriga is high in the vicinity of dense cores, the current distribution of YSOs does not suggest the formation of a large bound stellar group there.

Significant differences between these stellar populations also arise when a detailed comparison of the luminosity functions of their Class I and Class II sources is made (see, *e.g.*, Wilking *et al.* 1989; Kenyon *et al.* 1990). Spectral energy distributions for the YSOs and the resulting luminosity functions have been constructed by synthesising visible wavelength data with near- to far-infrared data, thus yielding the most reliable estimates for the YSOs' SED classes and bolometric luminosities. In regions of low source density, the completeness limit imposed by the *IRAS* sensitivity for the luminosity function in the Taurus-Auriga cloud is $>0.3\,L_\odot$ for Class I sources and $>0.5\,L_\odot$ for Class II stars. In ρ Oph, these limits are higher due to greater extinction in the cloud: Class I sources are completely sampled throughout the entire depth of the cloud core for $>1\,L_\odot$, but $1\,L_\odot$ Class II sources are completely sampled in only the outer $A_V\sim35^m$–40^m of the cloud. The luminosity functions for these two clouds are shown in Fig. 7, with the number of Class I and Class II sources in each bin indicated. In ρ Oph, the intermediate luminosity range (5.6–56 $L_\odot$) is dominated by Class I objects (80%) and their number drops with decreasing luminosity. This observation can be understood if these Class I sources form a population of heavily obscured 0.1–1 $M_\odot$ objects with an excess of luminosity relative to their Class II counterparts, *i.e.*, they derive part or all of their luminosity from accretion. Alternatively, it is possible that these Class I sources are very young 2–3 $M_\odot$ objects, implying that the cloud is forming stars sequentially in mass. In Taurus-Auriga, there are fewer Class I objects relative to Class II at intermediate luminosities (45%), and their number *increases* with decreasing luminosity. There are several selection effects present in ρ Oph which could give rise to the observed differences in these luminosity functions, *e.g.*, confusion in the *IRAS* data and the high visual extinction in ρ Oph could account for the drop in the number of Class I sources with decreasing luminosity. However, the segregation of luminosities by SED class for $L>5.6\,L_\odot$ appears to be a real effect in ρ Oph and cannot be accounted for by source confusion in the *IRAS* data (as determined by deep near-infrared imaging) or by reddening of Class II sources to produce Class I SEDs (as indicated by rising 25-100 μm SEDs). While the origin of the differences between these luminosity functions is unknown, several explanations are plausible. If intermediate luminosity Class I sources in ρ Oph are 2–3 $M_\odot$ objects, then perhaps stars in Taurus-Auriga have not formed as recently or are not forming sequentially in mass. On the other hand, if these Class I sources are 0.1–1 $M_\odot$ objects, then

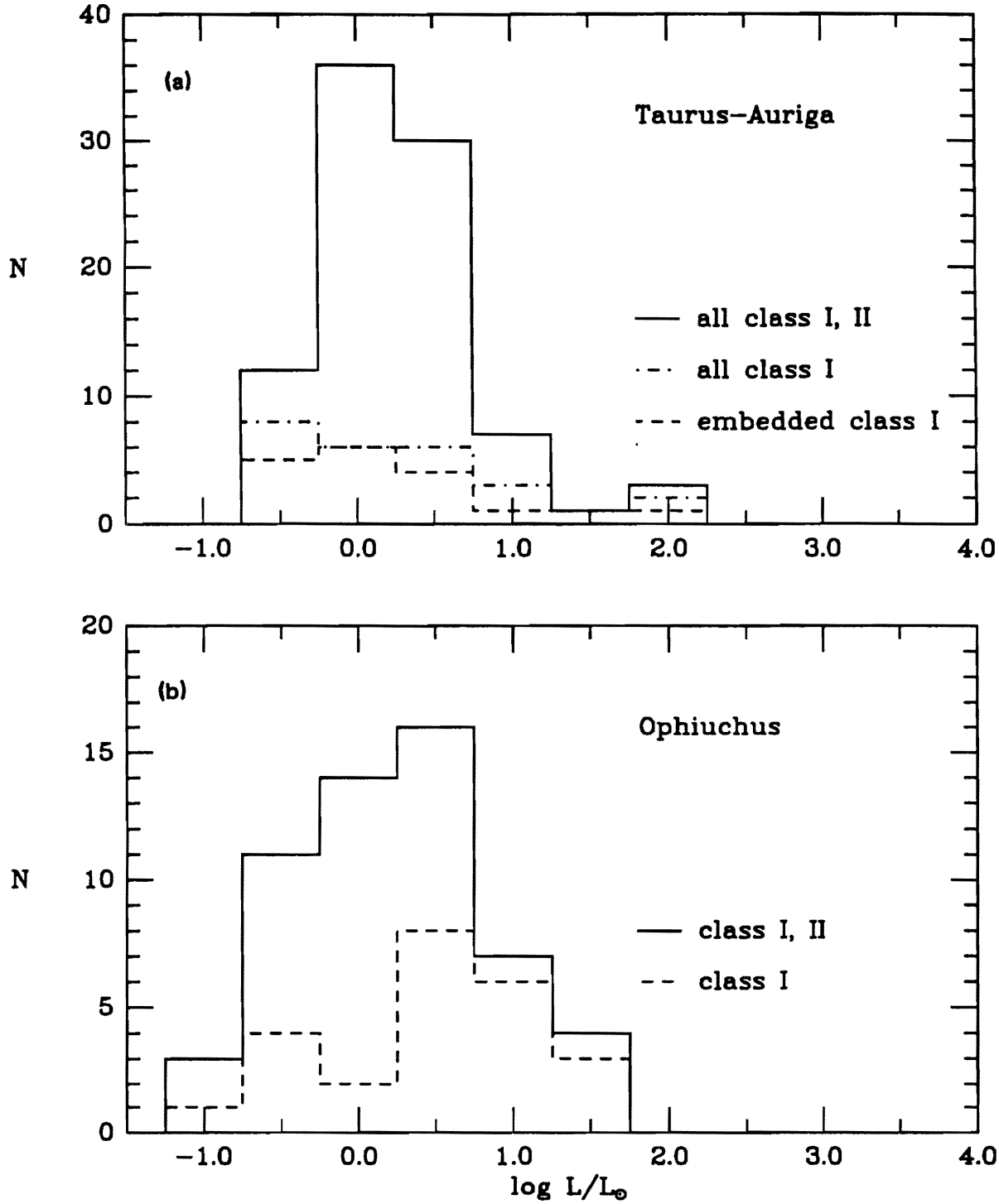


Figure 7 A comparison of the bolometric luminosity functions for young stellar objects in the Taurus dark cloud and in the ρ Oph molecular cloud core. The number of Class I and II sources in each bin is indicated. Significant differences are apparent between the two luminosity-limited samples. Figure taken from Kenyon *et al.* 1990, their Fig. 8.

perhaps the accretion rate, and hence luminosity, of protostars is lower in Taurus-Auriga relative to ρ Oph, as predicted by models for spherical accretion in cooler clouds (Adams *et al.* 1987).

Investigations into the low mass end of the IMF of the ρ Oph cluster are now possible using infrared array cameras, with high visual extinctions in the core minimising confusion with background field stars. A moderately deep 2.2 μm survey (to $K \sim 15^m$) of a 20 square arcminute area of the core by Rieke *et al.* (1989) revealed no new sources beyond those found by Wilking and C. Lada (1983), suggesting a deficiency of YSOs with masses below a few tenths of a solar mass. However, a subsequent survey by Barsony *et al.* (1989*b*) to $K \sim 14^m$ of a larger area (144 square arcminutes) led to the discovery of 35 new sources, and most recently, Greene (1991) surveyed some 650 square arcminutes on and off the densest parts of the cloud, finding almost 500 sources to a completeness limit of $K \sim 13^m$. As such surveys grow in area coverage, it becomes increasingly important to determine what fraction of these new sources are indeed embedded in the cloud by using multi-colour infrared photometry (*cf.* Greene 1991). However, one possible conclusion is that the IMF of a cloud can vary dramatically over size scales less than 0.5 pc, and that large areas of a cloud must be considered before comparisons can be made with other clouds.

The differences noted above between the populations of YSOs in Taurus-Auriga and ρ Oph have led to the idea that different mechanisms of star formation have operated in these clouds, but thus far the observational evidence is sparse. Vrba (1977) and Loren and Wootten (1986) have proposed that compression of the ρ Oph cloud by a shock wave propagating from the southwest has shaped the morphology of the cloud and dense cores, generated small velocity shifts in the molecular gas, and produced the high SFE in the core region. A more recent explanation for the high SFE in the ρ Oph core has been given by Uchida *et al.* (1990), based upon their discovery of rotational motions about the major axis of the filamentary streamer to the northeast. They suggest that these motions provide an angular momentum drain from the cloud core resulting in enhanced star formation. Consistent with these ideas that the ρ Oph core has lost its internal support, Shu *et al.* (1987) suggest that ρ Oph is an example of star formation resulting from cloud contraction where self-gravity dominates magnetic support, thus producing a high SFE. In contrast, magnetic fields may dominate the evolution of molecular cores in Taurus-Auriga resulting in longer contraction times and lower values for the SFE.

2. Other dark clouds and globules

There are a number of star-forming regions within several hundred parsecs of the Sun whose young stellar populations have yet to be examined as extensively as those in the Taurus-Auriga cloud or ρ Oph core. These regions include the Lupus dark cloud (125 pc), the R Coronae Australis cloud (130 pc), the filamentary streamers in Ophiuchus, L 1689/L 1709 (160 pc), the Chamaeleon dark clouds (115–220 pc), and globules selected from southern and northern hemisphere photographic surveys ($\leq$500 pc). Future studies of these regions will provide important comparisons with Taurus-Auriga and ρ Oph, and give further insight into the process of low mass star formation in dark clouds. Investigations of the YSO populations in several of these regions are briefly described below.

Like Taurus-Auriga, the Lupus dark cloud complex also has a filamentary appearance. It consists of 4 sub-regions, of which 3 are actively forming low mass stars (see Krautter 1991 for a review). Preliminary indications are that the YSO population also resembles that in Taurus-Auriga, *i.e.*, there appears to be a low ratio of embedded Class I sources to emission-line Class II stars. However, previous surveys for YSOs have selected against heavily obscured objects, and confirmation of the scarcity of Class I objects awaits a thorough analysis of the *IRAS* data for the region (see, *e.g.*, Carballo *et al.* 1991) and near-infrared imaging of the cloud. Since Class I objects are most often found associated with mass loss, one might expect a low incidence of HH objects/optical jets in Lupus. This is in fact observed (Krautter 1986; Heyer and Graham 1989), although high visual extinction in the cloud can produce the same effect (*e.g.*, as seen in the ρ Oph core). The early indications are that Lupus is an older star-forming region where activity has already died down. Consistent with this picture is the fact that the Lupus T Tauri population is dominated by M-type stars (Krautter and Kelemen 1987; see also Appenzeller *et al.* 1983). It will be interesting to see whether the *ROSAT* X-ray survey will reveal the large population of weak-emission T Tauri stars, particularly those with K spectral types, expected for a more mature star-forming region.

The R Coronae Australis dark cloud bears many similarities to the ρ Oph complex. The clouds are located about 17° out of the plane of the Galaxy, almost mirror images at galactic longitude $l \sim 355°$. The morphologies of their molecular gas are also similar, with lower density streamers of gas and dust extending from centrally-condensed cores (Loren *et al.* 1983), although different mechanisms could produce this morphology (Vrba 1977; Vrba *et al.* 1981; Fleck 1984). Like ρ Oph, the most active star formation is in

the core, where 13 YSOs distributed over a 0.08 pc^2 area centred on the star R Cr A comprise the Coronet cluster (see, *e.g.*, Taylor and Storey 1984; Wilking *et al.* 1986). In the absence of massive stars, the core could be the site of formation of a small gravitationally bound cluster, and yet overall the density of YSOs in the R Cr A cloud appears lower than in ρ Oph. Hα studies have yielded only $\leq$17 bona-fide emission-line stars (Marraco and Rydgren 1981) while at least 65 have been identified in ρ Oph (Wilking *et al.* 1987). Preliminary analyses of *IRAS* coadded survey data of the cloud core and vicinity reveal less than half the number of mid- to far-infrared sources seen in ρ Oph (16 vs 44) and only three of these are invisible, Class I sources (Wilking *et al.* 1991). The difference between the number of young stars in the two molecular clouds appears to be in rough proportion to their masses, *i.e.*, there is a smaller reservoir of molecular gas in the R Cr A cloud. Extensive near-infrared imaging of the cloud core is needed to characterise more fully the embedded population.

The Chamaeleon dark clouds (Cha I and Cha II) have recently been extensively explored through optical, near-infrared, far-infrared, and X-ray observations (Hyland *et al.* 1982; Jones *et al.* 1985; Whittet *et al.* 1987, 1991*a*,*b*; Feigelson and Kriss 1989; Assendorp *et al.* 1990; Prusti *et al.* 1991*a*,*b*; Schwartz 1991; Gauvin and Strom 1992). The distance is a particularly controversial parameter, and is somewhere in the range 115–220 pc (Whittet *et al.* 1987; Gauvin and Strom 1992). The streaky, filamentary structure found in the complex is once again reminiscent of the Taurus-Auriga clouds (see, *e.g.*, Mattila *et al.* 1990), although the star formation in Cha I is much more localised than in Taurus-Auriga: of the 81 YSOs identified over a 50 pc^2 area of the Cha I cloud, the great majority are concentrated in a $\sim$12–15 pc^2 region near the reflection nebulae Ced 110, 111, and 112 (Schwartz 1991; Prusti *et al.* 1991*b*). The distribution of spectral types for the optically visible T Tauri stars in Cha I is heavily weighted towards K2–M0.5 stars, suggesting a higher characteristic stellar mass than in the Lupus cloud (Krautter 1991). Prusti *et al.* (1991*b*) combined near-infrared photometry and *IRAS* fluxes to determine SEDs and bolometric luminosities for 60 of the YSOs, and thence derived a luminosity function for the association. When compared to the equivalent luminosity functions for ρ Oph and Taurus-Auriga, Cha I has the lowest average luminosity of all three, and fewer Class I objects (six) than either of the others. One possible interpretation is that the Cha I population is older. However, Gauvin and Strom (1992) compared the masses and ages of the optically visible YSOs in Cha I with those in Taurus-Auriga and found no significant differences. They suggest that the dearth of Class I objects in Cha I might indicate an episodic or variable star formation rate, with few stars formed recently. Finally, only $\sim$60% of the previously known T Tauri stars in Cha I were detected by *IRAS*, in either the main survey or the more sensitive pointed observations. As Whittet *et al.* (1991*a*) note, this implies that the *IRAS* data give an incomplete census of low mass Class II or III YSOs, even in the nearby dark clouds: deep near-infrared surveys such as those carried out by Hyland *et al.* (1982) and Jones *et al.* (1985) for Cha I are probably more effective in identifying Class II and III YSOs.

The Cha II cloud contains no reflection nebulae and is less conspicuous than the more extensively studied Cha I. Schwartz (1977) found a small number ($\sim$19) of Hα emission line stars along the line of sight towards Cha II, and these objects were recently confirmed as low luminosity (0.1–1.3 $L_\odot$) young classical T Tauri stars based on their near- and and far-infrared SEDs (Whittet *et al.* 1991*b*). Apart from one luminous ($\sim$40 $L_\odot$) Class I source with an associated outflow, the Cha II cloud lacks objects with luminosities $>$2 $L_\odot$ compared to Cha I, and the lower luminosity objects are not obviously clustered.

Recently, infrared studies have been made of more isolated star formation in small ($<$10 arcminute diameter), dark clouds within about 500 pc of the Sun, commonly referred to as Bok globules. Persi *et al.* (1990) have used the *IRAS* Point Source Catalog to analyse 482 southern hemisphere dark globules from a list compiled by Hartley *et al.* (1986). They have found only about 10% (53) are associated with point sources displaying a rising 12–60 μm flux distribution. Using near-infrared photometry, they have determined that 17 of these *IRAS* sources are PMS objects, with typical luminosities of 10–1000$\times(d/500\,\mathrm{pc})^2\,L_\odot$. Persi *et al.* (1990) conclude that star formation in small dark clouds may be very inefficient; however, as discussed earlier, observations over a broad range of wavelengths are necessary to sample completely a YSO population. A similar study of northern hemisphere ($-36° < \delta < 90°$) globules has been made by Yun and Clemens (1990). They used *IRAS* co-added images to search for evidence of star formation among the sample of 248 isolated clouds catalogued by Clemens and Barvainis (1988). They find 23% of the sample have associated far-infrared point sources, but argue, on the basis of the limiting sensitivity of their technique to PMS stars with $M>0.7\,M_\odot$, that *all* globules in their sample could harbour newly formed stars if the embedded stellar mass distribution follows the Miller-Scalo IMF. Clearly, the Persi *et al.* (1990) and Yun and Clemens (1990) samples provide useful target lists for follow-up studies with near-infrared cameras, *ISO*, and *SIRTF*.

C. Young stars associated with giant molecular clouds

In order to study the high mass end of the IMF, we must look to the giant molecular clouds (GMCs) where young OB stars are found. However, GMCs are not only the birthplaces of massive stars but also of low mass stars. In fact, since most of the integrated stellar mass in the IMF is in low mass stars and since most of the molecular mass is in GMCs, it follows that most low mass stars in the galaxy should form in GMCs, rather than in smaller, less massive dark cloud complexes like Taurus-Auriga and ρ Oph.

1. Orion (400–500 pc)

At 160 pc, the Sco-Cen OB association has the distinction of being the nearest to the Sun. However, there is no on-going high mass star formation in Sco-Cen, although low mass stars are still forming in the associated ρ Oph dark cloud. Thus it is the Orion OB association and GMC that present us with our closest view of on-going simultaneous low *and* high mass star formation.

We will begin by delineating the young populations *near* the Orion cloud complex, namely the stellar content of the adjacent OB association, Ori OB1. This will be followed by descriptions of the embedded clusters in the Orion A (L 1641) and Orion B (L 1630) cloud, starting with an in-depth discussion of the Trapezium Cluster, followed by briefer accounts of the clusters associated with OMC-2, NGC 2024, NGC 2023, NGC 2071, and NGC 2068. After discussing the clusters, we also discuss the underlying populations of their host clouds L 1641 and L 1630. Finally, we discuss the young stars in the nearby λ Ori region.

The stellar content of the OB sub-groups

The various sub-groups (1a, 1b, 1c, 1d) of the Ori OB1 association comprise a so-called 'fossil record' (Blaauw 1991) of relatively recent star formation, while new stars are still being formed in the nearby Orion A and B molecular clouds (see Fig. 8). These various components are perhaps all linked via sequential star formation, *i.e.*, the compressive action, via winds and supernovae, of one generation of O stars on adjacent molecular material leading to yet another burst of star formation (*cf.* B. Elmegreen and C. Lada 1977). A speculative sequence of events in Orion may have started with a first phase of star formation leading to the 1a sub-group some 7–12$\times 10^6$ years ago, perhaps triggered by the passage of the Orion GMC through the galactic disk (Franco *et al.* 1988) or by the effects of a runaway O star exploding inside the Orion molecular cloud (Blaauw 1991; A. Blaauw, personal communication). The 1a O stars may then have triggered the younger 1b sub-group ($\sim 5\times 10^6$ yrs), which includes the Orion Belt stars. The 1b sub-group is located between Orion B and Orion A, and it is tempting to speculate that in its turn, the 1b sub-group may have split the two clouds, and triggered star formation in both directions at once (a 'bifurcation'), *i.e.*, leading to the NGC 2024 cluster in Orion B to the north and the sub-groups 1c (a few $\times 10^6$ yrs) and 1d (the Trapezium Cluster; $\sim 10^6$ yrs) in Orion A to the south.

The stellar content of 1a, 1b, and 1c sub-groups was studied by Warren and Hesser (1977, 1978), with the conclusion that only stars earlier than A0 (about 3 $M_\odot$) are completely known. The number of B stars in 1a, 1b, and 1c are 121, 96, and 36, respectively, and the estimated number of supernovae thought to have occurred in 1a and 1b is 9 and 3, respectively (A. Blaauw, personal communication). Clearly, sub-group 1a must have been a very active site of star formation some 10 million years ago, much more active than the Orion clouds today.

As mentioned above, little is known about the low mass stellar content of the Orion OB1 association. However, recent Kiso Schmidt Hα surveys of the 1a and 1b sub-groups have revealed some 250 and 150 new emission line stars respectively, with magnitudes in the range $V=13^m$–17^m, *i.e.*, most likely low mass T Tauri stars (Kogure *et al.* 1989; Wiramihardja *et al.* 1989). A sizeable fraction (about 30%) of these emission line stars were found to be variable in Hα intensity over a time span of 18 months, again highlighting the limitations of single epoch searches for YSOs via Hα surveys. Future work will place the newly revealed Orion association members on the HR diagram and determine their masses, perhaps even their mass function (*cf.* Cohen and Kuhi 1979).

Proper motion surveys should be less biased, and the 1c sub-group (also known as the Orion Cluster, as distinct from the Trapezium Cluster, sub-group 1d) has long been a target for this technique, beginning with the classic work by Parenago (1954). He listed almost 3000 stars brighter than $B\sim 17^m$ in a 9 square degree area centred on the Orion Nebula, but due to the relatively crude proper motions, only tentative membership probabilities could be derived. Recent studies have obtained significantly improved results from new and archival material spanning up to 77 years. McNamara *et al.* (1989) studied a somewhat smaller region (7 square degrees) excluding the central emission nebulosity, and analysed 630 stars to a limit of $B\sim 14^m$, finding that approximately 40% of the stars are probable members. Restricting their study to the

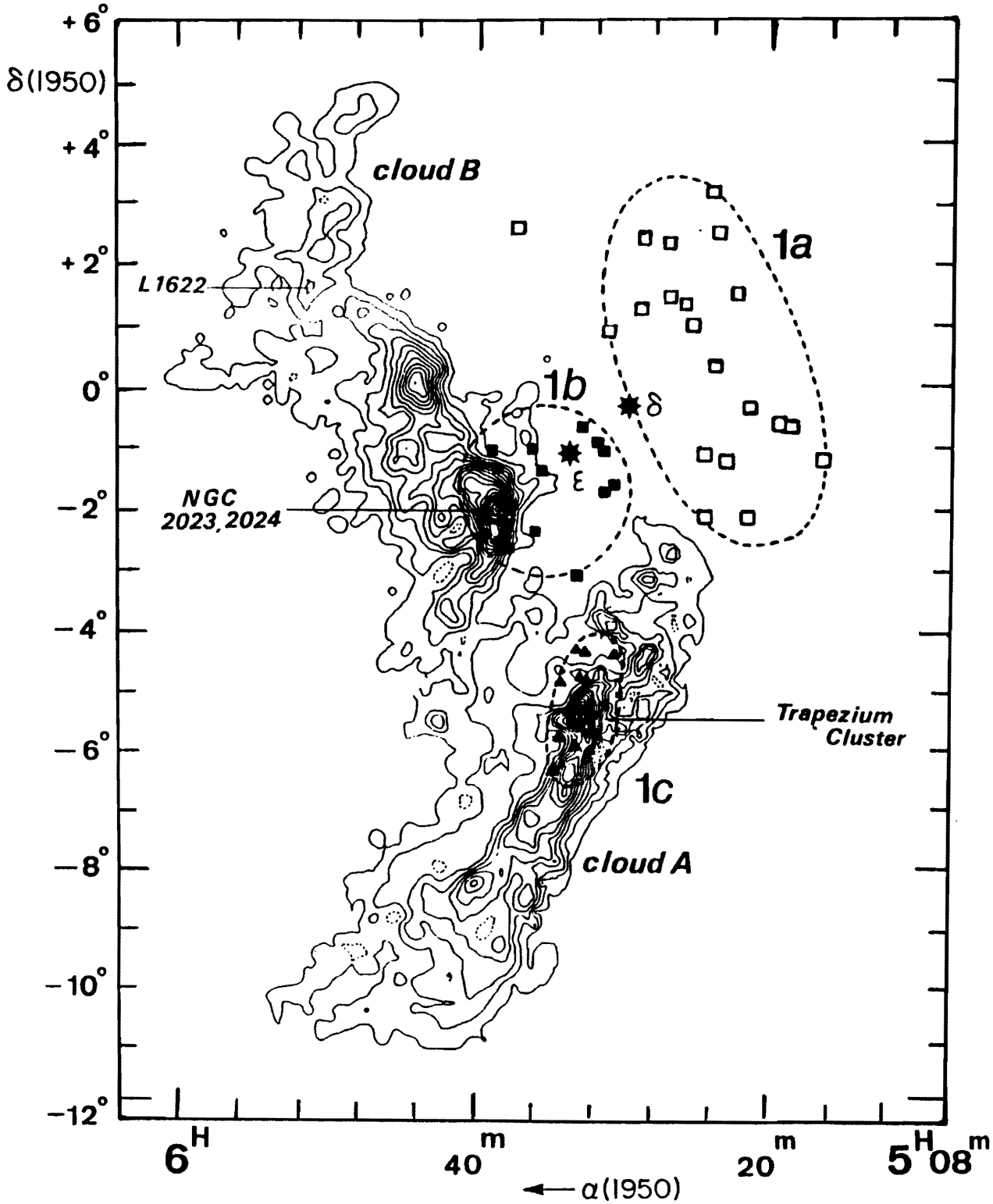


Figure 8 The Ori OB1 association showing the sub-groups 1a, 1b, and 1c with respect to the molecular clouds Orion A (L 1641) and B (L 1630) (Blaauw 1991). The 1a, 1b, and 1c sub-groups cover roughly 45×25, 25×20, and 20×10 pc, and are approximately 7–12, 5, and 3 million years old respectively. The 1d sub-group (the Trapezium Cluster) lies at the centre of the 1c sub-group.

73 stars brighter than $V{\sim}12^m.5$ within 30 arcminutes of the Trapezium, van Altena *et al.* (1988) obtained very high precision proper motions, and assigned membership to about 67% of the stars. Lastly, using deep red plates (down to $I{\sim}13^m$ in the bright nebulosity, and $I{\sim}16^m$ in the outer region) to cover a smaller 15 arcminute radius around the Trapezium, Jones and Walker (1988) detected more than 1000 stars, and found ~90% to be members of the Orion complex. From 693 low error and high membership probability stars, Jones and Walker (1988) derived a 1D velocity dispersion of about $2.3\,\mathrm{km\,s^{-1}}$, with a distribution that is more or less isotropic and independent of the distance from the Trapezium. Considering only the brighter stars, both Jones and Walker (1988) and van Altena *et al.* (1988) found a dispersion closer to $1.5\,\mathrm{km\,s^{-1}}$, and the latter study revealed that the two brightest stars in the Trapezium Cluster (θ^1Ori C and θ^2Ori A) have very high proper motions, indicating that both are being ejected, and will be more than 5 pc from the cluster within 10^6 years.

Finally, it is worth noting that a special program being carried out with the *HIPPARCOS* satellite is beginning to provide parallaxes for hundreds of the brighter stars in the Orion region.

The Trapezium Cluster

At the core of the Orion 1c sub-group, near the apex of the L 1641 molecular cloud, is the famous Orion Nebula (M 42, NGC 1976). Much is known about this nearby H II region, the massive stars of the Trapezium OB association (*i.e.*, the 1d sub-group) that ionise it, the background parent molecular cloud OMC-1, and the very young sources of the BN-KL complex embedded within it. Yet there has been remarkably little study of the *low mass* stellar content of the region, the so-called Trapezium Cluster (Herbig 1982).

Despite the extremely bright H II region nebulosity, it has been known for a long time that the Orion Nebula is host to an unusually large number of faint red stars (Trumpler 1931; Baade and Minkowski 1937). Recently, Herbig and Terndrup (1986) used narrow band optical (at ~5500 and 8000Å) imaging photometry to reduce the competition from nebular line emission, detecting ~150 stars over a region approximately 3×3 arcminutes in size. Excluding the OB stars, an extremely high stellar density in excess of $2200\,\mathrm{pc^{-3}}$ was derived, although the exact value depends on the volume the cluster is assumed to occupy. Some 68 cluster members were well enough measured to be placed on an HR diagram, allowing estimates of ages and masses by comparison with theoretical PMS tracks. A uniform dereddening, determined from spectroscopy of only 10 stars, was applied to all cluster members. The majority of the stars fell youngward of the 10^6 year isochrone, and including the OB stars, a mean mass density of $3000\,M_\odot\,\mathrm{pc^{-3}}$ was derived, equivalent to 0.6×10^5 H_2 molecules $\mathrm{cm^{-3}}$. This latter value is typical of the nearby molecular cloud material, implying that the cluster must have formed with a high star formation efficiency (>10%) from the cloud (Genzel and Stutzki 1989).

However, optical studies tell less than half the story. As we have discussed earlier in this chapter, the near-infrared is a much better wavelength range over which to survey young clusters, and even relatively low resolution and sensitivity raster scan studies at $2.2\,\mu$m demonstrated the existence of a yet higher stellar density than seen in the optical (Hyland *et al.* 1984). With the introduction of infrared imaging cameras, the Trapezium Cluster was fully revealed, with over 500 members in a 5×5 arcminute region centred on the Trapezium OB stars (McCaughrean 1988; McCaughrean *et al.* 1992).

Figure 9*a* shows a $2.2\,\mu$m image of the Trapezium Cluster: by comparison with an optical image of the same region (Fig. 9*b*), the cluster appears more symmetric as the optically obscured stars, including those behind the eastern 'dark bay', are revealed. The massive Trapezium OB stars are located right at the centre of the cluster, a feature common to many young clusters, as we shall see later (*e.g.*, R 136a in 30 Doradus). The extraordinary stellar density of the Trapezium Cluster can be well illustrated by comparing it to the embedded cluster in the core of ρ Oph. Figure 10*a* shows the stars in the central 5×5 arcminutes of the Trapezium Cluster, while Fig. 10*b* shows the core of ρ Oph *as it would appear if projected to the distance of the Orion Nebula.*

In the central 1 arcminute (0.14 pc) diameter core of the Trapezium Cluster, the stellar number density exceeds $10^4\,\mathrm{pc^{-3}}$, although again the exact value depends somewhat on the 3D geometry of the cluster. This density implies a mean separation between the cluster stars of ~0.045 pc (1.5×10^{15} m or 10^4 AU). Assuming this length to be equal to the fragmentation scale length in the original molecular cloud, and that fragmentation occurs promptly (*e.g.*, after shock compression) to create protostellar fragments with masses similar to those of the observed low mass stars (~0.2–0.6 $M_\odot$), we can derive a gas density and temperature by requiring the separation and mass to be equal to the Jeans length and mass respectively. In this case, we derive reasonable values of $\sim10^6\,\mathrm{cm^{-3}}$ for the density and ~10–20 K for the temperature. This raises the possibility that the original protostars in the Trapezium Cluster may actually have been touching. The

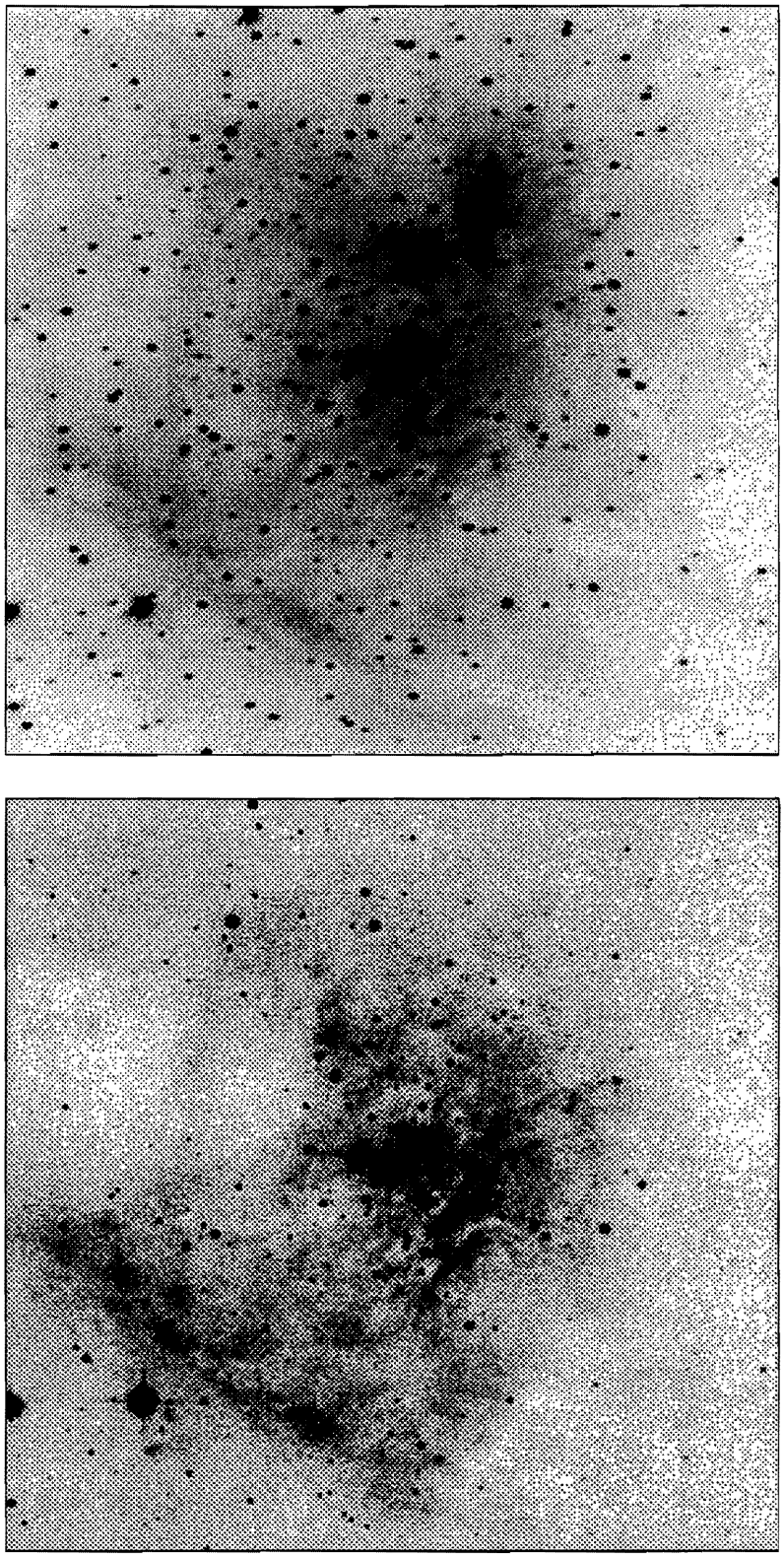


Figure 9*a,b* A K (2.2 μm) mosaic covering the central 5×5 arcminutes (~0.65×0.65 pc at 450 pc) of the Trapezium Cluster. Some 500 stars are seen to a completeness limit of $K \sim 15^{m}.5$. The data were obtained using a 62×58 pixel InSb array on the United Kingdom 3.8 m Infrared Telescope (McCaughrean *et al.* 1992). For comparison, an optical (I) photograph of the same region is also shown (photograph taken at the Anglo-Australian Telescope, and kindly provided by David Malin).

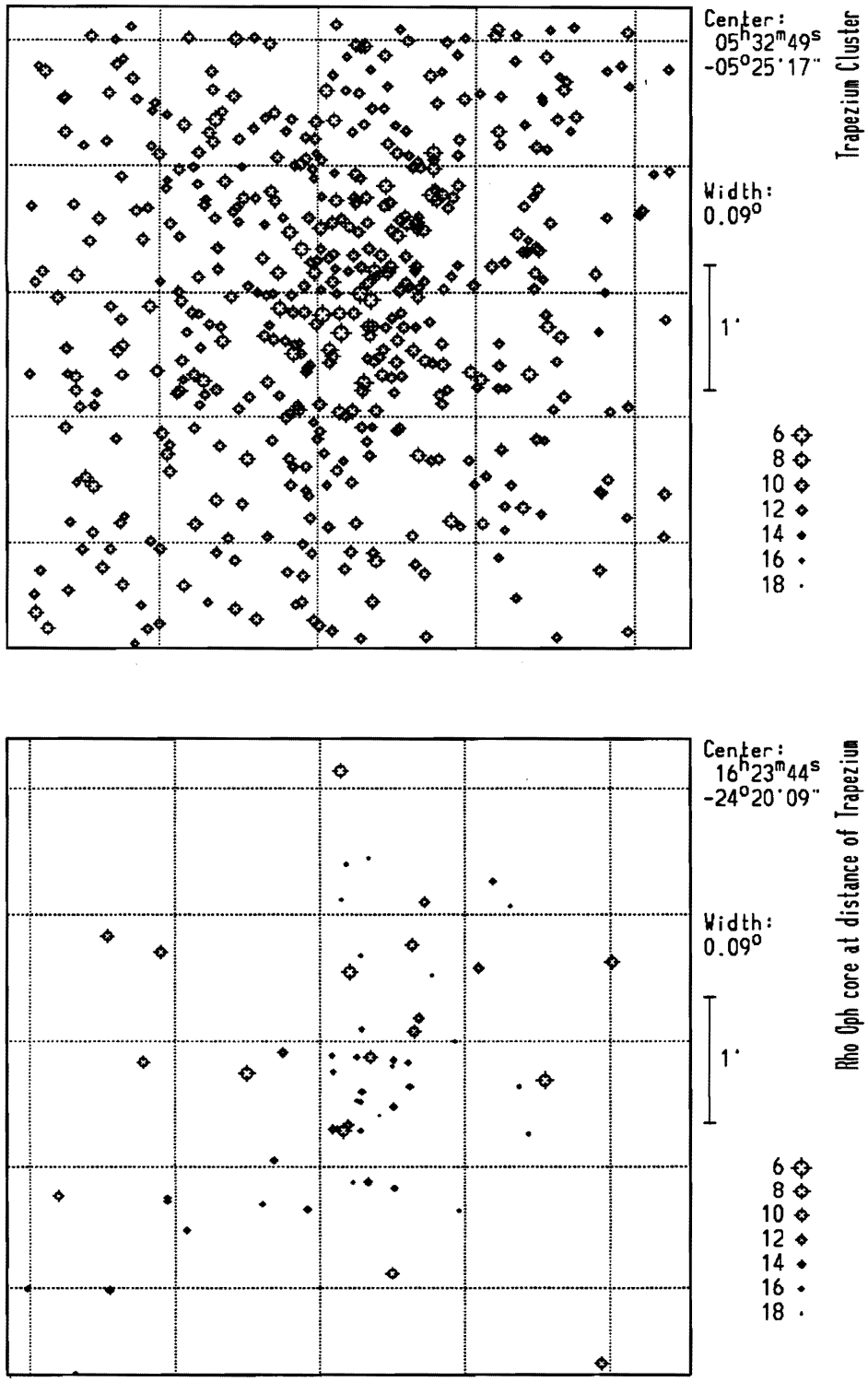


Figure 10*a,b* A comparison between the stellar density of the Trapezium Cluster and that of the embedded ρ Oph cluster. For this purpose the spatial separations and 2.2 μm luminosities of the ρ Oph cluster stars have been adjusted to place the cluster at an apparent distance of 450 pc, the distance of the Trapezium Cluster. It is obvious that the Trapezium Cluster is denser and that its members have a greater mean 2.2 μm luminosity. Trapezium Cluster data from McCaughrean *et al.* (1992); ρ Oph data from Wilking *et al.* (1989) and T. Morgan and G. Rieke (personal communication).

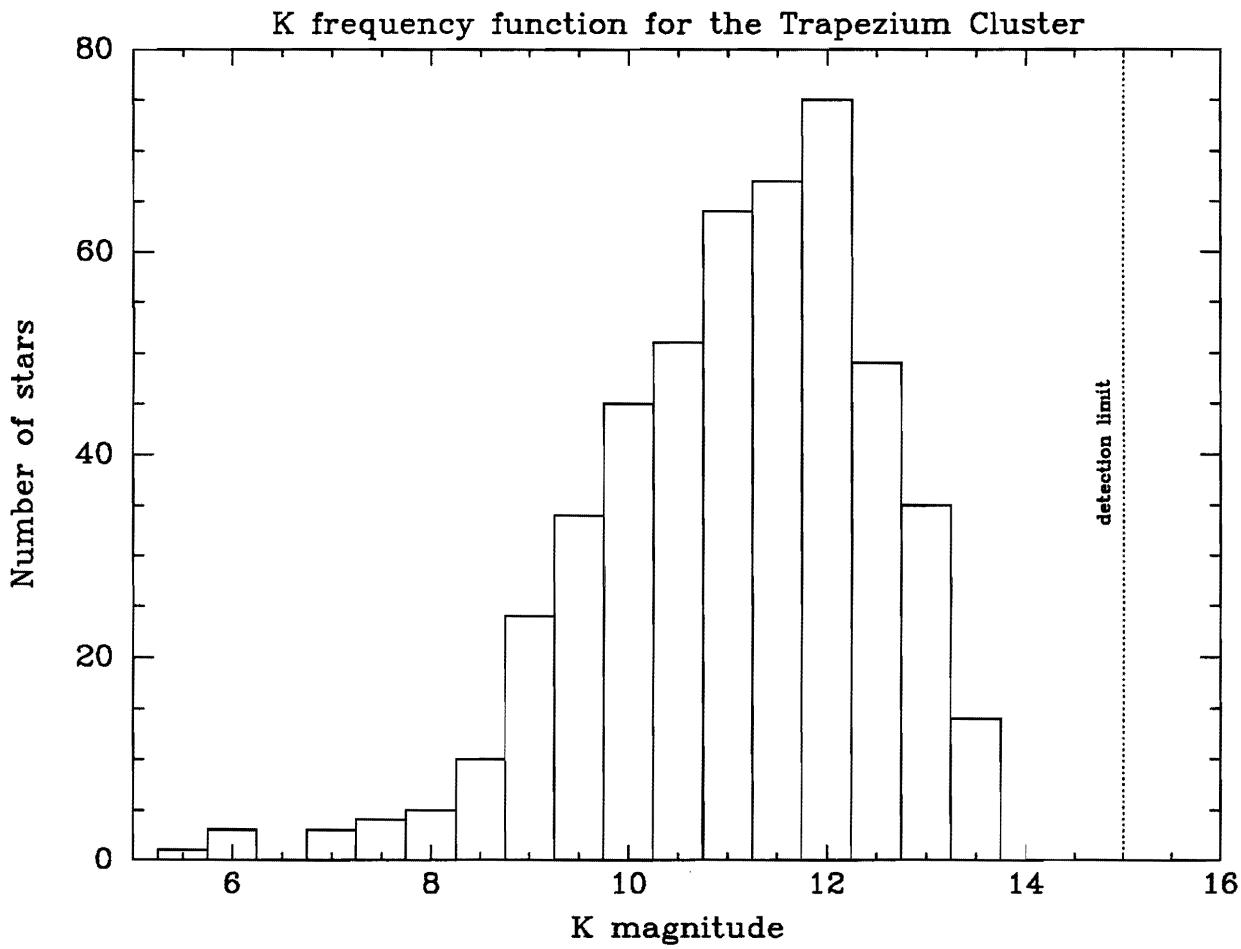


Figure 11 The raw (uncorrected for extinction) K (2.2 μm) luminosity function for ~450 stars of the Trapezium Cluster, as derived from the infrared mosaic of the inner 5×5 arcminutes of the cluster (McCaughrean *et al.* 1992). Note the very strong turnover in the luminosity function at $K \sim 12^{m}.0$, well above the completeness limit of $15^{m}.5$.

protostars probably had a core-envelope structure, with the cores competing gravitationally for material from the weakly-bound envelopes, continuing until the stellar mass spectrum was frozen due to lack of accretable material. Such a process can produce a reasonable IMF (Zinnecker 1982). An alternative scenario for the origin and evolution of a protocluster has been discussed by Myers (1991), predicting non-coeval formation of cluster stars in a continually deeper potential well due to gradual accumulation of protocluster gas (*cf.* Larson 1982).

There is an important point to be made about the Trapezium Cluster: it may be the only nearby star-forming region where we are dealing with a more or less complete and relatively uncontaminated sample. Firstly, the infrared images go deep enough to almost completely sample the entire stellar population, with a strong peak in the K frequency function at $12^{m}.0$, well above the detection limit of $15^{m}.5$ (see Fig. 11). The only substantial incompleteness in these data is due to unresolved binaries—very high resolution imaging will be needed to probe binaries with separations ~0.1 arcseconds (~45 AU, the peak in the distribution of semi-major axes for main sequence binary stars), and indeed, recent *HST* imaging has revealed binaries at these separations in the Trapezium Cluster. As the Orion Nebula is nearby, well out of the galactic plane at $b \sim -19°$, and towards the galactic anticentre at $l \sim 209°$, there is minimal foreground or background field star contamination. The only major potential for contamination comes from sources embedded in the background molecular cloud, OMC-1, and indeed, there are a relatively small number of very red sources, including the well known BN-KL complex, which are projected almost exclusively along the ridge of dense gas seen in sub-millimetre maps of the region (McCaughrean 1988; Mezger *et al.* 1990). One difficulty does arise however in determining the spatial extent of the Trapezium Cluster: recent larger near-infrared mosaics covering 15×15

arcminutes reveal a considerable number of stars over the wider area, albeit at a substantially lower density than in the cluster core. The problem is that many of the stars further from the core are probably members of the 1c sub-group, rather than the Trapezium Cluster, *i.e.*, the 1d sub-group. The question is, can any real distinction be drawn between the two? Are the Trapezium Cluster stars simply the youngest in a continuous phase of star formation that began with the 1c sub-group, or are the two sub-groups well separated in time? Either way, with one projected on the other, care must be taken in drawing conclusions regarding coevality *etc.*, as discussed below.

After applying a small extinction correction of $A_K \sim 0^m.5$ ($A_V \sim 5^m$), the peak in the Trapezium Cluster K luminosity function at $\sim 11^m.5$ corresponds to a naked PMS star of $\sim 0.3\,M_\odot$, assuming an age of 10^6 years: erroneously assuming a main sequence mass-K relation would give a much higher mass of $1\,M_\odot$. More subtly, it would also be wrong to claim that because the peak in the *luminosity* function corresponds to a $0.3\,M_\odot$ star, that there is also a peak in the *mass* function at $0.3\,M_\odot$: as we have seen in Section II.B, the problem is much more complicated than that, due to the time dependence of the mass-luminosity relation for PMS stars. In light of this, it is worth comparing the Trapezium Cluster KLF with the model KLFs shown in Fig. 2. The precise distance to the Trapezium Cluster still remains somewhat uncertain, but if we assume the widest possible range of 360–560 pc (corresponding to distance moduli of $7^m.8$ and $8^m.7$: Genzel *et al.* 1981; Anthony-Twarog 1982), we can see that the measured peak in the cluster KLF lies in the range $M_K \sim 2^m.8$–$3^m.7$. By comparing this to the position of the D-burning peak in the model KLFs, we would estimate an age of 1–2×10^6 years for the Trapezium Cluster, remarkably similar to the age determined by other methods (Herbig and Terndrup 1986). Despite the uncertainty in the distance to the Trapezium Cluster, that the observed Trapezium Cluster KLF has not been corrected for extinction, and that neither the observed or modeled KLFs account for infrared excess, this comparison nevertheless shows that the Trapezium Cluster is at least *qualitatively consistent* with a coeval, 1–2×10^6 year old cluster of stars drawn from a fully populated Miller-Scalo IMF.

A more rigorous analysis of the cluster mass function can be attempted using multi-colour infrared data. McCaughrean *et al.* (1992) have placed the stars on infrared colour-magnitude (*i.e.*, K vs $J-K$), and colour-colour (*i.e.*, $J-H$ vs $H-K$) diagrams, along with suitably transformed PMS tracks and isochrones. As discussed in Section II.B, it is almost impossible to make a unique determination of the mass of a PMS star if neither the reddening or age are known. Judging from the spread of stars along the reddening vector in the colour-colour diagram, there is a wide range of line of sight extinctions across the cluster ($A_V \sim 2^m$–20^m), and therefore the Herbig and Terndrup (1986) assumption of constant reddening is not appropriate. McCaughrean *et al.* (1992) suggest the more physically realistic assumption of a constant age. Under this assumption, all the stars would be moved parallel to the reddening vector in the colour-magnitude diagram until they intercept the chosen PMS isochrone, in this case 1–2×10^6 years. Counting the number of stars falling between any two PMS mass tracks, an approximate IMF would then be derived. As mentioned earlier, this procedure depends on there being little or no infrared excess from circumstellar disks. This question remains open for dense embedded clusters in general, although few of the 'normal' Trapezium Cluster stars (*i.e.*, those not associated with dense molecular cloud cores behind the cluster—see below) show much $H-K$ excess in the colour-colour diagram. Nevertheless, it is worth considering the effect that real excesses would have on this naïve dereddening technique. The foreground dust reddening would be overestimated, but the resulting error in the calculated mass would depend on the nature of the excess: if it was due to the reprocessing of stellar flux (a 'passive' disk), the mass would be overestimated, whereas if due to heating of the disk by accretion of infalling matter (an 'active' disk), the true stellar mass would be underestimated.

It is clear that the Trapezium Cluster warrants considerable future observational attention, as perhaps nowhere else is there a cluster near enough to us and relatively isolated from sources of contamination that we stand a fighting chance of understanding the birth, evolution, and ultimate fate of its members. In this way, it can also serve as an important prototype for other embedded clusters. With this in mind, we shall now discuss some specific questions about the Trapezium Cluster, questions which may also be applied to other young embedded clusters:

• **Are the Trapezium Cluster stars coeval?** In their study of the optically visible population, Herbig and Terndrup (1986) found little evidence for a relationship between mass and age in the cluster, with most of the stars $\leq 10^6$ years old. However, more recently, it has been suggested that the shape of the cumulative near-infrared (K) luminosity function indicates a wide spread in ages (Gatley *et al.* 1991). Based on the fact that the fainter section of their cluster LF parallels the field star LF, while the brighter part is shallower, and more like that expected for a Salpeter IMF, the claim is that the low mass stars are

older than the high mass stars. However, in making these comparisons, Gatley *et al.* (1991) used a main sequence field star LF, and a single power-law conversion from mass to K luminosity derived for massive main sequence stars. As the Trapezium Cluster is composed of mostly low mass pre-main sequence stars, these comparisons with main sequence derived LFs are inappropriate. As we saw earlier, the differential KLF for the Trapezium Cluster of McCaughrean *et al.* (1992) is consistent with model PMS luminosity functions for a completely coeval cluster. Again, while this does not imply that the Trapezium Cluster *is* coeval, any claim of non-coevality based on slope changes in the cumulative luminosity function is probably without basis.

Perhaps a more acceptable hypothesis given the lack of compelling evidence to the contrary, is that the Trapezium Cluster is more or less coeval, in the sense that the formation of the majority of its members was initiated at some 'time zero' by the same external event. This is necessarily somewhat vague. It is possible for example that most of the cluster members formed at the same time, but that when the high mass stars 'turned on', they initiated a second burst of low mass star formation via radiative implosion. Indeed, some stars seen in this region lie in molecular cloud OMC-1 behind the H II region, and *are* probably younger than average. Also, as we discussed above, care must be taken in defining the spatial extent of the Trapezium Cluster: at some radius, confusion with members of the older 1c sub-group will become a problem.

• **Why are the Trapezium OB stars at the centre?** With star formation initiated in a dense core, more stars would form towards the centre where the most material was available, with the most massive stars forming at the core by gradual mass accumulation due to clump-clump collisions in a deep potential well. This would give rise to the high degree of apparent spherical symmetry observed in the Trapezium Cluster, with a higher stellar density towards the centre, and the highest mass (OB) stars right in the middle.

Another possibility is that the OB stars arrived at the centre of the cluster by dynamical evolution. The 1D RMS velocity dispersion of the optically visible stars near the cluster centre is $\sim 2.5\,\mathrm{km\,s^{-1}}$ (Jones and Walker 1988), enough for about three crossings of the central parsec, assuming an age of 10^6 years. However, given the apparent independence of the velocity dispersions with respect to mass and distance from the cluster centre, it seems as though the mass segregation in the Trapezium Cluster is largely due to initial conditions, *i.e.,* the more massive stars *did* form in the cluster centre (Jones and Walker 1988).

At the same time, the Trapezium OB group itself is unlikely to be dynamically stable, with at least four massive components in close proximity: indeed the most massive star, θ^1Ori C, has a high proper motion and seems to be on the verge of being dynamically ejected (van Altena *et al.* 1988). Two of the other Trapezium OB stars (θ^1Ori B and θ^1Ori A) are eclipsing binaries (Lohsen 1976; Bossi *et al.* 1989; Popper and Plavec 1976), which suggests that their angular momentum vectors were closely aligned at the time of formation. One possible theory for the formation of the OB group that would result in such an alignment involves the fragmentation of a rotating ring (*e.g.,* Bodenheimer 1978; Lucy 1981). However, also see Larson (1990) for alternate possibilities.

• **Is there evidence for sub-structure?** In addition to the 'normal' members of the Trapezium Cluster, there are a number (~10% of the cluster) of very red sources seen almost exclusively to the west of the OB stars, projected against a ridge of dense sub-mm peaks (Mezger *et al.* 1990; McCaughrean *et al.* 1992). These sources include the BN-KL complex and those associated with a secondary highly collimated molecular outflow, OMC-1S (McCaughrean 1988; Schmid-Burgk *et al.* 1990). How are these related to the Trapezium Cluster? Are they spatially distinct star formation sites, or should they all be considered together? The BN-KL and OMC-1S sources are embedded in the molecular cloud OMC-1 behind the H II region M42, and are probably younger than the 'normal' Trapezium Cluster stars which are mainly in the H II region in front of the cloud (Herbig and Terndrup 1986). However, it is possible that they will merge at some point, implying that some 10^6 years from now there will be an age spread on the order of several $\times\, 10^6$ years in the Trapezium Cluster. Thus in principle, features in cluster luminosity functions may be due to age spreads of of the same order as the cluster age, making interpretation of the luminosity function complicated since it would depend not only on the IMF, but also on the history of star formation in the cluster. However, in the case of the Trapezium Cluster at least, the younger ridge sources constitute only ~10% of the total cluster population, and their effect on the current cluster luminosity function and any derived IMF is probably minimal.

• **Is the low mass IMF of the Trapezium Cluster different from that in regions like Taurus-Auriga?** Historically, the nebulosity of the Orion Nebula and other H II regions has created a bias against

the detection of low mass stars located near the massive stars which cause the nebular emission. Now that near-infrared imaging is revealing the cospatial low mass clusters, the notion that the Orion 1d sub-group (*i.e.*, the Trapezium OB stars) has fewer associated low mass stars and therefore a different IMF for low mass stars when compared regions like Taurus-Auriga (*cf.* Larson 1982), becomes difficult to maintain. A more plausible suggestion is that the low mass end of the IMF is the same for the two and that it is the high mass end that is different, *i.e.*, there are fewer massive stars in the Taurus-Auriga complex.

• **Do the Trapezium Cluster stars have circumstellar disks?** In low density star-forming regions, young stars are often seen to exhibit infrared and millimetre excesses attributed to dust in circumstellar disks. However, given the very high stellar density in the Trapezium Cluster, disk-disk interactions are very likely, and it is conceivable that the disks are stripped completely at an early stage, or perhaps that outer disks are removed, while inner disks survive. These ideas can be tested in the Trapezium Cluster by combining 3–5 μm imaging with the existing 2.2 μm data, to see if cluster members show a significant near-infrared excesses due to hot dust close to the sources. Also, 10 μm and millimetre continuum studies are needed to search for the progressively colder outer parts of disks. An unsuccessful attempt to detect 1.3 mm dust continuum from some cluster members was made by Chini, McCaughrean, and Zinnecker (unpublished data), using *IRAM* with an 11 arcsecond beam. The main problem with this single beam experiment was confusion with extended and structured emission from the background molecular cloud: what is needed is an interferometric study to resolve out the background emission.

• **Could the Sun have formed in a region like the Trapezium Cluster?** Related to the question of disks is the question of the formation of planets from such disks, and in particular, whether or not the Sun and its planetary system could have formed in an environment like the Trapezium Cluster. After all, even *bound* galactic clusters dissolve on a timescale of $\sim 10^8$ years due to the tidal effects of passing molecular clouds, and thus the fact that the Sun is not *currently* in a cluster does not tell us whether or not it once was. The appeal of the Sun forming in an OB cluster is that supernova pollution of the protoplanetary disk is a natural consequence of the cluster environment (Reeves 1978). Also, the misalignment between the rotation axis of the Sun and the ecliptic might be explained by gravitational perturbations by other cluster members (Mottmann 1977; Herbig 1982; Tremaine 1991). At the very least, it is important not to assume *a priori* that the Sun was born in a low density region like Taurus-Auriga, since the great majority of low mass stars appear to be born in clusters, in close proximity to other stars and not in relative isolation.

• **What is the fate of the Trapezium Cluster?** Will the Trapezium Cluster remain bound? Based on the cluster velocity dispersion and the mass of the cluster in stars as determined by Herbig and Terndrup (1986), Jones and Walker (1988) concluded that the cluster mass is an order of magnitude less than the mass required to be in virial equilibrium or bound. Although many more stars have been revealed in the near-infrared, they are mainly low mass stars, and the total cluster mass is probably still too small to keep the cluster bound if the same velocity dispersion applies to those stars. However, combining stars with the ionised and molecular gas, the virial criterion may be satisfied (Genzel and Stutzki 1989). The amount of gas ionised by the OB stars and lost due to over-pressure in the H II region is between 10–100 $M_\odot$ (F. Yusef-Zadeh, personal communication), less than the cluster mass and therefore not enough to unbind the cluster. Observations of fine structure lines in the far-infrared might help to determine more accurately the amount of ionised gas in and around the Trapezium Cluster.

Clearly, any mass loss loosens the cluster, and it is likely that it has expanded already and will continue to do so. However, if the mass loss is slow enough, a cluster can revirialise with a lower velocity dispersion and remain bound (C. Lada *et al.* 1984; Verschueren and David 1989). Therefore, whether or not the Trapezium Cluster will become an unbound OB association with attendant low mass stars is unknown. It is tempting to speculate that there may still be clumps of dense gas between the cluster stars, not yet evaporated by the ionising radiation, and perhaps helping to bind the cluster temporarily. Such clumps would be subject to considerable ablation and even radiative implosion, perhaps leading to another generation of low mass star formation in the Trapezium Cluster, triggered by the radiation of the OB stars. In this context, it is worth recalling the partially ionised globules seen close to the OB stars (Garay *et al.* 1987; Churchwell *et al.* 1987) and the warm ($\sim$300 K) dust arcs and shells seen in the same region, although the latter are notably *not* coincident with the former (McCaughrean and Gezari 1991). Also there are the small ($\sim$ few $M_\odot$) ammonia cores seen in the BN-KL complex (Migenes *et al.* 1989).

The OMC-2 cluster

Some 12 arcminutes north of the Trapezium cluster there is a cluster of compact near-infrared sources associated with a part of the L 1641 molecular cloud known as OMC-2 (Gatley *et al.* 1974). Recently, Pendleton *et al.* (1986), Rayner *et al.* (1989), and Johnson *et al.* (1990) have studied this cluster using high resolution infrared mapping, imaging, and polarimetry. Associated with a peak in molecular gas and dust emission and completely obscured in the visible, it is a small cluster with only a dozen sources to $K{\sim}17^m$ within a 0.3 pc diameter field. Three of the sources (IRS 1, 2, 4) are deeply embedded ($A_V{\sim}30^m$–40^m), and are probably intermediate mass YSOs, *i.e.*, Herbig Ae/Be stars. Two sources illuminate bipolar reflection nebulae, implying that circumstellar disks may be present. Direct mapping of the sub-millimetre dust continuum emission could prove the presence of such disks; this group of very young stars might be ideal to study the effects of disk-disk interactions, if they have occurred. Most of the remaining sources are low mass stars with relatively little extinction, possibly members of the wider Orion cluster (1c sub-group) rather than directly associated with the OMC-2 core. At present it is not known whether a more extended cluster of low luminosity PMS objects has formed in the same core as the bright embedded sources.

NGC 2024, NGC 2023, NGC 2071, and NGC 2068

The embedded clusters associated with the star-forming regions NGC 2024, NGC 2023, NGC 2071, and NGC 2068 in the L 1630 molecular cloud are discussed in detail by E. Lada *et al.* elsewhere in this volume. We give a brief description here to examine to what degree they may be viewed as analogues to the Trapezium and OMC-2 clusters in the nearby L 1641 cloud.

It was known from infrared raster scan maps that the ionising star of the H II region NGC 2024 is associated with a embedded cluster of young, lower mass stars (Barnes *et al.* 1989). But again only with infrared cameras was the true extent revealed, with about 300 members brighter than $K{\sim}14^m$ within a radius of 1 pc (Fowler *et al.* 1987; E. Lada *et al.* 1991*b*). Like the Trapezium Cluster, the spatial distribution of the young stars is centrally condensed, with the more luminous objects located toward the cluster centre. Similarly, the near-infrared luminosity function rises to about $K{\sim}12^m$–13^m before falling again. E. Lada *et al.* (1991*b*) noted that up to the turnover at least, the cumulative KLF for NGC 2024 is steeper than the Salpeter IMF.

Some 25 arcminutes south is the reflection nebula NGC 2023. Sellgren (1983) surveyed the associated cloud to $K{\sim}12^m$, finding a small cluster of 16 infrared sources within a $\sim$0.5×0.5 pc area, somewhat similar to OMC-2. The brightest source in NGC 2023 is an unreddened B1.5 V main sequence star that illuminates the nebula, but interestingly is not at the centre of the cluster. Surprisingly, a deeper imaging survey to $K{\sim}15^m$ by De Poy *et al.* (1990) found no additional cluster members; the flattening of their cumulative near-infrared luminosity function near $K{\sim}12^m$ was interpreted as either a dearth of low mass stars or as preferential obscuration of the lowest luminosity sources.

Finally, some 2.5° to the north-east of NGC 2024, there are two other embedded clusters associated with NGC 2068 ($\sim$200 members) and NGC 2071 ($\sim$100 members). Further details can be found elsewhere (Sellgren 1983; E. Lada *et al.* 1991*b*; C. Lada and E. Lada 1991), but relevant to the discussion here, it is worth noting that the KLF for NGC 2071 also shows evidence for a turnover at $K{\sim}12^m$ (E. Lada *et al.* 1991*b*).

The K luminosity functions of the L 1630 clusters were interpreted on the basis of a time-independent main sequence mass-luminosity relation, instead of accounting for PMS luminosity evolution. In fact, the cumulative KLFs for all the L 1630 clusters are similar in shape to that of the Trapezium Cluster, and as we have seen earlier, the latter is at least qualitatively consistent with a $\sim10^6$ year old coeval PMS population with a monotonically rising Miller-Scalo IMF. On this basis, there is probably no real justification for claiming a lack of low mass stars in any of these regions. Even so, the alternative hypothesis of preferential obscuration of the lowest mass stars can be tested by 10 μm imaging, as suggested by De Poy *et al.* (1990) in the case of NGC 2023.

The underlying stellar populations in L 1641 and L 1630

It is clear that there is vigorous high and low mass star formation in the form of embedded clusters in both L 1641 and L 1630. These clusters occupy only a small fraction of the total mass and volume of the clouds, suggesting that star formation is very localised. However, both L 1641 (Bally *et al.* 1987; Bally *et al.* in preparation; see chapter by Blitz) and L 1630 (E. Lada 1990; E. Lada *et al.* 1991*a*) are clumpy and filamentary like the Taurus-Auriga dark clouds, where isolated star formation is seen throughout the region. Therefore, it is necessary to examine the Orion clouds for evidence of any 'pedestal population' in order to

assess the relative importance of the cluster and isolated modes of star formation. A wider discussion of the clouds and their stellar content is given in the chapter by E. Lada *et al.*

Nakajima *et al.* (1986) surveyed some 1.4 square degrees of the L 1641 cloud in the near-infrared to a limiting magnitude of $K \sim 9^m.5$. Of the ~100 sources found, 15 sources were classified as PMS stars based on their near-infrared colour excesses, 6 of them newly identified. To the limits probed by Nakajima *et al.* (1986), the near-infrared luminosity function of L 1641 appears similar to that of L 1630 and the Trapezium Cluster.

K. Strom *et al.* (1989*c*) examined the properties of 123 *IRAS* sources over a ~9.5 square degree area in the field of L 1641, finding 93 of them to be young stars associated with the molecular cloud. Based on their SEDs, roughly 60% of the whole (123 objects) sample were classified as Class I sources, most of them without optical or near-infrared counterparts; the majority of the remainder are Class II sources with optical/near-infrared counterparts, and spectra typical of T Tauri stars and young emission line stars; the rest are Class III sources, all but one of which lie either in front of or behind L 1641. When compared to Taurus-Auriga, L 1641 is found to have a much larger fraction of luminous Class I sources: ~76% of the 93 *IRAS* sources associated with L 1641 have Class I SEDs, compared to ~25% of the sources in Taurus-Auriga. This difference is attributed to the fact that typical molecular cloud cores in L 1641 have higher optical depths than those in Taurus-Auriga, which leads to greater extinction and reprocessing of optical and near-infrared light out to far-infrared wavelengths. Also, as Orion is further away than Taurus-Auriga, we must beware of selection effects: the completeness limit for the L 1641 *IRAS* sources is $\sim 6\,L_\odot$ (K. Strom *et al.* 1989*c*), compared to $\sim 0.5\,L_\odot$ for Taurus-Auriga (Kenyon *et al.* 1990).

Thirty objects in the sample of K. Strom *et al.* (1989*c*) were detected by *IRAS* only, having no optical or near-infrared (5σ limit $K \sim 12^m.8$) counterparts. Nine of these *IRAS*-only sources were studied further through deeper near-infrared imaging (to $K \sim 16^m$) by K. Strom *et al.* (1989*a*). Most were found to be detected at $K \sim 15^m$, with all but one as single, isolated sources. This perhaps indicates that only a small number (~1) of stars form per core, with the caveat that these sources were only just detected in this survey, and that there may be small clusters of lower luminosity objects around each *IRAS* source. The obvious exception is *IRAS* 05338−0624, where K. Strom *et al.* (1989*b*) found a cluster of ~20 sources within a diameter of 0.16 pc. This is a remarkably dense clustering, although it is probably not fair to interpret all 20 sources as stars, as not all appear point-like (K. Strom *et al.* 1989*b*; K.-W. Hodapp, personal communication).

A study of the young stellar population of L 1641 was also made in X-rays using *EINSTEIN* IPC images (K. Strom *et al.* 1990). These images were centred near V 380 Ori (NGC 1999) and cover an area approximately half that of the *IRAS* study. Some 65 X-ray sources were found, 61 with stellar counterparts: HH 1 and HH 2 are two of the non-stellar X-ray sources. Five of the X-ray sources appear to coincide with optically identified *IRAS* sources: however, most of the *IRAS* sources suffer too much extinction to be seen in X-rays. Roughly two thirds of the X-ray sources show no optical Hα emission, indicating once again that X-ray surveys can uncover substantial numbers of PMS stars, apparently somewhat older than classical T Tauris. Conversely, of the 25 Hα stars found in the objective prism survey of Parsamian and Chavira (1982), 15 are not detected in X-rays. Thus the ratio of the number of *all* PMS stars (*i.e.,* X-ray stars plus Hα stars *not* detected in X-rays) to Hα stars in L 1641 is roughly 2. Although this number is somewhat dependent on limiting magnitude and completeness, it is nevertheless in marked contrast to the predicted ratio of ~10, based on an extrapolation of Taurus-Auriga sources (Walter *et al.* 1988; K. Strom *et al.* 1990, Appendix A).

Therefore there *is* a pedestal population of YSOs in L 1641, although the cluster mode of star formation appears to dominate in this region. A rough comparison of the number of sources in the known clusters (Trapezium Cluster, OMC-2, *IRAS* 05338−0624) to the total number of sources in the cloud (*i.e.,* the cluster sources plus the isolated *IRAS*, X-ray, near-infrared, and Hα sources), shows that about 80% of the stars in L 1641 are in clusters. However, most of the surveys of the pedestal population are likely to be quite incomplete, making this ratio an upper estimate: the X-ray and Hα surveys suffer from extinction, and the *IRAS* survey is complete only to $\sim 6\,L_\odot$ (K. Strom *et al.* 1989*c*). A more comprehensive near-infrared imaging survey is required to make a better assessment of the L 1641 pedestal population.

Such a survey *has* been made for the L 1630 cloud (E. Lada 1990; E. Lada *et al.* 1991*b*). From a survey of the cloud for dense CS 2–1 gas (E. Lada 1991*a*), regions with and without dense gas totalling ~0.7 square degrees were then surveyed to $K \sim 13^m$. Some 900 sources were detected, of which almost 60% are associated with the previously discussed clusters (NGC 2024, NGC 2023, NGC 2068, NGC 2071). Indeed, after correcting for background and foreground field star contamination of their survey, E. Lada *et al.* (1991*b*)

estimated that the cluster members make up as much as ~96% of the total number of stars actually associated with L 1630. This indicates an overwhelming predominance of the cluster mode of star formation in L 1630, although considerably more work is needed to distinguish genuine cloud members from field stars between the clusters, and even deeper surveys may be needed to probe fully the pedestal population.

The dominance of the cluster mode in L 1630 may be at least in part due to the effects of external triggering. The L 1630 clusters tend to lie on the western edge of the cloud, close to the young Ori 1a and 1b sub-groups. Also, there is a strikingly high concentration of Hα stars on the western edge of the L 1630 molecular ridge (Wiramihardja *et al.* 1989), and nearby, in the bright rimmed globule Ori-I-2, the YSO *IRAS* 05335−0146 may have been triggered by an O star (Sugitani *et al.* 1989). Thus triggering by the Ori 1a,b stars may have played an important part in the formation of the L 1630 clusters. When discussing this sort of triggering effect however, it is unclear whether the 'pressure' of the OB association actually produces protocluster condensations, or just pushes on pre-existing condensations: it may be both. Indeed, some form of a two step process does appear to be in operation in L 1630. While four of the five most massive (>200 $M_\odot$) cores in L 1630 are host to the four dense stellar clusters, the fifth core (LBS 23) does not appear to be forming stars at present (E. Lada 1990; E. Lada *et al.* 1991*a,b*).

In summary, the current star formation in both L 1630 and L 1641 appears to be dominated by the cluster mode, although more work is needed to obtain a more accurate census of the pedestal populations. One point to bear in mind when determining the relative importance of the cluster and isolated modes in a GMC, is that a part of a molecular cloud currently forming only a very low space density of stars may also become the site of a dense cluster in the future, perhaps due to material being piled up and/or triggered by massive stars of an earlier generation.

The λ Orionis region

The λ Orionis region of star formation lies some 15° north of the Orion Nebula (see, *e.g.*, Shevchenko 1979 for a POSS mosaic). The OB association consists of an O 8 III star (λ Ori itself) and 12 B stars at the centre of a large spherical H II region, at the edge of which lies an H I shell coincident with a ring of dark molecular clouds, the latter seen to glow spectacularly in *IRAS* 100 μm images (Maddalena and Morris 1987). The whole complex has a diameter of ~10°, ~70 pc at a distance of 400 pc. Some 83 Hα emission objects, *i.e.*, low mass PMS stars, have been found in the region. Most are concentrated on the bright-rimmed inside edges of the dark clouds B 30 and B 35, *i.e.*, on the side of the clouds facing the OB association, with most of the remainder scattered in a more or less linear fashion between the two clouds (Duerr *et al.* 1982). Duerr *et al.* (1982) noted that the amount of material in the H I shell (~10^5 $M_\odot$) is comparable to the amount of molecular gas found in a GMC. Thus they proposed that the region around λ Ori is essentially a well-preserved 'fossil' GMC, recently exposed by the action of the star. They find a star formation efficiency in the region of only 0.2–0.3%.

Mathieu and Latham (unpublished data, as described by Mathieu 1986) have made a radial velocity study of about 30 of the Hα stars in the λ Ori region, and found that the 1D stellar velocity dispersion is small, ~2 km s^{-1}, similar to the dispersions found for stars in other GMCs (*e.g.*, the Ori OB1c sub-group: van Altena *et al.* 1988; Jones and Walker 1988). Locally, near B 30 and B 35, the stellar velocity dispersions are lower, at about 1 km s^{-1}, similar to the CO line widths in the clouds themselves (Maddalena *et al.* 1986; Maddalena and Morris 1987), and therefore these stars are probably bound to these clouds, much as the stars were bound to the original GMC. However, most of the original molecular material in the region has been swept into an expanding shell (Maddalena and Morris 1987), and the escape velocity for the global system is much lower than the current stellar velocities: with the removal of the gas, the stellar system has become unbound and will ultimately disperse.

2. Other galactic H II regions

The bulk of the Galaxy's giant molecular clouds and massive star-forming regions lie at distances greater than that of the Orion complex. Nevertheless, even low mass stars can now be detected in many of these regions, and in the past few years, many dense embedded clusters have been revealed. Some of these are summarised here, roughly in order of increasing heliocentric distance.

S 106 (600 pc)

In studies of S 106, the focus has been an embedded O9–B0 V star (IRS 4) and the biconical H II region which it excites (see, *e.g.*, Staude *et al.* 1982; Bally *et al.* 1983; Hayashi *et al.* 1990). In particular, there is some controversy over whether or not a dense molecular disk or ring structure exists around IRS 4,

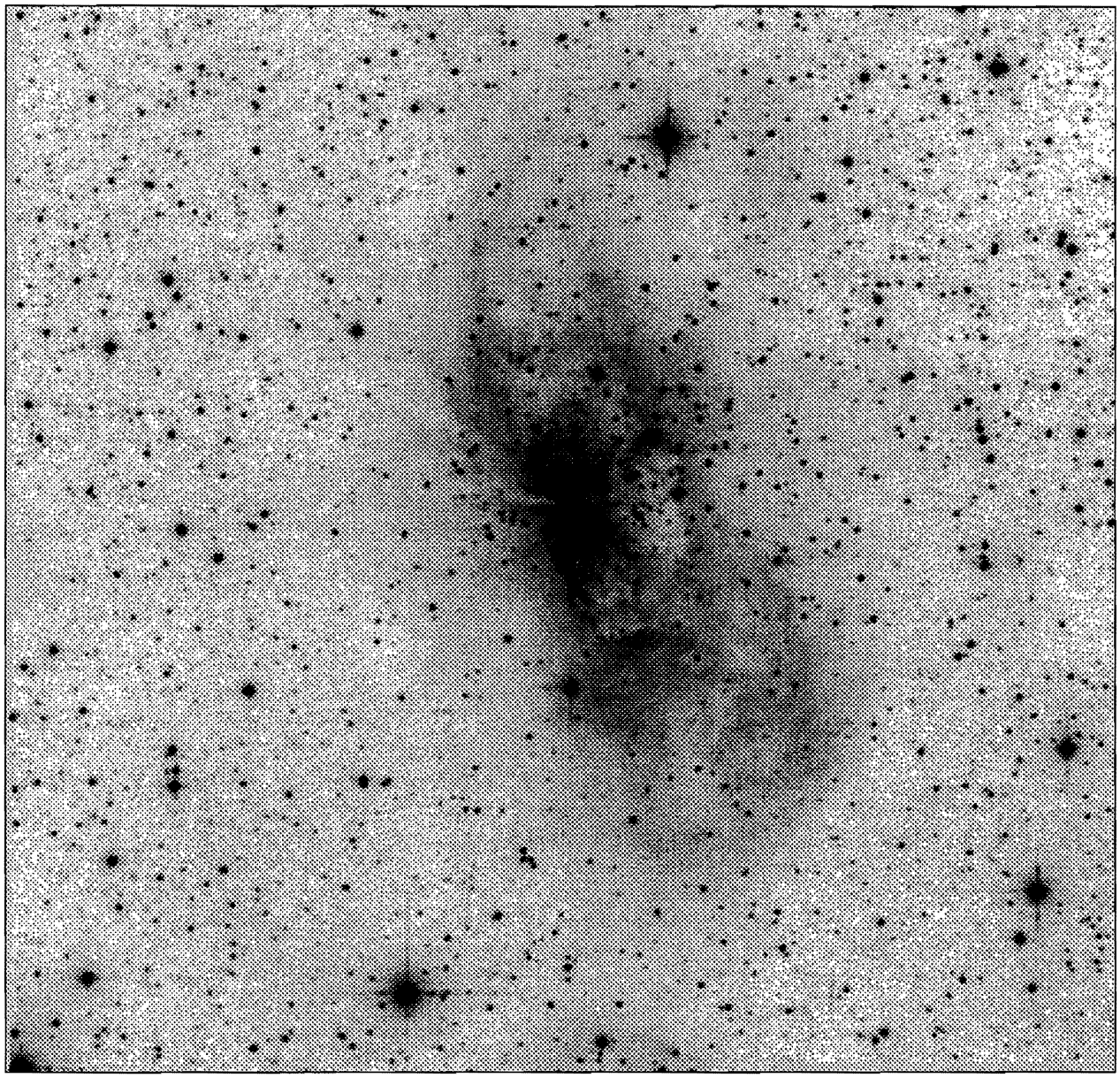


Figure 12 A K (2.2 μm) mosaic of the H II region S 106, covering ~10×10 arcminutes (~1.75×1.75 pc at 600 pc). The data were obtained using a 256×256 pixel HgCdTe infrared array at the University of Hawaii 2.2 m (Rayner 1992). Some 200 stars are probable PMS members of a cluster centred near S 106 IRS 4.

constraining the ionisation to form the biconical nebula (Mezger *et al.* 1988; Barsony *et al.* 1989*a*; Loushin *et al.* 1990). Figure 12 shows a recent 2.2 μm image, revealing both a large number of embedded point sources, and highly structured loops and arcs in the nebula (Rayner 1992). Analysis of an earlier 2.2 μm image has shown that IRS 4 is near the centre of a cluster of over 200 point sources, with about 90% of them within a radius of 1.5 arcminutes of the OB star (Rayner *et al.* 1991*a*; Hodapp and Rayner 1991). With a completeness limit of $K \sim 14^{m}.0$, the faintest objects detected by Hodapp and Rayner (1991) are probably low mass PMS stars between 0.2–0.5 $M_{\odot}$, based on a distance of 600 pc, a derived average extinction of $A_V \sim 13^{m}.5$, and an assumed cluster age of 10^6 years. A direct age estimate was made by Hodapp and Rayner (1991), who find that only 4 out of 80 cluster members with masses above 1 $M_{\odot}$ show evidence for local nebulosity and high intrinsic polarisation, and therefore ongoing mass loss. This, combined with an typical duration of 5×10^4 years for the mass outflow phase in YSOs (Fukui 1990), suggests to them that star

formation has been going on in S 106 for 1–2×10^6 years, *i.e.*, they infer an age spread of this order, if the star formation rate has been constant. The latter is an implicit assumption: there is no obvious evidence to counter the possibility that most of the cluster formed in a single short burst, and that there is some secondary star formation occurring now, perhaps including IRS 4 itself.

The K luminosity function does not exhibit any hint of a turnover down to the completeness limit of $14^m.0$. In contrast, if the Trapezium Cluster were moved to a distance of 600 pc and an extra $A_K \sim 1^m.0$ of extinction added, its luminosity function turnover would still be detectable to that limit. Therefore at first sight, it seems as though the two clusters may be different. On one hand, if the S 106 cluster is *older* than the Trapezium Cluster, then any peak in the luminosity function due to deuterium burning (Section II.B) would have moved to lower masses and be undetected at the current completeness limit. On the other hand however, the angular spacing between the S 106 stars seems smaller than that for the Trapezium Cluster stars, which could indicate an even higher stellar density and perhaps a *younger* age for the S 106 cluster. Perhaps a simpler explanation that would fully reconcile these contradictory pieces of evidence is that S 106 is further away than the nominal 600 pc, and indeed uncertainty in the spectral classification of IRS 4 and the number of stars foreground to the nebula imply that it could be as far away as 2 kpc (Th. Neckel, personal communcation; Rayner 1992).

NGC 2264 (900 pc)

The young ($\sim 10^7$ yrs) open cluster NGC 2264 lies at a distance of 900 pc, in the Mon OB1 association between the O star S Mon and the famous Cone Nebula. From their optical colour-magnitude diagram, Adams *et al.* (1983) found that the cluster, contrary to previous claims, does have low mass stars, and also that there is an age spread in its members of $\sim 10^7$ years. Stahler's (1985) analysis confirmed this age spread, but did not confirm the sequential build up in mass space nor the exponential increase in star formation rate in the cluster claimed by Adams *et al.* (1983). In addition, selection effects prevent us from trusting that the optical surveys have revealed the complete stellar population. *IRAS* data on the embedded cluster have been analysed by Margulis *et al.* (1989), who identified 18 Class I and 8 Class II sources, with the caveat that two thirds of these sources are probably associated with two or more YSOs. All seven of the far-infrared sources with $>100\,L_\odot$ were found to be Class I objects. Near-infrared imaging is required to reveal the embedded population in this region, since part of the 'optical' cluster is obscured by a molecular cloud (Crutcher *et al.* 1978), and may in fact be cut in two by it (Mathieu 1986).

NGC 6334 (1.7 kpc)

Figure 13 shows a far-infrared map of the NGC 6334 molecular cloud in which several separate condensations are discerned, with a projected spacing of around 10 pc at a distance of 1.7 kpc. This region has recently been studied in detail by Straw and Hyland (1989) and Straw *et al.* (1989). Straw *et al.* (1989) made a near-infrared raster scan survey of the embedded populations in 11 regions of NGC 6334 that show indications of on-going star formation, and found several hundred sources to a completeness limit of $K \sim 14^m$, corresponding to a main sequence stellar mass of $\sim 1\,M_\odot$ if unobscured, or $\sim 4\,M_\odot$ if embedded in the molecular cloud cores typically with $A_V \sim 30^m$–40^m. In several of the regions, a large fraction of the sources were seen to have $H-K$ excesses, indicating PMS objects. In order to determine masses, the majority of the sources were plotted in an infrared colour-magnitude diagram ($J-K$ vs. K), and then projected back along a standard reddening vector until they intercepted the main sequence. A main sequence absolute M_K magnitude versus mass relation (similar to that shown in Fig. 3) was then used to determine the individual masses, and thence the IMF. Sources showing some evidence (*e.g.*, spectroscopic) for being PMS objects were dereddened back to suitably transformed PMS tracks, although as noted elsewhere in this chapter, masses derived by this procedure depend strongly on the chosen isochrone. The general conclusion from the work of Straw *et al.* (1989) is that the stellar mass distribution in the NGC 6334 complex is similar to that found in other young visible clusters and embedded clusters, *i.e.*, roughly equal to the Salpeter IMF.

There are a number of problems with the general approach of Straw *et al.* (1989) which illustrate some of the difficulties encountered when converting measured fluxes into masses for embedded stars. Firstly, many of the objects were red enough that they were only detected at K but not at J, leading to a complicated dereddening scheme in which the J magnitude was calculated via a number of ad hoc assumptions. Secondly, some of the objects may be background giants, which must be discriminated against spectroscopically and removed from the IMF determinations, although Straw *et al.* (1989) calculated that in most of their regions, contamination by background field sources was not that important. Thirdly, Straw *et al.* (1989) did not discuss the effects of infrared excess emission at all. Lastly, some of the sources assumed to be on the main

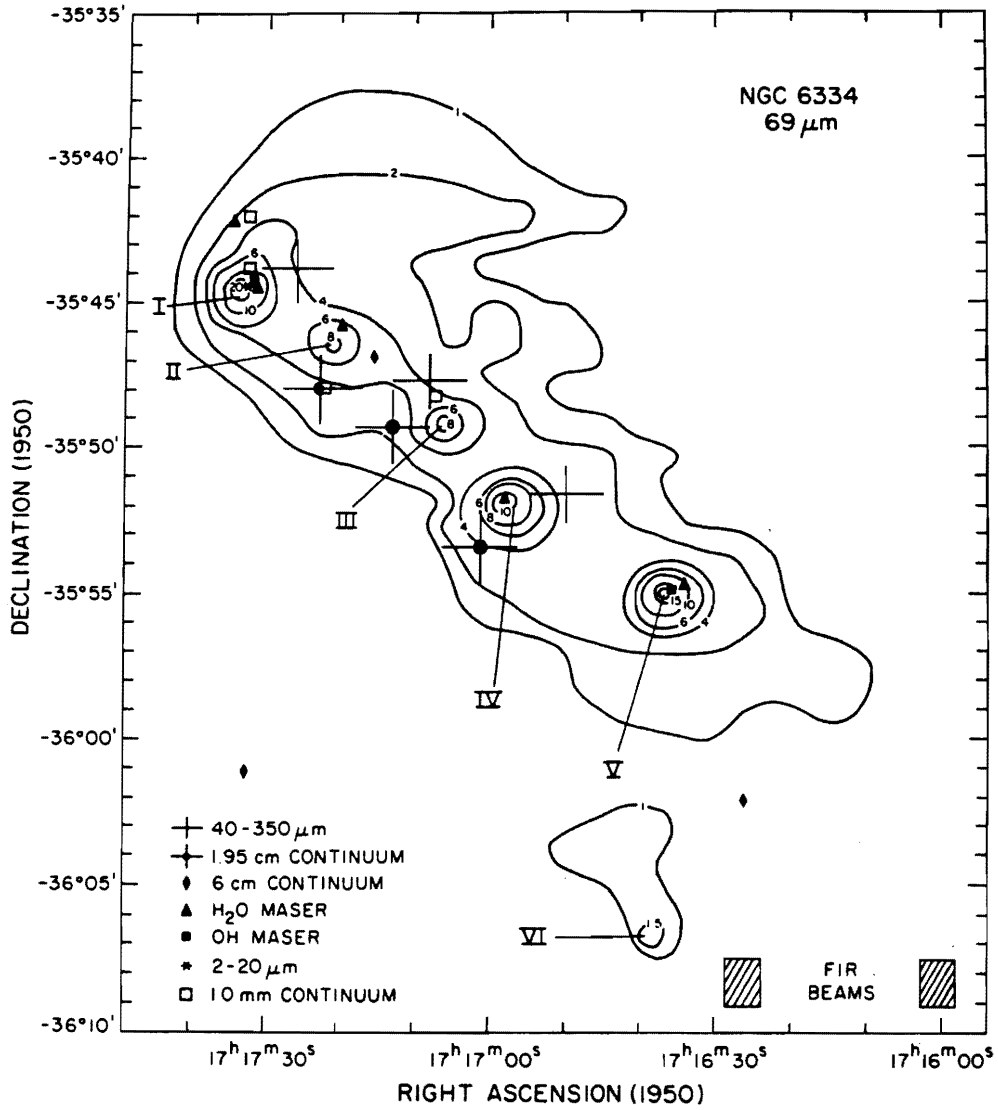


Figure 13 A *KAO* map (40–250 μm filter, effective wavelength 69 μm) of the NGC 6334 molecular cloud and star formation region, from McBreen *et al.* (1979). Note the characteristic spacing of the luminous far-infrared sources, indicated by the Roman numerals. The beam size is of order 1–2 arcminutes.

sequence may actually be young, and Straw *et al.* (1989) assessed the error that can be made by assuming the stars to be main rather than pre-main sequence: it can be huge. For example, an object at $K=11^m.0$ and $J-K=3^m.0$ in the colour-magnitude diagram could either be a 5 $M_\odot$ ZAMS object obscured by $A_V \sim 4^m$, or an unobscured young (10^5 yr) T Tauri star of mass 1 $M_\odot$ at the top of its Hayashi track. Deep optical CCD imaging in the *I*-band (*cf.* Hunter and Massey 1990) may help separate heavily extincted sources ($A_V > 15^m$) from less heavily extincted ones, which in turn will help to discriminate ZAMS from PMS stars.

M 17 (2.2 kpc)

The M 17 H II region and the adjacent molecular cloud is a well-studied site of massive star formation and has a very high ratio far-infrared luminosity to molecular gas mass (Mooney and Solomon 1988). A cluster of OB stars within an obscured portion of the H II region is responsible for most of the observed radio continuum and far-infrared emission (Beetz *et al.* 1976; Gatley *et al.* 1979; Chini *et al.* 1980). Recent near-infrared imaging at *J*, *H*, and *K* of a 9×9 arcminute area of the complex (Fig. 14) clearly defines the true size and extent of the cluster, revealing about 100 stars of spectral type B9 and earlier within a 2.8 arcminute (1.8 pc at 2.2 kpc) radius (C. Lada *et al.* 1991). In addition, these observations indicate that

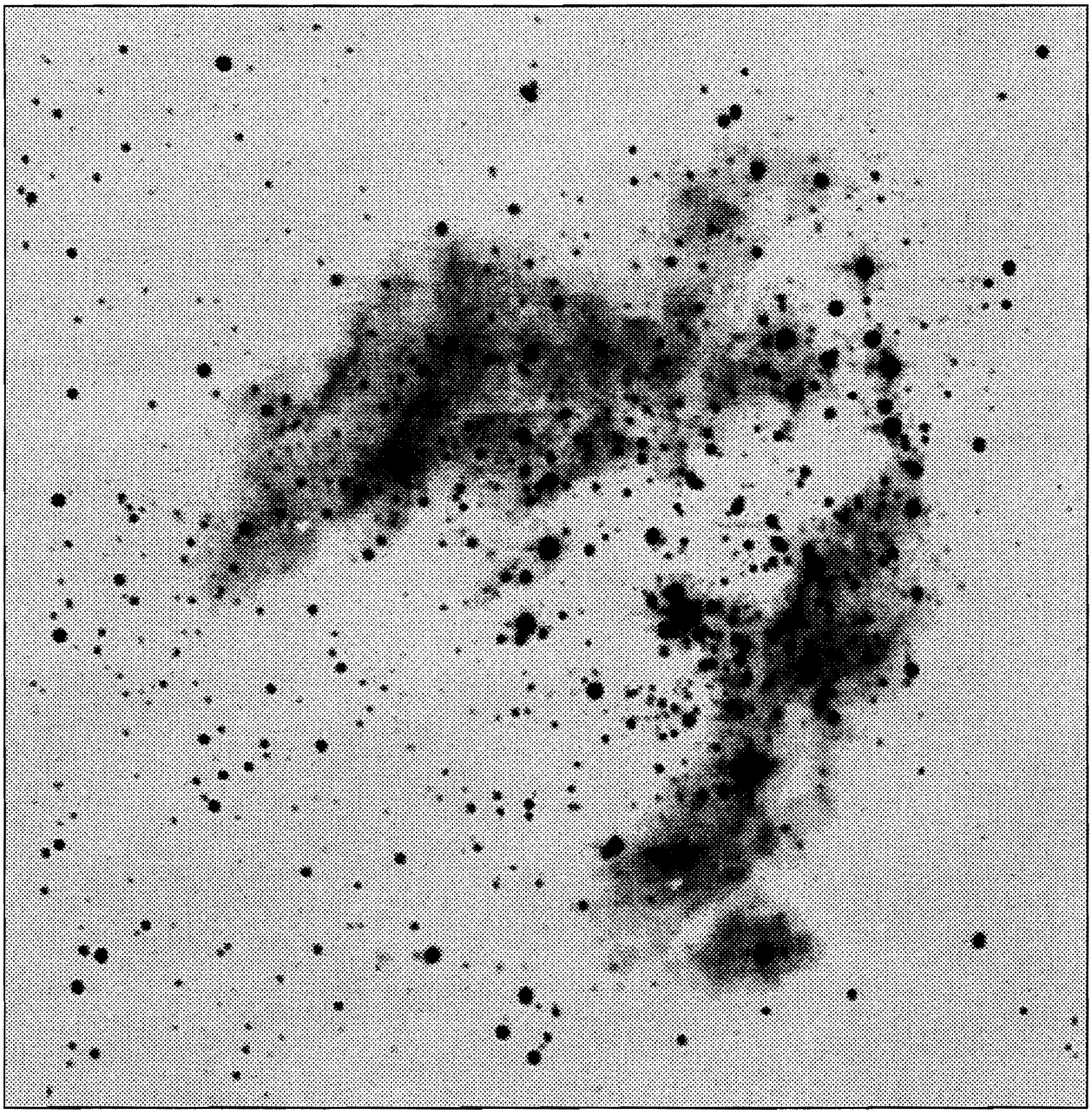


Figure 14 A near-infrared (1–2.5 μm) mosaic of M 17 covering ~9×9 arcminutes (~5.8×5.8 pc). Approximately 100 stars (B9 or earlier) towards the centre of the image have been identified as cluster members. The data were obtained using a 256×256 pixel PtSi array on the KPNO 2.1 m telescope (C. Lada *et al.* 1991).

most of the cluster members possess infrared excesses, suggesting that circumstellar disks may play a more important role in the early evolution of OB stars than previously suspected. The cumulative K luminosity function for the cluster stars, after subtraction of an unobscured background field, displays a slope which is significantly shallower than that observed for field stars, but which is consistent with that of the Salpeter IMF. Despite the fact that the cluster members are believed to be on the main sequence, C. Lada *et al.* (1991) point out that comparisons with the IMF may be complicated by the apparent ubiquity of excess emission at 2.2 μm.

Deeper infrared images should reveal the extent of the low mass population of the cluster. However, it is worth noting that for regions such as M 17, within the inner galaxy and close to the line of sight towards the Galactic Centre, confusion will be extreme due to the very high density of field stars, particularly those

behind the star-forming region which are revealed as the extinction in the molecular cloud is penetrated in the near-infrared. Separating cluster and field stars will be very difficult in such regions.

In a larger scale study, D. Elmegreen *et al.* (1988) searched for *IRAS* sources coincident with bright photographic near-infrared stars over a 25 square degree region of M 17 SW, the GMC to the south-west of M 17. Of the almost 2000 *IRAS* point sources in this region, some 360 were classified as embedded based on their positions either the 12-25-60 μm or 25-60-100 μm *IRAS* colour-colour diagrams, with 22 sources classified as embedded in both. Some of these 360 sources were identified with previously known compact H II regions, three of them beyond M 17, while many of the remainder are consistent with embedded late O to late B type stars. By blinking B and I photographs, just over 2000 bright near-infrared stars were identified in the same region, of which 20 were found to lie within 1 arcminute of an embedded *IRAS* source. D. Elmegreen *et al.* (1988) suggest that at least 60% of these coincidences are likely to be physical associations. Some 13 of these stars were seen on both the B and I plates, and assuming these sources to be at the distance of M 17, their colours and magnitudes are also consistent with embedded ($A_V \sim 7^m$) B stars. Thus these results lend support to the idea that there may be 20–50 B stars in the M 17 SW cloud (Stutzki *et al.* 1988), and therefore also suggest a large population of lower mass PMS stars.

S 255/S 257 (2.5 kpc)

S 255 and S 257 are diffuse, low excitation H II regions associated with two early B stars, part of a small complex of H II regions (S 254–S 258) in the Gem OB1 association. They have diameters of ~2.5 pc and their centroids have a projected separation of 3.8 pc, assuming a distance of 2.5 kpc to the complex. Between them is a dense molecular cloud (Evans *et al.* 1977; Mezger *et al.* 1988; Heyer *et al.* 1989) with a double, embedded near/mid-infrared source (S 255-IR) which radiates about $8 \times 10^4\ L_\odot$ in the far-infrared (Beichman *et al.* 1979).

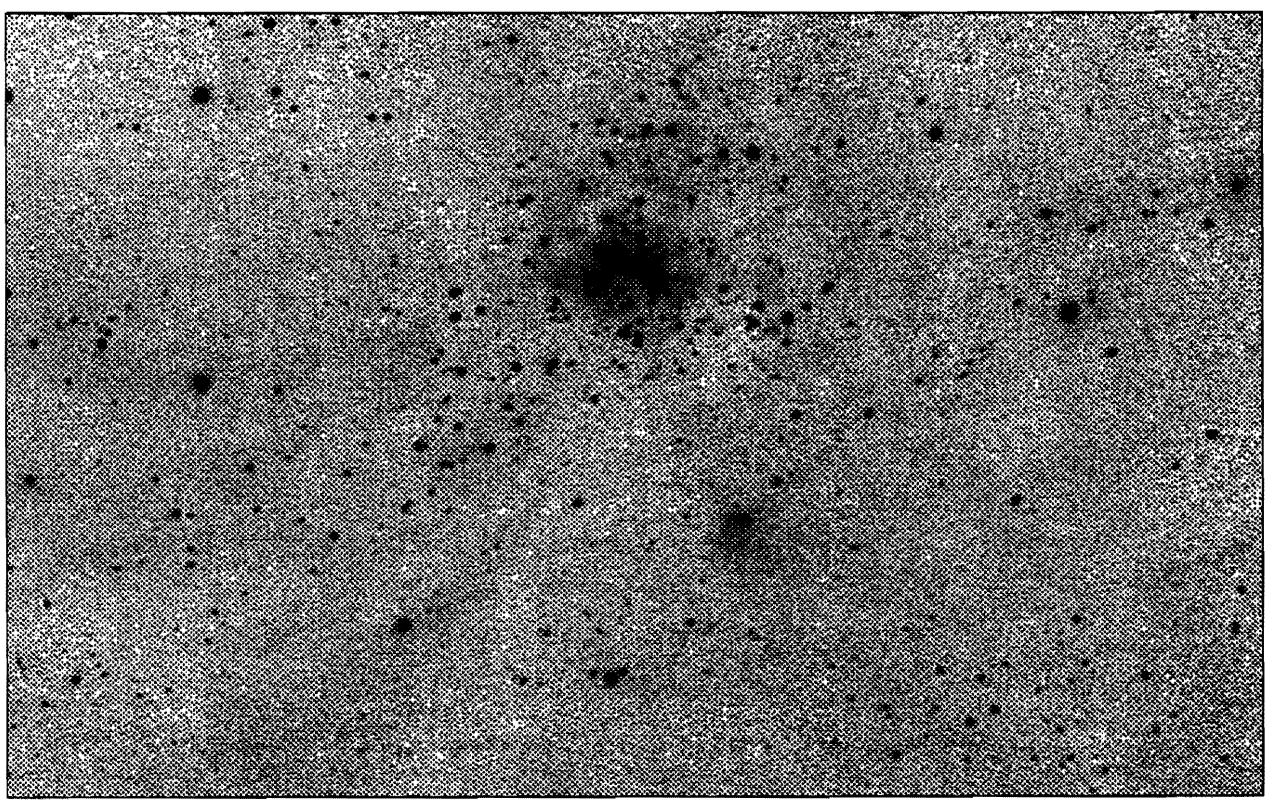


Figure 15 A K (2.2 μm) mosaic of the S 255/S 257/S 255-IR region covering 8×5.2 arcminutes (~5.8×3.8 pc at 2.5 kpc). At left centre and right centre are the two B0 stars which excite the H II regions S 255 and S 257: note that they have no cospatial clusters. Between the two H II regions the infrared cluster associated with the source S 255-IR. The data were obtained using a 128×128 HgCdTe infrared array at the Steward Observatory 2.3 m telescope (McCaughrean *et al.* 1991).

Near-infrared images of the region show the bright embedded source S 255-IR surrounded by a dense cluster of ~175 lower luminosity objects within a ~1 pc radius (McCaughrean *et al.* 1991; Tamura *et al.* 1991; see Fig. 15), most of them probably cluster members judging from the local field star density. The cluster appears to be sandwiched between two peaks of molecular emission (Snell and Bally 1986; Heyer *et al.* 1989), apparently at the position where two clouds are colliding, and it is possible that the cluster formation was triggered by the compression due to that collision. Perhaps the most remarkable feature of this region is that in contrast to the dense cluster between them, the two B stars exciting the H II regions S 255 and S 257 appear to be more or less isolated, *i.e.,* they do not seem to have cospatial low mass clusters, at least to a 5σ point source sensitivity limit of $K \sim 16^m.5$, corresponding to a $\sim 10^6$ year $0.2\,M_\odot$ star behind $A_V \sim 10^m$. There are several possible explanations here. The B stars may have been dynamically ejected from the embedded cluster, a possibility that can be tested by radial velocity measurements. Perhaps the high mass stars formed first in S 255 and S 257, and low mass stars have yet to form; this seems unlikely in light of the nearby dense cluster of high and low mass stars that shows every sign of being younger than the S 255 and S 257 H II regions. Or perhaps a cloud *can* form high mass stars without also forming low mass stars: this would support the theory of separate modes of high mass and low mass star formation, *i.e.,* bimodal star formation (*cf.* Güsten and Mezger 1982), in which case this complex appears to be our only concrete example of such so far.

W 3 (OH) (3 kpc)

The ultracompact H II region W 3 (OH) coincides with a cold, luminous source of infrared, millimetre continuum, and OH maser emission, which points to the existence of an embedded massive star or group of stars (Wynn-Williams *et al.* 1972; Reid *et al.* 1980; Dreher and Welch 1981; Turner and Welch 1984). A 2.2 μm image of W 3 (OH) shown in Fig. 16 reveals an associated cluster of lower luminosity embedded sources (Rayner *et al.* 1991*a*): more than 150 objects are found within a 1 pc radius, assuming a distance of 3 kpc. However, the most important feature of this image may be that which is unseen. High resolution far-infrared observations by Campbell *et al.* (1989) have resolved the compact source (FWHM ~ 13 arcseconds at 100 μm), and their models allow us to estimate the dust column density in the volume over which the stars are distributed (see also Richardson *et al.* 1989). With the assumption of a central cavity of radius 3.3×10^{14} m (the radius of the ultra-compact H II region) and an $r^{-1.5}$ density profile outside this radius, they derive a visual extinction towards the central compact source of $\sim 1000^m$, which implies an $A_V > 30^m$ even at a radius of 10 arcseconds (0.15 pc) from the cluster centre. Thus somewhat surprisingly, near-infrared images of this region may give an incomplete picture of the young stellar population near the core, showing only the stars embedded in the outer 'skin' or 'shell' of the protocluster condensation.

Other galactic clusters

In the last few years, near-infrared cameras have revealed many other young embedded clusters in the galaxy, many of which have so far only been discussed in conference proceedings, preprints, and unrefereed journals. There are too many to discuss in detail, but some are listed here for completeness. These include clusters associated with the Serpens dark cloud (Eiroa and Casali 1989), NGC 3603 (Moneti and Zinnecker, in preparation, as shown by Melnick 1989), W 75 N (Moore *et al.* 1991), S 228 (Carpenter *et al.* 1991), LkHα 101 (Barsony *et al.* 1991), Mon R2 (Aspin and Walther 1991), GM 24 (Tapia *et al.* 1991), S 235, S 269, GL 437 (Rayner *et al.* 1991*a*), W 51 (Goldader and Wynn-Williams 1991), and NGC 7538 (Rayner *et al.* 1991*b*).

3. Clusters in the Magellanic Clouds (55 kpc)

Studies of the IMF in Large and Small Magellanic Cloud clusters are now tractable using sensitive CCD detectors and sophisticated software for crowded field photometry. The advantage of these studies is that Magellanic Cloud young clusters both extend to higher stellar masses (hence the name 'blue populous clusters') and have a larger number of stars of all masses than the Galactic open clusters (Elson *et al.* 1989). Thus they can provide more meaningful statistics overall, and in particular at the high mass end. Furthermore, as the clusters are all at the same distance, an intercomparison of their individual IMFs is easier.

30 Doradus

The centre of the 30 Doradus or Tarantula Nebula has long been a focus of attention. Weigelt and Baier (1985) resolved the luminous central object R 136 into at least eight individual stars using 2D optical speckle interferometry, a result recently confirmed by direct UV imaging using the *FOC* of the Hubble

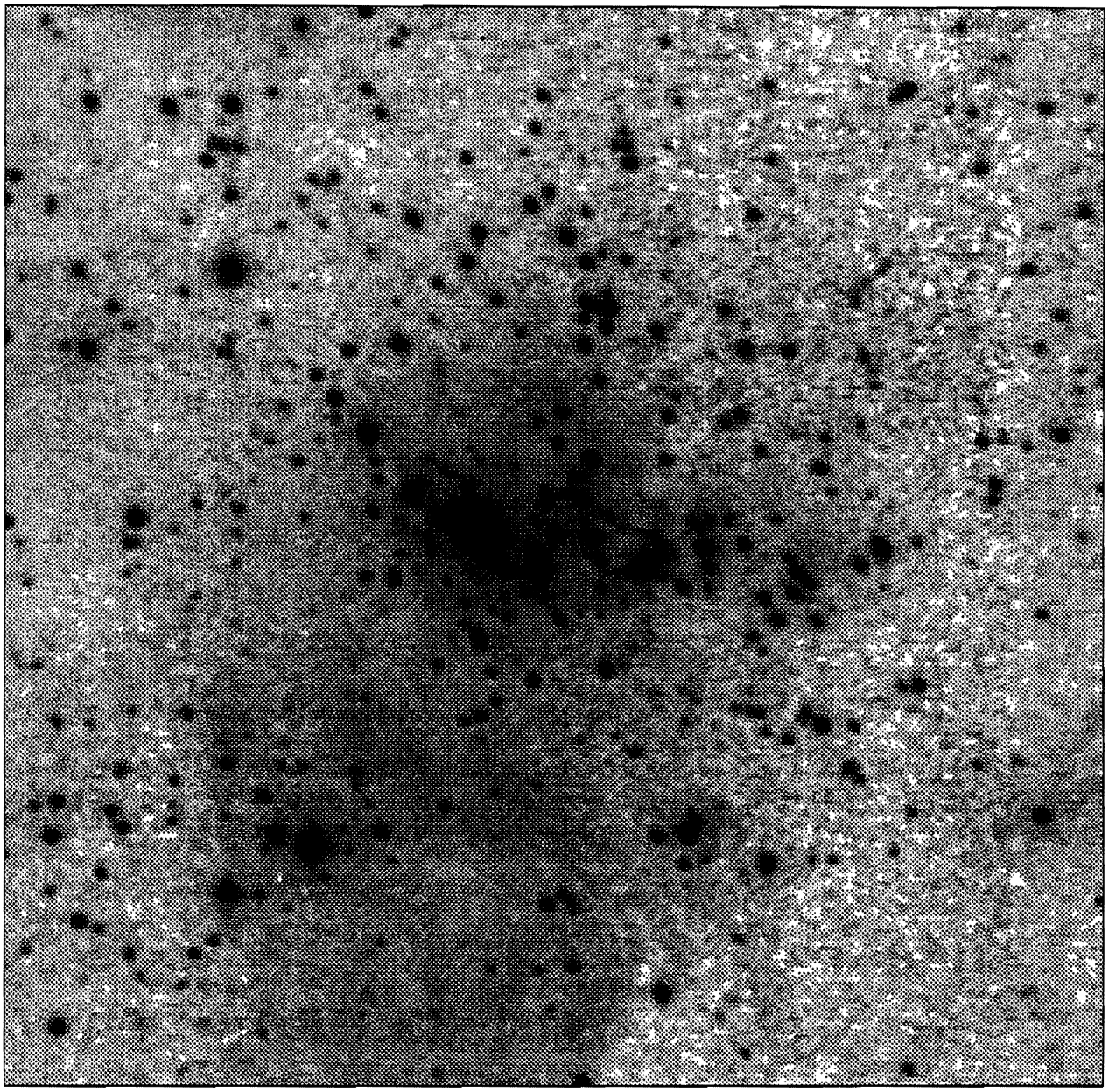
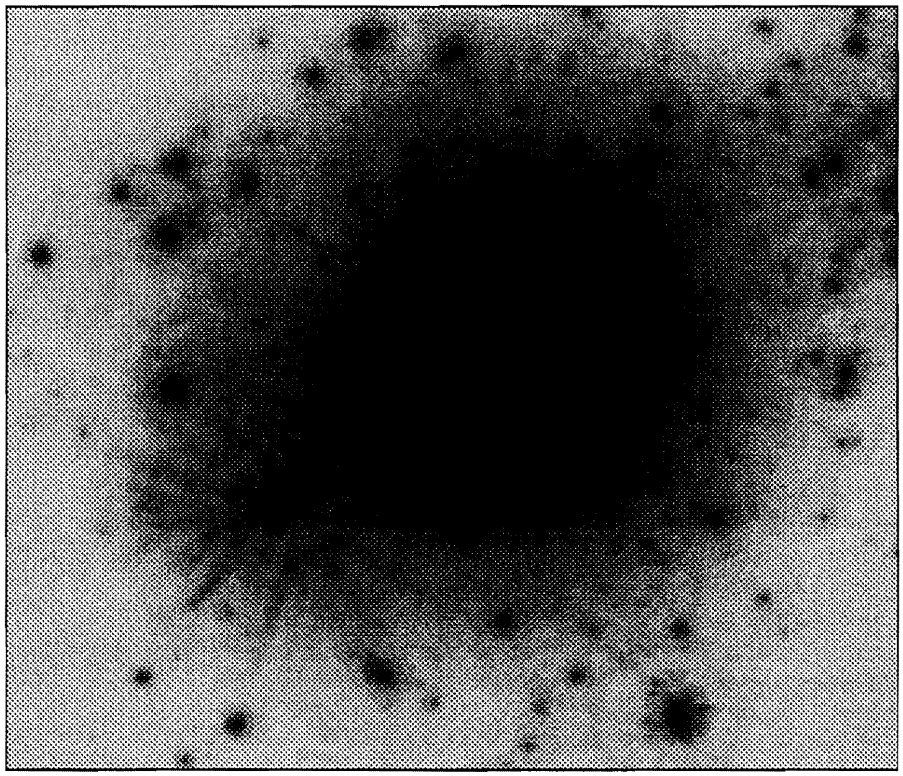


Figure 16 A K (2.2 μm) image of the infrared cluster associated with the W 3 (OH) ultracompact H II region, covering ~3.5×3.5 arcminutes (~3×3 pc at 3 kpc). There is so much extinction towards the core of the cluster that the innermost stars are probably not detected in this image. The data were obtained using a 256×256 pixel HgCdTe infrared array at the University of Hawaii 2.2 m telescope (Rayner *et al.* 1991*a*).

Space Telescope (Weigelt *et al.* 1991). On a slightly larger scale, a deconvolved direct image taken with the *ESO* 2.2 m revealed some 30 stars in a ~4×4 arcsecond (~1×1 pc at 55 kpc) region surrounding R 136 (Maaswinkel *et al.* 1988). More recently this region was imaged with the Planetary Camera of the *WF/PC* on the *HST*. In the raw image (*i.e.*, not deconvolved to remove the spherical aberration of the *HST* primary), at least 300 stars are seen within a 2 arcsecond radius of the R 136 core. For the 22+ visible B and earlier type stars within a 1 arcsecond diameter circle centred on R 136, a conservative minimum stellar density of $5\times10^4\,M_\odot\,\mathrm{pc}^{-3}$ has been estimated (B. Campbell, personal communication). See Fig. 17*a* for the *HST WF/PC* image and Fig. 17*b* for a recent ground-based speckle image of a slightly smaller region (Pehlemann *et al.* 1992).



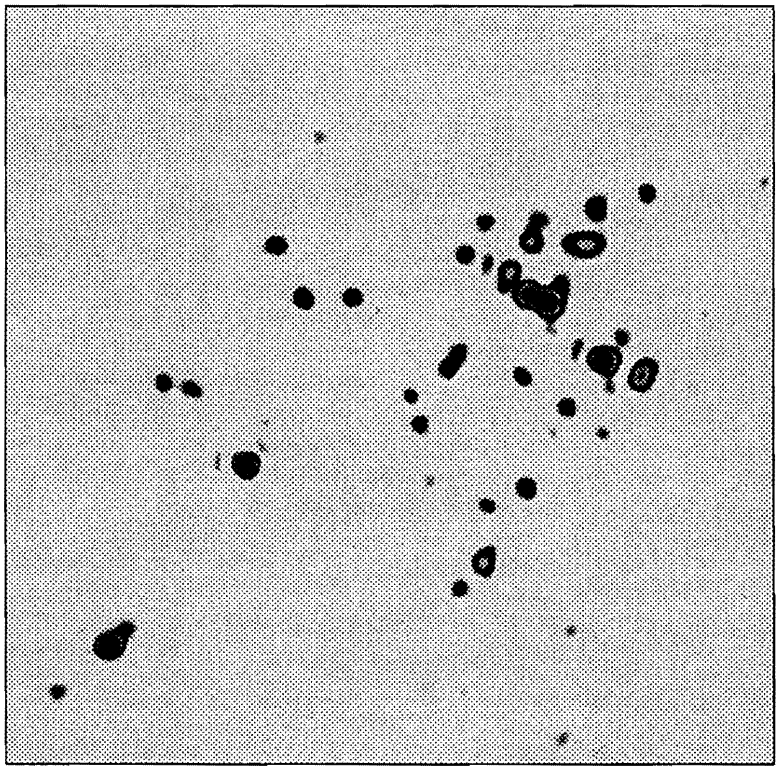


Figure 17*a,b* Optical (~5470 Å) image of the central ~11.5×10 arcsecond (~3.1×2.7 pc at 55 kpc) region of the 30 Doradus cluster, taken with the *WF/PC* of the Hubble Space Telescope (B. Campbell, personal communication). Note that the massive stars are located near the cluster centre. For comparison, a ground-based image of the inner ~4.8×4.8 arcsecond (~1.3×1.3 pc) region obtained using speckle techniques is also shown (Pehlemann *et al.* 1992).

While the 30 Dor cluster has many more high mass stars and extends to much higher individual stellar masses (up to 250 $M_\odot$), there are nevertheless many similarities with the prototypical galactic young cluster, the Trapezium Cluster: the most luminous stars in 30 Dor are at the centre of the cluster, surrounded by lower mass stars; the cluster age is $\sim 10^6$ years (Melnick 1985); and in addition to the optical cluster, there is evidence for recent and on-going star formation in this region, in the form of four highly luminous (1–5×10^4 $L_\odot$) infrared sources found in a $\sim 80\times110$ pc survey centred on R 136 (Hyland and Jones 1991), and a number of red reflection nebulae interpreted as clumps of gas with embedded young massive stars (Walborn and Blades 1987; Walborn 1990).

Based on the cospatial presence of red supergiants and OB stars, McGregor and Hyland (1981) suggested that there had been at least two distinct bursts of star formation in the 30 Dor region. They advanced the idea that a wave of star formation had moved from the periphery to the centre (R 136) of the 30 Dor cluster and that new stars had formed at the intersection of the prominent wind-blown bubbles or shells in the region, powered by older massive stars in the outer parts of the cluster. However, Melnick (1985) pointed out that the red supergiants seem to be uniformly distributed in the region, suggesting that relatively quiescent star formation may have been occurring throughout the region for 10–20×10^6 years, with a single violent burst of star formation leading to the nebula and massive OB cluster more recently, only some 2×10^6 years ago.

Another scenario for the triggering of the most recent phase of star formation is suggested by the impression that star clusters seem to form at the apex of a cloud exposed to external compression, combined with the striking fact that 30 Dor, the most luminous star-forming region in the LMC, is located on the leading edge of the motion of the LMC through the halo gas of our galaxy. X-ray observations with *ROSAT* should reveal the hot gas associated with any bow shock preceding the LMC, and hydrodynamical calculations should then demonstrate whether or not this particular form of external compression could have triggered the formation of the 30 Dor cluster.

Finally, that 30 Dor is near the end of the LMC bar, *i.e.*, the bulk of the old stars, has suggested yet another possible source of triggering: in many irregular galaxies, vigorous star formation is seen to occur near the end of an underlying stellar bar, perhaps due to increased gas compression there (D. Elmegreen and B. Elmegreen 1980; Gallagher and Hunter 1984).

An all-important question is whether or not 30 Dor is home to any low mass (*i.e.*, sub-solar) stars. As it is the nearest prototype of a starburst system, the current paradigm for starbursts would predict the suppression of low mass star formation in 30 Dor. There is currently no direct proof for a lack of low mass stars in 30 Dor, and even though their detection would be extremely difficult, this very important experiment may be possible in the near future, by coupling adaptive optics, infrared arrays, and an 8 m class telescope. If the 30 Dor cluster is found to contain low mass stars, there would be important implications for the notion of bimodal star formation in more distant starburst galaxies. Also, any such discovery would reinforce the hypothesis that the 30 Dor cluster may actually be a young globular cluster, *i.e.*, similar to those that formed 10–15×10^9 years ago in the haloes of most galaxies, including our own. Its mass of $\sim 10^5$ $M_\odot$ (Melnick 1985) is indeed similar to that of the old globular clusters.

Finally, since the 30 Dor cluster is so massive, the whole range of stellar masses should be populated in significant numbers according to any reasonable IMF. Current population synthesis models do not contain good templates for young metal-poor populations (*cf.* Bica and Alloin 1986*a*,*b*), and therefore the stellar content of 30 Dor might be considered a unique 'template initial stellar population', useful for models of protogalactic evolution at times when the metallicity was far below solar.

Other LMC/SMC clusters

In addition to the young 30 Dor cluster, the Magellanic Clouds are home to a number of somewhat older (10^7–10^8 yrs) clusters, the luminosity and mass functions of several of which have recently been studied in detail by Mateo (1988) and Sagar and Richtler (1991) using CCDs, and by Elson *et al.* (1989) using photographic plates.

As part of his study of LMC and SMC clusters across a wide age range, Mateo (1988) determined the IMFs for the young clusters NGC 330 in the SMC ($\sim 10^7$ yrs) and NGC 1711 in the LMC ($\sim 5\times10^7$ yrs), finding both to be characterised by a power-law with slope $y = -2.4 \pm 0.6$ (*cf.* $y = -1.35$ for the $dN/d\log m \propto m^y$ form of the Salpeter IMF) for stars in the mass ranges $\sim$2–12 $M_\odot$ and $\sim$2–7 $M_\odot$ respectively. In contrast, Sagar and Richtler (1991) found a slope of $y = -1.5 \pm 0.3$ for NGC 1711: it is likely that this significant disagreement is due to the different incompleteness corrections applied, the technique of Mateo (1988) tending to overcorrect, resulting in a steeper IMF, and that of Sagar and Richtler (1991) tending to undercorrect,

leading to a shallower IMF. It may well be that the correct IMF slope for NGC 1711 is somewhere between the two results, $y \sim -1.9$ (Mateo 1990; M. Mateo, personal communication).

For two other clusters in their sample, NGC 2164 and NGC 2214, Sagar and Richtler (1991) derived roughly the same slope of $y \sim -1.1$, close to the Salpeter and Miller-Scalo values for stars in the corresponding mass range of 2–14 $M_\odot$. From their photographic photometry of these clusters however, Elson *et al.* (1989) derived almost flat IMFs, with slopes $y = -0.8$ and $y = +0.2$ across the mass range $\sim$1.5–6 $M_\odot$, a result at least partially accounted for by their not using PSF fitting techniques: crowding tends to discriminate preferentially against fainter stars, thus flattening the derived IMF slope. Following this tack even further, Sagar and Richtler (1991) discussed the effect of unresolved optical and physical binaries. If plentiful (>50%), these can also flatten the slope of the *derived* IMF significantly, particularly if the slope of the *intrinsic* IMF is already rather flat. For example, in the extreme case of all observed stars actually being paired with another star of random mass, an intrinsic Salpeter slope of $y = -1.35$ would be flattened to a measured value of $y \sim -1.0$. Finally, looking at their study of five LMC/SMC clusters (NGC 1711, NGC 2004, NGC 2100, NGC 2614, and NGC 2214) as a whole, Sagar and Richtler (1991) found no strong evidence for mass segregation (*cf.* Sagar *et al.* 1988 and references therein), although they did not study the crowded inner cores (<5 pc radius) of the clusters.

There remain significant uncertainties in IMF slope determinations for LMC/SMC clusters due to their relatively large distance, corresponding technique questions (*e.g.*, PSF fitting, incompleteness corrections), and choice of comparison stellar models. However, there does seem to be some consensus emerging, with IMF slopes slightly steeper than Salpeter, and evidence for cluster to cluster slope variations (M. Mateo, personal communication). Higher spatial resolution data may begin to settle some of these issues in the near future.

IV. THE QUESTION OF THE EXISTENCE OF BROWN DWARFS

Since the publication of *Protostars and Planets II* (Black and Matthews 1984), there has been an increasing interest in finding observational evidence for the existence of brown dwarfs, *i.e.*, sub-stellar objects (<0.08 $M_\odot$) that are not massive enough to ignite hydrogen burning (D'Antona and Mazzitelli 1985). There are many low mass stars just above this critical mass, and it seems reasonable to expect many objects below it, as the minimum Jeans mass in a collapsing cloud is <0.01 $M_\odot$ (Low and Lynden-Bell 1976; Rees 1976). Also, in a more general sense, it seems unlikely that the physical processes of nuclear fusion that determine whether or not a star is massive enough to burn hydrogen have much to do with the processes that governed the fragmentation and initial phases of collapse that resulted in that star. If the empirically determined Miller-Scalo IMF for stars (a half-gaussian in log-mass, peaking at 0.1 $M_\odot$) extrapolates as a descending gaussian below the peak, as some hierarchical fragmentation models would suggest (Zinnecker *et al.* 1980; Zinnecker 1984; see Fig. 18), one would expect as many sub-stellar objects in the range 0.01–0.1 $M_\odot$ as PMS stars in the range 0.1–1.0 $M_\odot$. Liebert and Probst (1987) and Stevenson (1991) have presented extensive, thorough reviews of the theory and observations of these objects, but in the present context of young stellar populations, we shall give a brief account of searches for *young* brown dwarfs in regions such as Taurus-Auriga and the Pleiades, where low mass stars are known to have recently formed or are still forming.

There are major observational advantages in searching for young brown dwarfs. Firstly, the search area is much better defined, because regions with young stars, *i.e.*, clusters, are more coherent in space and time than the galactic disk in general. Secondly, young brown dwarfs are easier to detect than old brown dwarfs because they are still rather bright due to very slow quasi-static contraction. For example, at a distance of 125 pc, probable Pleiades brown dwarfs (age $\sim 10^8$ yrs) are expected to be at $I \sim 17^m.5$ and $K \sim 14^m.5$ (Simons and Becklin 1991*b*, derived from Burrows *et al.* 1989). In Taurus-Auriga at 140 pc, probable brown dwarfs should be at $I \sim 14^m.0$ and $K \sim 11^m.0$ assuming an age of $\sim 10^6$ years, or $I \sim 15^m.7$ and $K \sim 12^m.7$ at $\sim 10^7$ years (derived from the PMS tracks discussed in Section II.B, provided by I. Mazzitelli). These magnitudes are for objects on the star:brown dwarf dividing line at 0.08 $M_\odot$, and therefore genuine brown dwarfs (<0.08 $M_\odot$) would be somewhat fainter. Even so, such objects should still be well within the capabilities of current optical and infrared imaging systems: it is their positive identification that poses significant problems. This is mainly due to contamination by background field stars, but also partly due to a lack of knowledge about exactly where to draw the line between very low mass stars and brown dwarfs in a young cluster. On the latter point however, recent theoretical models suggest that in the HR diagram of a young ($\leq 10^8$ yrs)

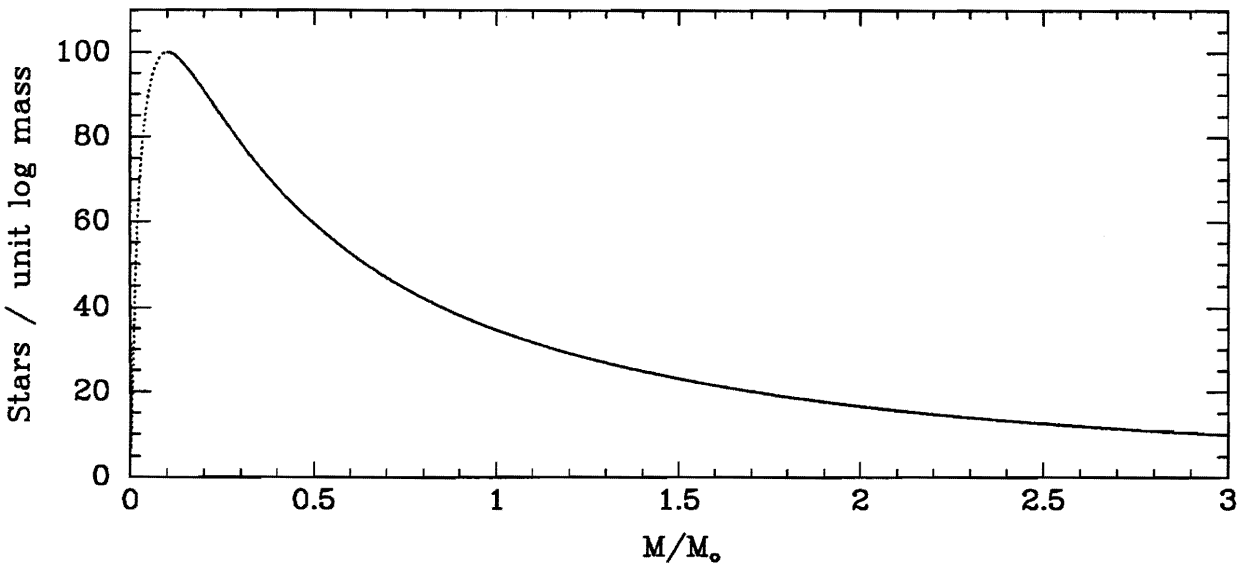


Figure 18 Lognormal model IMF for low mass stars according to Zinnecker (1984). The IMF shown here is the relative number of newly-born stars as a function of mass (in units of solar mass) per unit mass interval. This curve is very similar to the well known Miller-Scalo IMF, except for the (lognormally continued) extrapolation to sub-stellar masses.

cluster, brown dwarfs should be well segregated from very low mass stars, primarily in $T_{\rm eff}$ rather than L (Stringfellow 1991).

If the putative brown dwarf population *can* be kinematically and spectroscopically identified for a given star-forming region of known distance and age, we should then be able to determine whether the luminosity function is rising or falling with decreasing luminosity. This question has obvious implications for the IMF and for the 'missing mass' problem. In order to address these wider issues however, it is not enough to search for brown dwarfs occurring as binary companions (see, *e.g.*, Zuckerman and Becklin 1987; Becklin and Zuckerman 1988; Henry and McCarthy 1990): it is also necessary to assess the existence of a 'free-floating' population. In that context, we will discuss searches for this population in Taurus-Auriga, ρ Oph, the Pleiades, and the Hyades.

Forrest *et al.* (1989) carried out a 2.2 μm (K) imaging survey in the immediate vicinity (within a few tens of arcseconds) of 26 known PMS members of the Taurus-Auriga association. Of the 20 new objects detected, four were classified as Taurus-Auriga members based on their proper motions. These four have K magnitudes ranging from $14^{m}.2$–$15^{m}.8$, leading to estimated masses $\sim 0.01\,M_\odot$, and all are far enough separated from the nearby PMS star that they would more likely be free-floating than part of a bound multiple system. However, these candidate Taurus-Auriga brown dwarfs seem strangely scattered in the near-infrared colour-colour diagram, and follow-up optical spectroscopy seemed to rule out the possibility that they are very cool objects (Stauffer *et al.* 1991). So at least for the time being, there appears to be no strong case for a large brown dwarf population in Taurus-Auriga.

The same seems to be true for ρ Oph, the subject of several recent near-infrared surveys. While Rieke *et al.* (1989) surveyed the ρ Oph dark cloud core to a limiting magnitude of $K \sim 14^{m}$ and found no new sources over and above those found in a previous shallower survey to $K \sim 12^{m}$ (Wilking and C. Lada 1983), another survey to $K \sim 14^{m}$ over a larger area did reveal some 35 new sources (Barsony *et al.* 1989*b*). However, there is no indication that these sources are necessarily sub-stellar, and although an even deeper survey (to $K \sim 15^{m}.5$) finally uncovered three as-yet unconfirmed brown dwarf candidates (Rieke and Rieke 1990), the present conclusion is that there is no evidence for a ***substantial*** brown dwarf population in ρ Oph.

A limited start at the search for brown dwarfs in the Pleiades was made by Skrutskie *et al.* (1986), who looked at eight known cluster members and found no faint near-infrared companions. Searching for a free-floating population of brown dwarfs, CCD surveys in the central region of the Pleiades were made by Jameson and Skillen (1989) and Stauffer *et al.* (1989), covering 125 square arcminutes at R and I, and 900 square arcminutes at V and I respectively. Although in both cases a small number ($\sim$5) of very faint, very red sources were found to fall in the part of the colour-magnitude diagram expected for brown dwarfs,

Stauffer *et al.* (1989) concluded that the mass distribution peaks near $0.2\,M_\odot$, and falls rapidly thereafter, so that brown dwarfs are not a major component of the Pleiades.

In contrast, Hambly and Jameson (1991) used R and I Schmidt photographic data to study the faint stellar and sub-stellar content of a 3° diameter region centred on the Pleiades. After a statistical subtraction of field star contamination as determined from the outer regions of their plates, they placed a lower limit of 30 on the potential number of brown dwarfs in the whole cluster, and concluded from their I luminosity function that the mass function is flat at the lowest masses. Finally, looking in the wavelength region where low mass stars and brown dwarfs are most luminous, Simons and Becklin (1991*a,b*) surveyed some 200 square arcminutes over several regions of the Pleiades in the near-infrared using the *UKIRT* infrared camera to $K=17^m.0$, and in the optical using a CCD camera. Control fields 5° away at the same galactic latitude were also surveyed to assess the field population. Plotting an I vs $I-K$ colour-magnitude diagram overlaid by theoretical brown dwarf curves at the appropriate age, they isolated sources that lay close to the lower main sequence. After correcting for the background population, they were left with some 22 ± 10 free-floating objects with nominal masses in the range $\sim$0.04–0.1 $M_\odot$, and a mass function that continues to rise steeply through the star:brown dwarf dividing line. When extrapolated to the whole cluster, these results imply a much larger population of sub-stellar objects than that of Hambly and Jameson (1991), with objects in the 0.04–0.1 $M_\odot$ range contributing some 200 $M_\odot$ to the total Pleiades cluster mass of $\sim$1000 $M_\odot$, as determined from velocity dispersion measurements (van Leeuwen 1980, 1983).

The results of Hambly and Jameson (1991) and Simons and Becklin (1991*b*) indicate that if most stars in the galactic disk are formed in clusters and if the Pleiades is a typical cluster, then it is reasonable to suppose that brown dwarfs in the field are common. However, it must be noted that all these large area surveys of the Pleiades used the temperature calibration for low mass stars derived by Berriman and Reid (1987), which Stringfellow (1991) has recently found to be erroneous. This places the results of Jameson and Skillen (1989) and Hambly and Jameson (1991) in serious doubt, and those of Stauffer *et al.* (1989) and Simons and Becklin (1991*b*) somewhat less so. This finding, along with the present degree of uncertainty in evolutionary models of very low mass stars and brown dwarfs against which the observations are tested, suggest caution in interpreting the observational data. Also, as all the various authors point out, definite confirmation of any of these brown dwarf candidates as Pleiades members awaits accurate proper motion studies.

The older (6×10^8 yrs) but closer ($\sim$40 pc) Hyades cluster has also been surveyed for faint members (Leggett and Hawkins 1988, 1989). Using Schmidt plates, they selected objects with large $R-I$ colours for follow-up near-infrared (J,H,K) photometry, in order to derive near-infrared luminosity functions. It is worth noting here that it probably makes more sense to talk in terms of the near-infrared LF for low mass stars and brown dwarfs than the usual optical LF, since the former is much closer to the bolometric LF than the latter, due to the relatively cool temperature of these objects. Leggett and Hawkins (1988, 1989) found a near-infrared LF for the Hyades which peaks at absolute magnitudes $M_J=7^m.6$, $M_H=7^m.0$, and $M_K=6^m.7$, corresponding to $\sim$0.2 $M_\odot$. Henry and McCarthy (1990) dispute the significance of this peak, suggesting that unresolved binaries may be boosting the bright end of the luminosity function, while depressing the faint end. Hubbard *et al.* (1990) calculated bolometric luminosity functions for stars and sub-stellar objects spanning the range 0.03–0.2 $M_\odot$, and compared their model luminosity functions for the age of the Hyades with the observations of Leggett and Hawkins (1988, 1989). They inferred that the mass distribution does not rise with decreasing mass over the mass interval studied. This is consistent with the negative result of a high sensitivity 1–2 μm photometric search for cool, low mass companions to 8 white dwarfs in the Hyades (Zuckerman and Becklin 1987).

It is interesting to note (*cf.* Hubbard *et al.* 1990) that it is at a cluster age about equal to that of the Hyades that the luminosity function begins to separate into two components: that of the brown dwarfs and that of the lower main sequence. Therefore deeper surveys of the Hyades may be able to differentiate between these two components. In older clusters, the brown dwarfs become harder to detect, since they will have evolved to even lower luminosity. On the other hand, Stringfellow (1991) presents isochrones spanning a mass range of 0.01–0.2 $M_\odot$ and an age range of 10^6–3×10^8 yrs. As mentioned above, he emphasises that the best opportunity to discover brown dwarfs may be in even younger clusters ($\leq10^8$ yrs), where the brown dwarfs should also be well segregated from the very low mass stars in the HR diagram.

Finally, it is worth reporting the observational results on the low mass stellar content of much older systems, globular clusters, as some of these may yet contain their low mass initial stellar population. Drukier *et al.* (1988) and Richer *et al.* (1990) have both investigated the luminosity function of M 13 (metallicity

[Fe/H]=−1.4) and concluded that the derived mass function rises steeply below $0.4\,M_{\odot}$ with no sign of flattening at the lowest observable masses (0.2–$0.4\,M_{\odot}$). The more metal rich M 71 and more metal poor NGC 6397 exhibit flatter (but still rising) mass functions in the same mass range (Richer *et al.* 1990; Fahlman *et al.* 1989). Thus, contrary to earlier data (McClure *et al.* 1986), the most recent CCD photometry does not indicate a correlation between the slope of the mass distribution at the lowest masses and the metallicity of a cluster, but instead suggests that the steepest mass functions are found in the dynamically least evolved clusters, such as M 13. Dynamically older systems, such as M 71 and NGC 6397, may have lost a much greater fraction of their low mass stars due to evaporation, thus making for a shallower slope at the low end of their mass functions (Richer *et al.* 1990). This is now further confirmed for a larger sample of globular clusters, implying a very large initial population of low mass stars and perhaps even brown dwarfs in globular clusters, and possibly in the Galactic halo in general (Richer *et al.* 1991). Thus it seems that the conditions for forming very low mass stars and brown dwarfs may be more favourable in Population II than in Population I regions (*cf.* Zinnecker 1986*b*).

V. SUMMARY AND OUTLOOK

In conclusion, we return to the questions posed in the introduction, summarise our present knowledge and ignorance about young stellar populations, and take a speculative look forward to some of the problems that may be addressed between now and the time of *Protostars and Planets IV*.

In most H II regions, massive stars do not appear alone but are usually accompanied by a cluster of low mass PMS stars; *i.e.*, low mass stars and high mass stars form in the same molecular cloud cores. Evidence for high mass stars without accompanying low mass stars (bimodal star formation) is very rare, while there are many examples of the converse, namely low mass stars without high mass stars. Taking the Galaxy as a whole however, it remains an open question whether the majority of low mass stars form as cluster members near OB stars, or as a more widely dispersed background population in giant molecular clouds unrelated to OB stars. Recent results discussed in this and other chapters of this volume seem to indicate a move toward the former hypothesis.

Clusters of PMS stars associated with OB stars form from dense gas concentrations in molecular clouds. It appears that some clusters owe their origin to the triggering push of adjacent active regions which compress pre-existing overdense clumps ('obstacles'); *e.g.*, the ρ Oph cluster and those in L 1630. Thus there is evidence for sequential star formation (*cf.* B. Elmegreen 1989). In some cases, two daughter sites of star formation may spring from one mother site: as discussed earlier, the Trapezium Cluster and the NGC 2024 cluster may both be siblings of the Orion 1b association, and a similar form of bifurcation may also have operated in the Sco-Cen association (de Geus *et al.* 1989). Other clusters may form as self-initiated independent condensations in molecular clouds, *e.g.*, as in NGC 6334. If star formation in clusters is triggered, the age spread of the cluster stars should be small, while in self-initiated protocluster condensations, the individual clumps should have a larger age spread, probably governed by the timescale of the loss of magnetic support in the individual protostellar clumps.

The evolution of the IMF, star formation rate, and star formation efficiency in a protocluster are not yet well known. The IMF is thought to evolve from the clump mass spectrum, which in turn must be regulated by a balance of clump collision and fragmentation processes. The clump mass spectrum is relatively flat ($dN/dM \propto M^{-1.5}$), with most mass in the massive clumps, while the final stellar mass spectrum is steeper ($dN/dm \propto m^{-2.35}$), with most mass in the low mass stars. Preferential fragmentation of the massive clumps and mass-dependent feedback processes could steepen the flat clump spectrum by the required amount to result in the final stellar mass spectrum. Clump collisions should be more prevalent near the protocluster centre, in which case we would expect more massive clumps near the centre, implying that the more massive stars are born predominantly near the cluster core. The more massive a protocluster cloud, the deeper its central potential well, which should lead to a correlation between total cluster mass and the most massive stars formed in the cluster, as seems to be observed.

At the time of *Protostars and Planets II* (Black and Matthews 1984), it was generally felt that low mass stars form first and over a long timescale (few $\times\,10^7$ yrs) throughout a GMC. If and when high mass stars form, they dissipate the reservoir of material, preventing further star formation (S. Strom 1985). This paradigm was based on observational evidence including the age spread of T Tauri stars (Cohen and Kuhi 1979) and of the low mass members of the Pleiades (Herbig 1962*a*). The same 'low mass first, high mass later' build-up in the IMF was found for the young clusters NGC 2264 and NGC 6530 (see, *e.g.*, Iben and

Talbot 1966; Adams *et al.* 1983), although S. Strom (1985) cautioned that these conclusions rested heavily on comparisons of the observational data with theoretical PMS tracks. Indeed, subsequent reanalyses have shown the same data to be more consistent with simultaneous formation of stars of all masses and a roughly constant star formation rate in young clusters (Stahler 1985; Schroeder and Comins 1988).

There probably is a low level of low mass star formation throughout a GMC to begin with, but when massive stars finally form, they are generally accompanied by vigorous low mass star formation in the same molecular core, as indicated by the extensive clusters of low mass stars seen surrounding OB stars in their H II regions. It is unknown to what degree these events are truly simultaneous: for example, the low mass star formation may actually be triggered by radiative implosion or the powerful winds from the massive stars. In any case, the notion of 'coevality' in a cluster may be hard to define both theoretically and observationally on timescales of $<10^6$ yrs. Even if the collapse of a dense molecular core is triggered at some 'time zero' by an external event, the collapse and accretion phases for stars over a range of masses may be quite different. Low mass stars may acquire their final mass first, but will then take a long time to reach the ZAMS; high mass stars may take longer to accumulate their mass, but then evolve rapidly onto the ZAMS. By the time the cluster becomes visible, there may well be an *apparent* spread in stellar ages. Observationally, any test of coevality depends on comparing the positions of stars in an HR diagram with theoretical isochrones. The isochrones are difficult to model for both high and low mass stars (*e.g.*, are the accretion rates constant?), and it is difficult to place photospheres in an HR diagram accurately when they are partially or totally obscured by dust. At this time, only the rather general conclusion can be made that in all clouds, stars have formed coevally to within ten million years, while in the cases of ρ Oph and the Trapezium Cluster, it appears that most stars have formed coevally to within a few million years.

In more detail, complex star formation histories in star clusters may be the rule rather than the exception. We cannot trust present PMS tracks enough to unravel the complex time sequences of star formation with confidence. It can be speculated that the time evolution of the total star formation rate in a cluster may be described by $1/f$ noise (*cf.* Bak *et al.* 1988). This implies self-organised weak chaos, characterised by 'memory effects': rare short periods of vigorous star formation alternate with more frequent periods of low level activity.

Similarly, the star formation efficiency in a protocluster is a highly time-dependent quantity, namely the integral of the star formation rate up to a given time, if star formation is still occurring. The asymptotic, overall star formation efficiency with which a cluster will form probably depends on the initial conditions, most importantly on the mean gas density but probably also on the total mass of the protocluster (*cf.* Pandey *et al.* 1990). High protocluster densities apparently lead to high star formation efficiencies: for example, in the Trapezium Cluster, the protostellar envelopes must have been touching each other at the time of formation. We speculate that triggered clusters will form with a higher star formation efficiency, will be more compact, and also more coeval, than self-initiated clusters. Conversely, it is clear observationally that outside of massive cores of molecular clouds, the star formation efficiency is always low: for example, the total stellar mass to total gas mass ratio is at most a few percent in the Taurus-Auriga complex (which lacks a massive core), as it is outside the core of the ρ Oph region.

The study of star formation in clusters as opposed to isolated star formation raises many interesting new problems: for example, it may be that a full distribution of stellar masses with a large spread in mass only comes about because the primary sites of star formation are protoclusters in which a rich variety of competing processes takes place. If so, future studies of the initial stellar population should focus even more on young star clusters.

Observationally at least, this task will be made easier by likely technological innovations and evolutions during the next decade. Infrared array detectors have emerged as perhaps the key component for studies of young stellar populations. These arrays have increased in size from 32×32 to 256×256 pixels since *Protostars and Planets II* in 1984, and arrays with more than 10^6 pixels are anticipated within the next few years, allowing us to survey all galactic massive star-forming regions for all but the very youngest and most deeply embedded stars. By using these arrays at high spatial resolution, even the remotest galactic clusters will be disentangled, and binarity in the nearer regions probed. Active and adaptive optics techniques will be used on the new generation of large ground based telescopes ($\sim$8–16 m effective aperture) to achieve extraordinary resolutions $\sim$0.02–0.2 arcseconds) in the near-infrared, while a near-infrared camera under development for the Hubble Space Telescope will yield a unique combination of high spatial resolution and very low background at 1–2 μm. Near-infrared spectroscopy will also gain enormously from advanced arrays:

the first generation of array spectrometers are now available, and promise much in the understanding of the physical nature of sources revealed by camera surveys.

Mid- and far-infrared array detectors may be somewhat behind the near-infrared arrays in terms of size, but major technological breakthroughs have been made in preparation for the next generation of cryogenic infrared space observatories, *ISO* and *SIRTF*. While *IRAS* used a small number of individual detectors for an all-sky survey, both *ISO* and *SIRTF* will use large array detectors for pointed observations, and the great increase in sensitivity should result in fundamental changes in our knowledge of the youngest, coolest, and most deeply embedded sources in star formation regions. At far-infrared and sub-millimetre wavelengths, high sensitivity and spatial resolution will be made possible with *SOFIA*, an airborne 2.5 m telescope.

Complementary progress is being made at other wavelengths. The *ROSAT* X-ray observatory, already in operation, will detect many new weak-emission T Tauri stars in the nearer regions such as Taurus-Auriga; the larger *AXAF* will provide the spatial resolution and sensitivity needed to probe the X-ray emission from young stars in the clusters associated with GMCs. Studies of molecular clouds—the raw material of star formation—are benefitting from the new large millimetre and sub-millimetre telescopes already in operation or under construction, including the *IRAM* 30 m, the 15 m *SEST*, the 15 m *JCMT*, the 10 m *CSO*, the Nobeyama 30 m, and the 10 m *SMT*. Linking arrays of telescopes, millimetre interferometry will allow studies of the smallest scales of molecular cloud cores and clumps, in an effort to relate the cloud mass spectrum to the stellar mass spectrum. In addition, sub-millimetre interferometers should allow us to resolve cold disks around young stars where planets and/or binary stars are believed to form.

With the ever larger fields of view, higher spatial and spectral resolution, and greater sensitivity afforded by new instrumentation and techniques, we will be able to take a more global view of star formation within a cluster, a molecular cloud complex, or our whole galaxy, rather than concentrating intently on the detailed physics of single objects. For the interpretation of these larger scale observations, we require theoretical advances, such as improved PMS evolutionary tracks, including the effects of disk accretion. At the same time, the new observations can be expected to stimulate new theories.

An understanding of the problems of star formation and early stellar evolution is clearly an important part of our understanding of the origin of the solar system and planet formation. Also, as stars are the basic building blocks of galaxies, these very same problems bear heavily on our comprehension of galaxy formation and evolution, and many of the large scale cosmological questions related to the early universe. Therefore, if most stars form in dense clusters, then it is clear that the formation and early evolution of clusters and the stars that comprise them must be better understood.

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