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THE NATURE, ORIGIN AND EVOLUTION OF EMBEDDED STAR CLUSTERS

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ABSTRACT Star clusters are born in molecular clouds. During their formation and early evolution clusters are heavily obscured by dust contained within the clouds. Infrared observations are necessary for the identification and investigation of such embedded young stellar systems. The recent development of imaging infrared array cameras has enabled the first systematic studies of embedded protoclusters in the galaxy. Initial investigations suggest that rich embedded clusters are quite numerous and that a significant fraction of all stars formed in the galaxy may begin their lives in such stellar systems. These clusters contain extremely young stellar objects and are important laboratories for star formation research. However, observational and theoretical considerations suggest that most embedded clusters do not survive emergence from molecular clouds as bound clusters. Understanding the origin, nature and evolution of embedded clusters requires understanding the intimate physical relation between embedded clusters and the dense molecular cloud cores from which they form.

INTRODUCTION

Clusters have been long recognized as important laboratories for studies of stellar evolution. This is because stars in such groups share the common heritage of being formed from the same progenitor molecular cloud. Embedded clusters are particularly important in this regard since their study provides insights into the phenomena of stellar creation and early life. These are areas into which the fundamental theory of stellar evolution has yet to be successfully extended. Considerable progress has been achieved in the last few years in the quest to develop a comprehensive theory of star formation (e.g., Shu, Adams and Lizano 1987; Lada and Shu 1990). However, these theoretical advances have been aimed at achieving an understanding of the formation of single low mass stars from isolated cloud cores. The natal environment of a massive core which is capable of forming a cluster is quite different than that of a low mass core which produces only one or two isolated new stars and one might expect fundamental differences in the physics of the star formation process between such regions.

For example, complex interactions between multiple protostellar fragments in a cluster forming core may give rise to the particular form of the Initial Mass Function (IMF) observed in the galaxy (Salpeter 1955). The physics of binary and multiple star formation could also be quite different in a massive cloud core densely crowded with protostellar objects.

The observational study of partially embedded clusters has been of interest to astronomers for many years and a few relatively nearby such systems have been investigated at various times and with various degrees of thoroughness. Among the best studied examples are NGC 2264 (e.g., Walker 1956; Adams, Strom and Strom 1983; Margulis, Lada and Young 1989), The Trapezium cluster (Herbig and Terndrup 1986), M17 (Beetz *et al.* 1976) and IC 5146 (Herbig 1966, Lada and Elmegreen 1979). Deeply embedded clusters have only been the object of direct study since the development of sensitive infrared telescopes. The first deeply embedded cluster to be extensively studied was the cluster associated with the Ophiuchi dark cloud (Grasdalen, Strom and Strom 1973; Wilking and Lada 1983). With the recent development of infrared array cameras astronomers, for the first time, have the ability to survey and systematically study the embedded stellar populations of molecular clouds. Renewed interest in understanding the nature and significance of embedded clusters has been stimulated by the early results achieved from such investigations. In this contribution we will discuss some of the most recent and interesting observational developments pertaining to embedded cluster studies and interpret these developments in the context of our current understanding of the nature and evolution of these interesting star clusters.

BACKGROUND

It is useful to begin this discussion by defining what constitutes a stellar cluster. Empirically, a cluster or an association is defined as: *a group of stars of the same physical type whose surface density significantly exceeds that of the field for stars of the same physical type.* Clusters are distinguished from associations by their higher stellar space densities. For the purposes of this paper, we consider clusters to be groups of stars which are physically related and whose observed *stellar* mass volume density would be sufficiently large, if in a state of internal virial equilibrium, to render the group stable against tidal disruption by the galaxy (i.e., $\rho_* \gtrsim 0.1$ $M_\odot pc^{-3}$; Bok 1934) and by passing interstellar clouds ($\rho_* \gtrsim 1.0$ $M_\odot pc^{-3}$; Spitzer 1958). To distinguish clusters from multiple star systems we arbitrarily require that a cluster consist of more than 10 members. Therefore, for this review, we define a stellar cluster as: *a group of 10 or more physically related stars whose stellar mass density exceeds 1* $M_\odot pc^{-3}$. An association, on the other hand, would be defined as a loose group of 10 or more physically related stars whose stellar space density is considerably below the tidal stability limit of 1 $M_\odot pc^{-3}$ (Blaauw 1964). We can characterize clusters by their richness: clusters with 100 or more members we designate as rich and those with less than 100 members as poor. Further, clusters, as defined above, can be classified into two environmental classes depending on their association with interstellar matter. *Embedded clusters* (the subject of this paper) are clusters which are fully or partially embedded in interstellar gas and dust. *Exposed clusters* are clusters with little or no interstellar material within their boundaries. Embedded clusters can also be considered *protoclusters* since upon emergence from a molecular cloud, they will become exposed clusters. Similar classifications can be applied to associations.

Our basic definition of a cluster includes stellar systems of two dynamical types or states. *Bound clusters* are systems whose total energy (kinetic + potential) is negative. When determining the total energy we include contributions from any interstellar material contained within the boundaries of the cluster. *Unbound clusters* have total energies which are positive. That is, unbound clusters are clusters whose space densities exceed 1 $M_\odot pc^{-3}$ but whose internal motions are too large to be gravitationally confined by the stellar and non-stellar material within the boundaries of the cluster. (Again, a similar classification can be applied to associations).

We note that according to our criteria the Hyades stellar system, which has survived as a recognizable stellar group for nearly 7 x 10^8 years would not be considered a cluster but in the present epoch would be classified as an association since its space density is significantly less than 1 $M_\odot pc^{-3}$. On the other hand, NGC 2264, which IRAS observations have shown is a partially embedded system (Margulis, Lada and Young 1989), would be considered a cluster even though it is unlikely to survive to an age of only a few times 10^7 years as a recognizable stellar group after its complete emergence from its parental molecular cloud.

EMBEDDED CLUSTERS: OBSERVATIONAL PROPERTIES

Identification and Membership

Infrared surveys of dark clouds are necessary to reveal embedded clusters, since many if not all members will be heavily obscured. The initial identification of an embedded cluster is typically made by a survey at a single infrared wavelength or color (typically 2.2 μm or K-band). The existence of a cluster is established by an *excess* density of stars of a given type (e.g., bright 2.2 μm sources) over the background. For example, Figure 1 shows the location of K-band infrared sources detected in a systematic survey of the L1630 GMC (Lada(E) *et al.* 1991). About 1,000 sources are present. Their distribution on the sky is not uniform and roughly half the sources are located in four well defined clusters. This is shown in Figure 2 which plots the surface density of infrared sources as a contour map. In this map the second lowest contour corresponds to a source surface density which is ten times that of the background. Here star counts clearly reveal the presence of embedded clusters.

In general, however, the ease of identifying a cluster depends sensitively on the richness of the cluster, the apparent brightness of its members, its angular size or compactness, its location in the galactic plane, and the amount of obscuration in its direction. For example, it would be particularly difficult to recognize a spatially extended, poor cluster of faint stars located in a direction where there is a high background of infrared sources (e.g., l =0.0, b = 0.0).

Identifying the individual members of a cluster is a considerably more difficult task than establishing its existence. In particular, for most clusters, the source density of intrinsically faint members is usually only comparable to, or even significantly less, than that of background/foreground objects. In such circumstances cluster membership can be determined only on a statistical basis

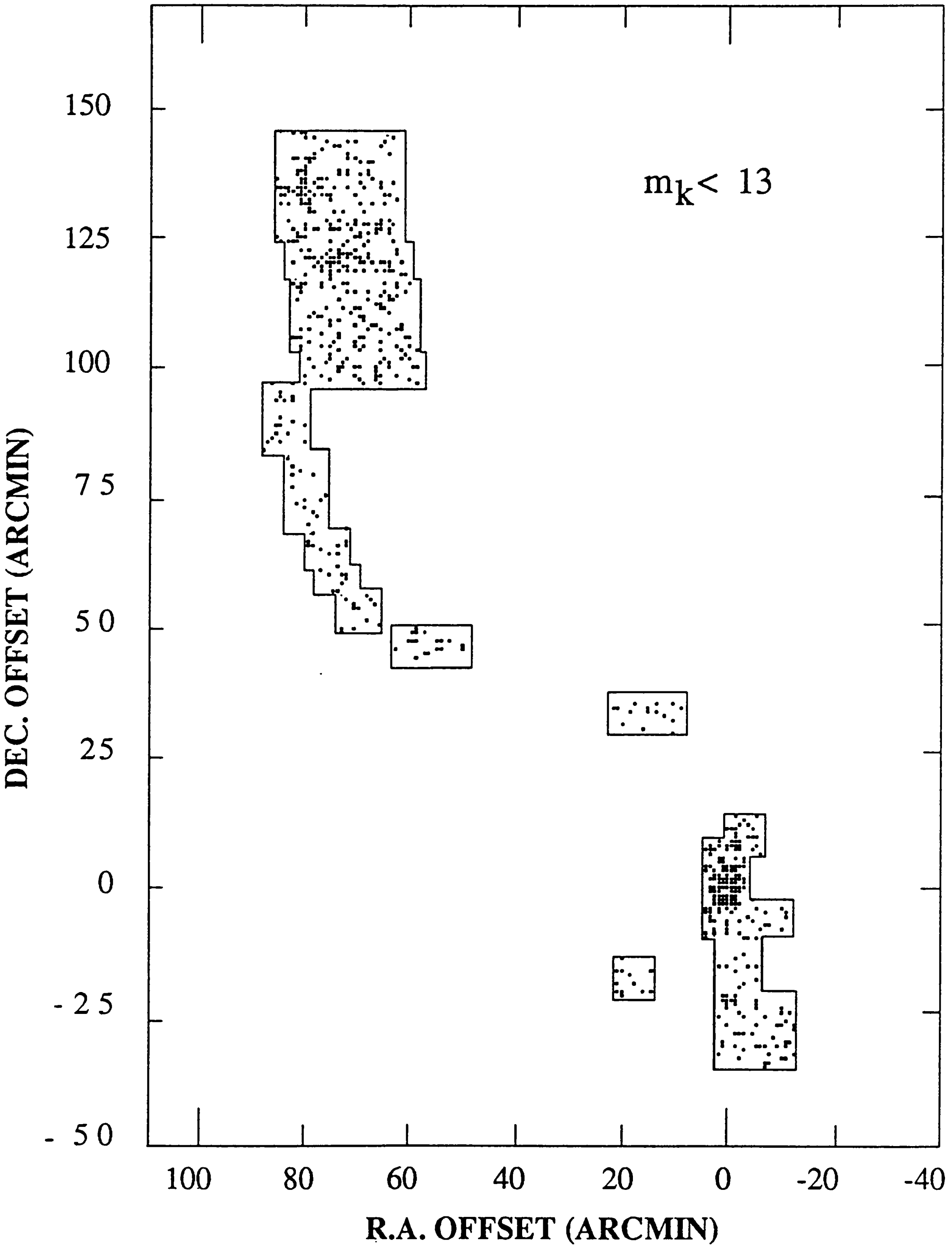

Figure 1. Distribution of 2.2 μm sources (m_K < 13) towards the L1630 Molecular Cloud. The solid lines correspond to the regions surveyed.(From Lada (E) et al. 1991)

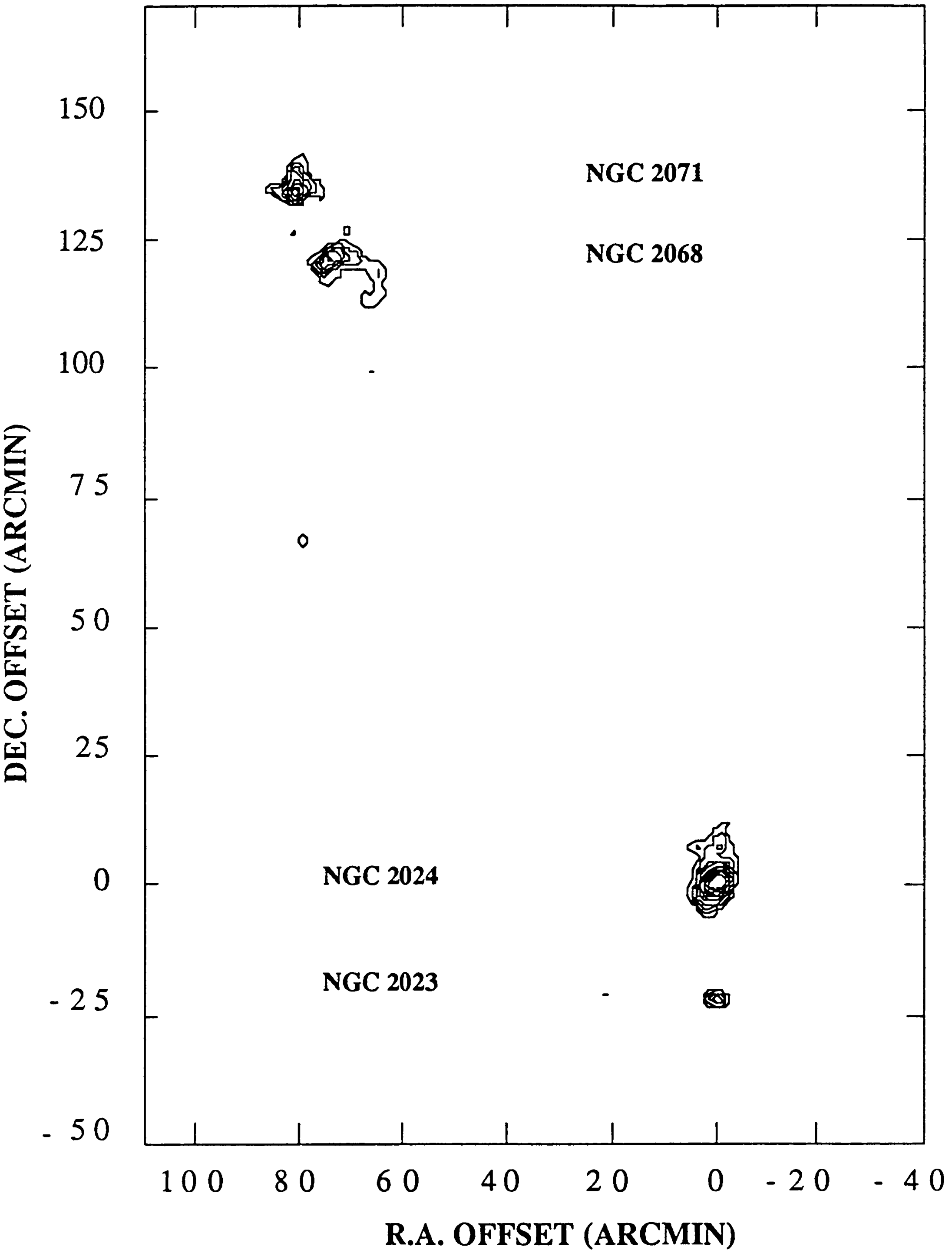

Figure 2. The surface density of 2.2μm sources ($m_K < 12$) towards the L1630 Molecular Cloud is presented in the form of a position-position contour map. The lowest contour level corresponds to 5 times the background/foreground density of stars and subsequent contour levels are multiples of this value. Four embedded clusters were identified by Lada et al. (1991) from this map at 10 times the background/foreground density. These embedded clusters are associated with the well known star forming regions NGC 2071, NGC 2068, NGC 2024 and NGC 2023. (From Lada (E) et al. 1991)

using star counts. Consequently, determining whether or not a specific star in the region is a cluster member or a field star is not possible. In these situations other independent information (e.g., proper motions, spectra, multi-color photometry) is needed to establish the membership of individual sources.

In Figure 3a (top) we show the distribution of bright and faint K-band sources observed by Lada(C) *et al.* (1991) in the direction of M17 where a heavily obscured cluster of OB stars is known to be located (Beetz *et al.* 1976). Within the circle, the surface density of infrared sources was found to be enhanced by a factor of 2 over that of the field, which was determined to be well represented by the rectangular slice of sky at the left edge of the plot. Thus about half the observed sources within the apparent boundaries of the M17 cluster are actually field stars. Determining which half of the stars are members is not possible from the K-band data alone. From multi-color (JHK) photometry, however, individual members can be identified. This is demonstrated in Figure 3b which displays the distribution of stars with excess infrared emission over the entire region. The infrared excess stars are highly spatially clustered, all falling within the cluster boundary determined from star counts. Since there are no field stars observed with infrared excess, each star in this figure is no doubt a member of the cluster.

Number and Distribution

In addition to the well known embedded clusters, such as the Trapezium, NGC 2264, and ρ Ophiuchi, infrared array camera surveys (largely unpublished) have revealed a growing number of such objects in nearby regions (e.g., S255, McCaughrean *et al.* 1991; L1641N Strom, Margulis and Strom 1990). However, the size of the embedded cluster population in the galaxy or even the local solar neighborhood is not known. To directly obtain an accurate census of the number of embedded clusters in a single GMC, let alone the galaxy, is a difficult task. Only recently has the first sensitive, large scale survey for embedded stars in a GMC been performed.

An unbiased census of embedded stars in the L1630 molecular cloud in the Orion complex has been obtained with the aid of an imaging array camera at near-infrared wavelengths (Lada(E) *et al.* 1991). A significant portion of the L1630 cloud was imaged at 2.2μm. Approximately 3000 $1' \times 1'$ fields were observed, covering an area of $\sim$ 0.8 square degrees. The survey was estimated to be complete to a K magnitude of 13 which at the distance to Orion corresponds to a 0.6 $M_\odot$ main sequence dwarf. Therefore the observations were sensitive enough to detect both high and low mass young stellar objects in the cloud and to investigate the clustering properties of these embedded and obscured young sources.

As a result of this survey, four spatially distinct, embedded clusters were identified which satisfy the criteria outlined earlier (Figure 1 and 2). These clusters turn out to be associated with the well known star forming regions, NGC 2071, 2068, 2024 and 2023. The smallest cluster, associated with the reflection nebula NGC 2023, has a radius of 0.3 pc and contains only 21 sources ($m_K < 14$). The largest and most spectacular of the four clusters contains more than 300 objects within a radius of 1.0 pc and is associated with the HII region NGC 2024. Optical images of this region are noted for the presence of a dark, obscuring dust lane. Early infrared studies of the HII region (Grasdalen 1974)

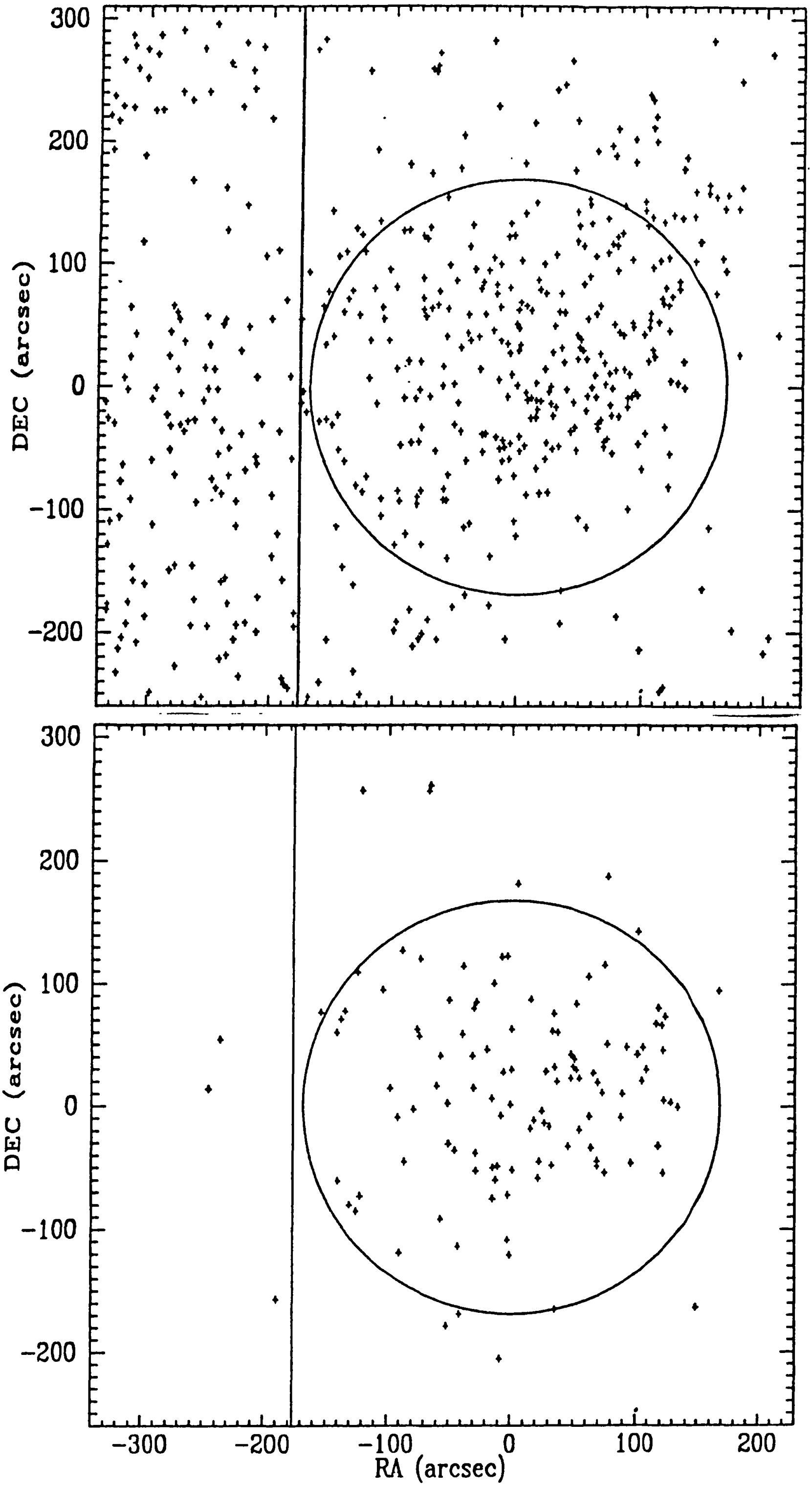

Figure 3. A-Positions of 2.2μm band infrared sources toward M17. The circle indicates the boundary of the cluster determined from star counts. The area to the left of the vertical line has the same area as the cluster and was found to well represent the field star distribution in this direction of the sky. B- Positions of all stars within the region which display significant excess infrared emission. (From Lada(C) et al. 1991).

identified a bright embedded infrared source in the middle of the dust lane. More recently, a survey using a single beam infrared photometer uncovered ~ 30 near infrared sources in this region (Barnes *et al.* 1989). Figure 4 presents K band infrared array camera image of NGC 2024 obtained by Lada (E.) *et al.* (1991). Many new sources are present in this image illustrating the advantage of high resolution imaging techniques.

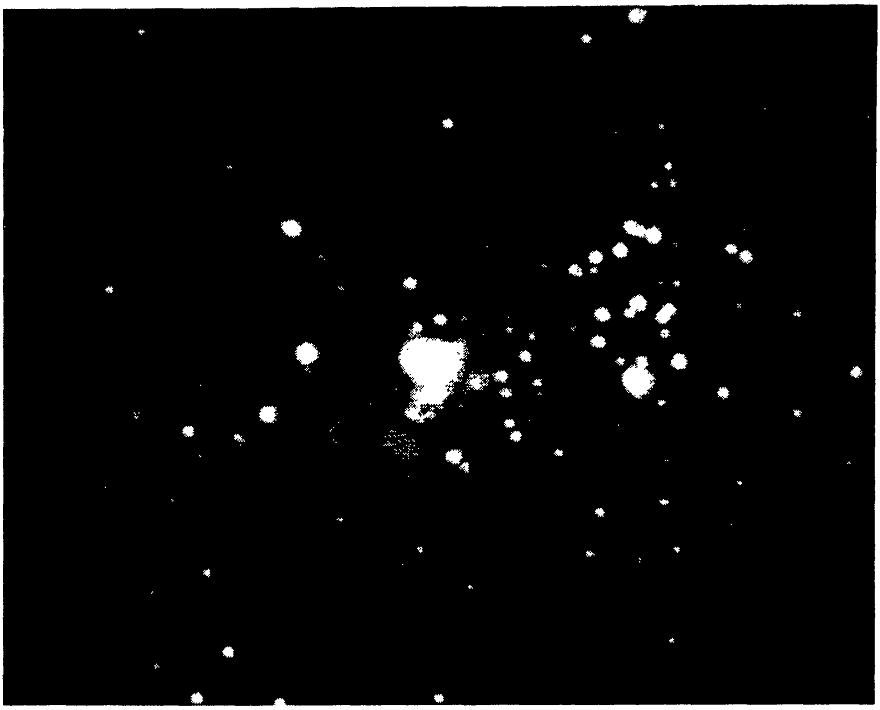

Figure 4. Distributions of the 2.2μm sources in the NGC 2024 embedded cluster. This K-band image (from Lada (E.) et al. 1991) is a mosaic of 64 1′ x 1′ fields. The sensitivity limit of this image is estimated to be $m_K < 14$.

The basic physical properties of the four embedded clusters are summarized in Table 1. All four clusters are centrally condensed. The stellar densities of the clusters are high, ranging from ~ 70 pc^{-3} to ~ 180 pc^{-3} for the regions contained within the cluster boundaries. These densities resemble the stellar densities of other young star forming regions such as the star forming core of the Rho Ophiuchi cloud. (e.g., Wilking and Lada 1983). In addition, two of the infrared clusters, NGC 2071 and NGC 2024, show evidence for spatial magnitude segregation, with the brighter sources displaying a tendency to be more centrally condensed than the fainter sources. This may represent a segregation in mass resulting from either the equipartition of stellar kinetic energies, the initial distribution of the star forming gas or some combination of these.

TABLE 1
Properties of Embedded Clusters

Cluster	# of Sources	Cluster Radius (pc)	Stellar Mass Density ($M_\odot pc^{-3}$)	Total Mass Density ($M_\odot pc^{-3}$)	SFE † %
NGC 2023[1]	21	0.30	185	2800	7
NGC 2071[1]	105	0.59	122	650	20
NGC 2068[1]	192	0.86	72	170	42
NGC 2024[1]	309	0.88	108	260	42
ρ Ophiuchi[2]	94	0.70	124	564	22
Trapezium[3]	142	0.44	1800	?	?

† SFE = M_{stars} / (M_{stars} + M_{gas})
(1) Lada 1990; (2) Wilking, Lada and Young 1989; (3) Herbig and Terndrup 1986

The most striking and surprising result of the 2.2 μm survey is that the vast majority of the detected sources believed to be embedded in the cloud are concentrated in the four well defined clusters. Lada (E.) *et al.* (1991) find that 58% of the objects they detected are contained within the four clusters. However, many of these sources are background/foreground field stars. After correction for the presence of field stars, Lada (E.) *et al.* (1991) estimate that approximately 96% of the total number of sources actually associated with the *entire* molecular cloud are contained within the four clusters! Moreover, the three richest clusters (see Table 1) contain the vast majority of these embedded stars. The total area covered by the four embedded clusters equals only 18% of the total region surveyed. From these results, Lada (E.) *et al.* (1991) conclude that star formation in L1630 is a highly localized process even for stars of low mass. Apparently in the L1630 cloud, the vast majority of stars that have formed in the cloud have formed in three rich embedded clusters. This leads to the astonishing conclusion, that if the L1630 GMC is typical of GMCs in the solar neighborhood, most star formation in GMCs and therefore in the galaxy may likely occur in the environment of dense clusters and not in isolated protostellar systems. Indeed, if we assume that the L1630 cloud is typical of other GMCs in its cluster forming properties, we can estimate the total number of rich embedded clusters, N_{EC}, within 2 kpc of the sun as follows:

$$N_{EC} \approx 3 \text{ x } N_{GMC} \approx 36$$

where N_{GMC} is the number of local GMCs (12; Blitz 1980). For a constant rate of cluster formation, we can predict that the number of visible (exposed) open clusters formed over the last 10^8 years should be:

$$N_{VC} \approx \frac{\tau_{VC}}{\tau_{EC}} \text{x}\ N_{EC} \approx 720$$

where the lifetime of the embedded cluster phase, τ_{EC}, is estimated to be 5 million years (Leisawitz, Bash and Thaddeus 1989). Clusters which reach an age of 10^8 years are most certainly bound since they have survived for a period equal to about ten internal crossing or dynamical times (for a cluster similar in density and size to the Pleiades). However, within 2 kpc of the sun only 94 exposed clusters are observed with ages of 10^8 years or less (Elmegreen and Clemens 1985). The ratio of observed to predicted clusters with ages 10^8 years or less is ≈ 0.13. If L1630 is a typical cloud, one must be able to reconcile its large population of embedded clusters with the observed (relatively small) number of exposed clusters. Evidently, few clusters survive their emergence from molecular clouds as long-lived bound systems, such as the Pleiades. Indeed, many of the catalogued 94 exposed clusters themselves may be unbound, since bound and unbound clusters are hard to distinguish from each other when their ages are shorter than about 10^7 years (Lada, Margulis and Dearborn 1984) and 17 of 94 or 18% of the exposed clusters within 2 kpc have ages that are this young. In this context it is interesting to note that Roberts (1957) estimated that only 10% of all stars born in the galaxy were formed in exposed clusters. This is an order of magnitude lower than the estimate of the fraction of all stars formed in embedded clusters within the L1630 cloud. Is L1630 unusual in its cluster forming properties or do embedded clusters rarely evolve into bound systems after their emergence from a molecular cloud? The key to resolving this basic question involves understanding the nature of one of the most basic properties of embedded clusters: their physical association with interstellar gas and dust.

EMBEDDED CLUSTERS: BASIC PHYSICAL PROPERTIES

Association with Interstellar Gas and Dust

Embedded clusters are distinguished from other types of clusters by their intimate association with the interstellar gas and dust from which they form. Therefore, to fully understand the nature of embedded clusters requires knowledge of *both* their stellar and gaseous contents. In the L1630 GMC an extensive survey for dense molecular gas (Lada, Bally and Stark 1991) has enabled the first systematic investigation of the relationship between dense gas and embedded clusters (Lada 1990). A substantial area of the L1630 cloud, including the regions surveyed at 2.2 μm, was mapped in the 2→1 transition of CS, in order to trace dense ($n > 10^4$ cm^{-3}) gas. The total area covered by the survey was $\sim$ 3.6 square degrees or $\sim$ 20% of the molecular cloud as measured in CO (Maddalena *et al.* 1986). CS emission was detected over $\sim$ 10 % of the area surveyed, revealing very clumpy structures. In fact, forty two individual dense cores were identified. These cores have masses ranging from < 8 M$_\odot$ to 500 M$_\odot$. Most have masses less than 100 M$_\odot$ and only 5 cores have masses greater than 200 M$_\odot$. The distribution of clump masses (for $M > 20$ M$_\odot$) can be described by the powerlaw, $dN/dM \propto M^{-1.6}$, where N equals the number of cores per solar mass interval. The spectral index, α = -1.6 implies that a significant amount of the mass of the dense gas is contained in the most massive cores. Indeed, approximately 50% of the total mass of dense gas in L1630 is contained within the 5 most massive cores. These 5 cores cover a total area of $\sim$ 2 pc^2 or only 1% of the total area surveyed, indicating that the dense gas in the surveyed region is confined to a small area. Moreover, the cores appear to be distributed in groups with the small cores clustered around the most massive ones. This further indicates that the dense gas is highly localized within this cloud.

The CS and 2.2 μm surveys of the L1630 molecular cloud provide the most complete census of dense gas and young stellar objects within a single giant molecular cloud to date. Comparison of these surveys shows that the embedded clusters are coincident or nearly coincident with 4 of the 5 most massive CS cores (Lada 1990). These results are summarized in Figure 5 which displays the locations and extents of the embedded clusters and the dense molecular gas in the L1630 molecular cloud. Apparently, the formation of embedded clusters in L1630 occurs in regions having both high density and substantial gas mass. Further comparison of the stellar and dense gas components of the L1630 embedded clusters, reveals that in all cases the mass of the dense gas associated with (and presumably contained within) an embedded cluster is considerably larger than the total mass of the embedded stars (Table 1).

Another fully embedded cluster for which both the gas and stellar content have been extensively studied is the cluster embedded in the ρ Ophiuchi dark cloud. Molecular line observations towards this cluster reveal the presence of a large centrally condensed core (Wilking and Lada 1983). This core is a region of high visual extinction, with A_V as high as $\sim$ 100 magnitudes (Vrba *et al.* 1975, 1976; Chini *et al.* 1977; Chini 1981; Wilking and Lada 1983). Wilking and Lada (1983) have mapped the core in C^{18}O, which is a good tracer of gas column density. They find the core to be 1 pc x 2 pc in size and to contain $\sim$ 600 $M_\odot$ of gas. Estimates of the star formation efficiency (SFE = $M_{stars}/(M_{stars} + M_{gas})$ of this system produce a SFE $\gtrsim$20% (Wilking and Lada 1983; Wilking, Lada and Young 1989). In this example, as in the L1630 clusters, the stellar mass of the cluster is a small fraction of the mass of the dense molecular core within which it is embedded.

Finally, the close association of the embedded clusters with dense molecular gas indicates the extreme youth of these systems. Consider the extensive study of the relation between exposed clusters and molecular clouds (Leisawitz, Bash and Thaddeus 1989). This important study showed that exposed (open) clusters with ages $\leq$ 5 x 10^6 years were frequently associated with molecular clouds, while clusters with ages larger than 5 x 10^6 years were rarely if ever associated with such clouds. This finding indicates that on average the total duration of formation and emergence of a cluster from a molecular cloud is on the order of 5 million years. Extrapolation of this result to embedded (mostly invisible) clusters strongly suggests that on average their ages are significantly less than 5 million years.

Nature of Embedded Members

Once an embedded cluster is identified additional observations of its members can provide important information concerning the nature of its members and in doing so probe important aspects of the processes of star formation and early stellar evolution. Since embedded clusters are partially or fully embedded within molecular gas and dust, the stars within them are

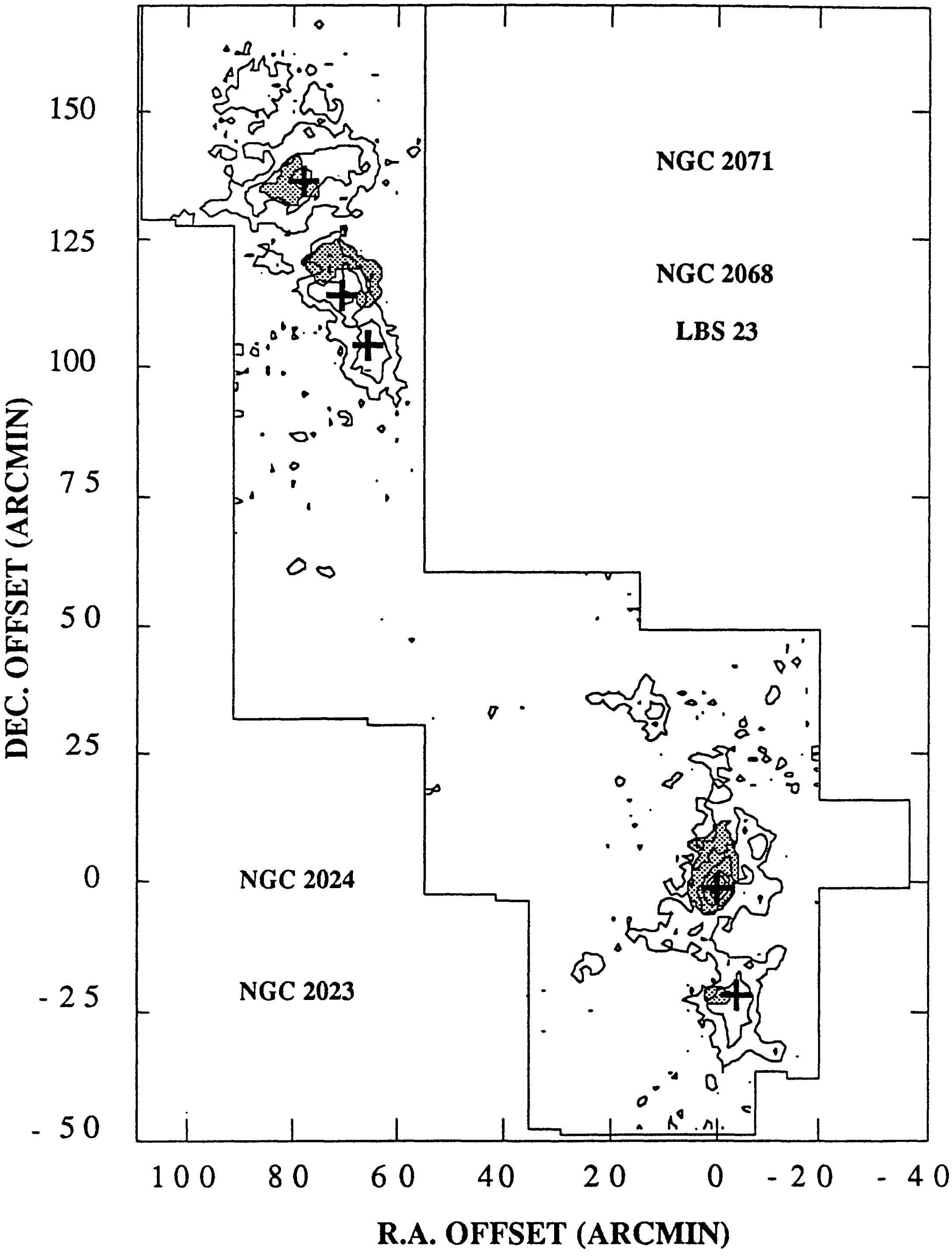

Figure 5. Locations of the embedded stellar clusters and dense cores in the L1630 Molecular Cloud (from E. Lada 1990). The shaded regions represent the location and extent of the embedded clusters. The distribution of dense gas is presented as intensity contours of CS(2→1) emission. In addition, the peak intensity positions of the 5 most massive CS cores (M>200 $M_\odot$) are represented by crosses.

believed to be extremely young. Because these stars are associated with varying amounts of circumstellar gas and dust, they radiate significant portions of their luminous energy in the infrared portion of the spectrum (Lada 1987). Indeed, their emergent infrared energy spectrum (i.e., $Log \lambda F_\lambda$ *vs.* $Log \lambda$) is directly determined by the nature and distribution of the material surrounding them. Observational studies have shown that YSOs can be meaningfully classified into three distinct morphological classes based on the shapes of their broad-band 1-100μm energy distributions (Lada 1987; Adams, Lada and Shu 1987). Class I sources have strong "infrared excess" emission (i.e., their energy distributions are significantly broader than that of a single blackbody) and consequently, their energy distributions are characterized by positive slopes at wavelengths longer than 2 μm. These sources are likely protostellar in nature (Adams, Lada and Shu 1987). Class II sources also have infrared excesses, but their spectral energy distributions are characterized by decreasing slopes at wavelengths longer than 2 μm. When observed at optical wavelengths, class II sources have the emission line characteristics of T Tauri stars and are thought to be associated with disks (Lynden-Bell and Pringle 1974; Rucinski 1985; Adams Lada and Shu 1987; Kenyon and Hartmann 1987; Rydgren and Zak 1987). Class III sources have little or no near-to mid- infrared excess emission and their energy distributions are characterized by reddened blackbody shapes. These sources include young main sequence stars and also younger pre-main sequence stars that no longer have disks such as the so-called naked or weak-lined T Tauri stars (e.g., Walter 1987). These classifications are thought to represent phases of a more or less continuous sequence of early stellar evolution from protostar to young main sequence star (Adams, Lada and Shu 1987).

Observations of the infrared energy distributions of the members of embedded clusters therefore are useful for statistical studies of early stellar evolution and star formation. For example, determining the relative numbers of sources in each class can provide, in principle, information on the age of the cluster, the duration of star formation within the cluster and perhaps even the mass infall rate for its protostellar population (e.g., Wilking, Lada and Young 1989). In addition, the energy distributions of embedded YSOs in clusters can be integrated to determine bolometric luminosities of the sources. For an individual source, uncertainties about detailed source geometry can lead to uncertainties in these luminosity determinations which are on the order of a factor of about 2. However, these uncertainties average out when considering a large number of sources, and the luminosity function determined for a cluster as a whole is likely to be a reasonably accurate representation of the true luminosity function (Wilking, Lada and Young 1989). This is important because such a luminosity function is a *direct* measure of the initial luminosity function (ILF) of the embedded cluster, a crucial parameter in understanding the formation of stars (e.g., Lada and Wilking 1984). Unfortunately, lack of a detailed understanding of protostellar and early stellar evolution precludes the possibility of transforming the observed ILF into the (physically important) initial mass function (IMF). To date, the most detailed determination of an ILF for an embedded cluster is that obtained for the cluster embedded in the dense core of the ρ Ophiuchi dark cloud (Wilking, Lada and Young 1989). Figure 6 shows the luminosity function determined for the cluster. Although, there is marginal evidence for departures in this frequency distribution of source luminosities from that expected for a distribution of stars whose masses are given by the IMF for

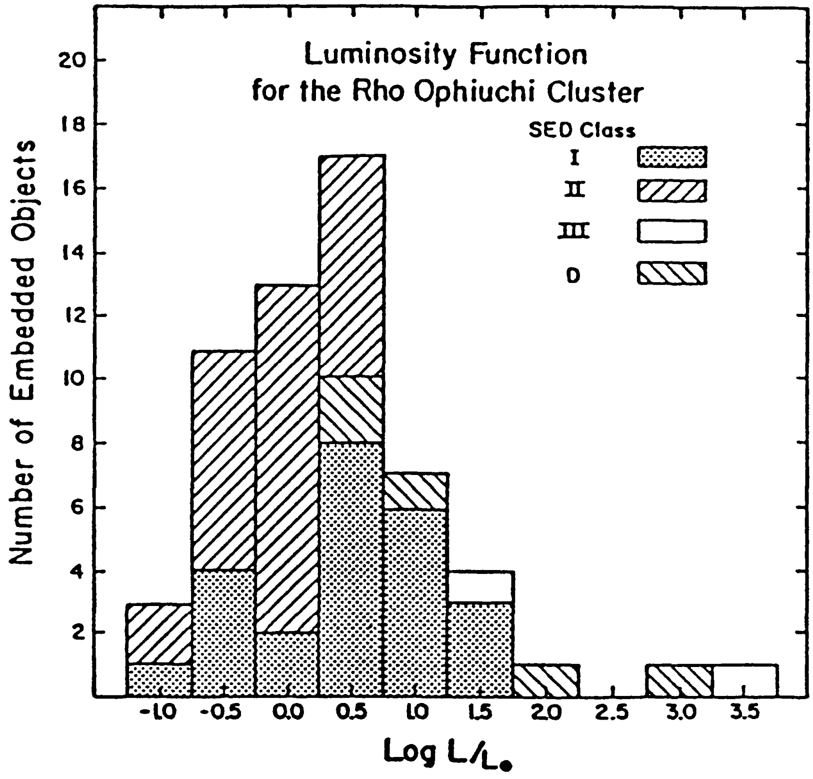

Figure 6. The observed luminosity function of the embedded members of the cluster in the Ophiuchi dark cloud (Wilking, Lada and Young 1989). Class I and II sources are indicated. Class I sources clearly dominate the population for luminous sources while Class II objects dominate the population at low luminosities.

field stars (specifically, there is an apparent deficit of intermediate luminosity objects compared to what is expected from the IMF), the statistical uncertainties due to small numbers and our ignorance of protostellar evolution, make such evidence far from compelling. However, observations and determinations of the luminosity functions of the embedded stars in other clusters and clouds could be very important. In particular, significant differences in observed ILFs could provide direct evidence for cluster-to-cluster variations in the form of the luminosity function and indirectly place constraints on the physics responsible for the origin of the IMF.

Although the luminosity function in the Ophiuchi cluster does not enable strong constraints to be placed on the underlying IMF, it does provide interesting insights to the nature of the embedded sources in the cluster. In particular, as is shown in Figure 6, sources that are more luminous than about 5 $L_\odot$ are almost exclusively Class I objects, while at lower luminosities the bulk of the sources are Class II. This suggests that on average Class I sources are more luminous than Class II sources. If the Class I and II sources in the cluster are progenitors of similar mass stars, then stars likely undergo luminosity evolution as they progress from Class I to Class II. Apparently, sources in the Class I phase have an additional source of luminosity not present in Class II objects. Theory predicts that protostars should be more luminous than T Tauri stars because of the presence of infalling envelopes around protostars that are obviously absent for T Tauri stars. The luminosities of the Class I sources in the Ophiuchi cluster are in fact consistent with those predicted by protostellar theory (Adams, Lada and Shu 1987). Thus the observed luminosity segregation of Class I sources in the luminosity function of the Ophiuchi cluster may provide very strong, although indirect, evidence for a protostellar nature for these objects (Wilking, Lada and Young 1989). In any event observations of embedded stars in this cluster show that it is comprised of stars in the earliest stages of stellar evolution and strongly confirms the notion that embedded clusters are extremely young objects.

FORMATION AND EVOLUTION OF EMBEDDED CLUSTERS

Formation of Embedded Clusters

Star formation occurs in the dense gas of molecular clouds. Therefore one expects that the formation of an embedded cluster is preceded by the formation of a large and massive dense core within a molecular cloud. To understand how an embedded cluster forms we must understand two basic physical processes: 1) the formation of a massive, dense molecular core in a molecular cloud and 2) the subsequent development of stars from the dense gas in the core. To date, we have acquired very little knowledge about the formation process of dense cores, moreover, we do not even understand how molecular clouds themselves form from the interstellar medium. However, recent studies of molecular cloud structure provide valuable information concerning some of the important aspects of embedded cluster formation. For example, the slope of the mass spectrum of dense cores derived from observations of the L1630 cloud indicates that even though low mass cores outnumber high mass cores, most of the mass of dense gas in that cloud is contained within the more massive cores. Indeed, in L1630 the five most massive cores (i.e., $M \gtrsim 200\ M_\odot$) are found to account for at least 50% of the total mass of dense gas in the cloud. Since these massive cores have sizes 1-2 orders of magnitude smaller than that of the GMC itself, and contain a substantial fraction of all the dense gas needed to form stars, we expect that a large fraction of the newly formed stars in the cloud should be found in embedded clusters. Apparently, the observation that the vast majority of star formation in L1630 has occurred in clusters may be explained to a large extent by the fact that most of the dense gas in the cloud is contained within a few localized and massive, dense cores.

The observations of L1630 appear to confirm the notion that stars form almost exclusively in dense gas and that clusters form from massive cores. However, these conditions do not appear to be sufficient for cluster formation. The L1630 cloud was also found to contain a massive, dense core (LBS 23) that is not associated with a recognizable cluster. Moreover, another massive core (NGC 2023) was found to contain only a very poor cluster. In these two massive cores the level of star forming activity is considerably lower than that in the three other comparable mass cores which are producing rich clusters. The lack of a substantial embedded cluster in two of the five massive cores is intriguing, given the levels of star formation in the 3 most active cores in the cloud, which together account for 97% of the embedded sources but only 30% of the dense gas found in the L1630. This is reflected in the derived star formation efficiencies. For example, NGC 2024, NGC 2071 and NGC 2068 cores are associated with rich clusters and have star formation efficiencies on the order of 20-40%. In contrast, LBS 23 and NGC 2023 exhibit SFEs $\sim$ 7%. The vastly different levels of star forming activity in these cores could either be a result of fundamental differences in some basic physical property of the cores (e.g., structure of internal magnetic fields) or to evolutionary effects. Understanding the differences in activity between these cores should have important implications for understanding the process of star formation. However, at the present time the origin of embedded clusters remains a mystery. It is likely that future investigation and comparison of the physical conditions in massive dense cores with and without rich clusters will provide important new insights into the processes of embedded cluster formation and stellar birth.

Dynamical Evolution: Emergence From Molecular Gas

Although the origin of embedded clusters is a complete mystery, the subsequent dynamical evolution of embedded clusters and their emergence from molecular clouds are well posed theoretical problems which have been extensively studied both analytically (e.g, Hills 1980; Mathieu 1983; Elmegreen 1983; Elmegreen and Clemens 1985; Verschueren and David 1989; Verschueren 1990) and numerically (Lada, Margulis and Dearborn 1984). In this section we will briefly summarize the current theoretical understanding of the physics which governs the emergence of clusters from molecular clouds and the formation of bound stellar systems. As discussed earlier, clusters form in dense, massive molecular cloud cores. These systems are strongly gravitationally bound, as can be ascertained from their very high mass densities and moderate internal velocity dispersions (i.e., 2-4 km/s). However, as Table 1 suggests, star formation is relatively inefficient in such systems. In such a circumstance the gravitational glue which binds the system of gas and stars is largely provided by the gas. The stars orbit in a very deep potential well with orbital velocities characteristic of the virial velocities of the dense gaseous core (i.e., $\sigma \approx (G[M_{stars} + M_{gas}]/r)^{0.5}$). As long as the star formation efficiency is not very high, the evolution of the stellar cluster sensitively depends on the evolution of the gas.

Molecular outflows, stellar winds and HII regions from the more massive stars in an embedded cluster can violently disrupt the molecular gas in a dense core on time scales which are shorter than or comparable to the dynamical time of the system. When this occurs the dynamical response of the stars which are left behind will depend primarily on the star formation efficiency achieved in the core at the moment of gas dispersal. The condition for the cluster to remain bound in the face of rapid gas removal is that the escape speed from the cluster, $V_{esc} \approx (2GM/r)^{0.5}$, is less than σ the instantaneous velocity dispersion of embedded cluster stars at the time of gas dispersal. Thus a bound group will emerge only if the star formation efficiency (SFE $= M_{stars}/(M_{gas} + M_{stars})$) is greater than 50%. However, depending on exactly how much residual gas is left after star formation, the cluster could undergo considerable expansion before

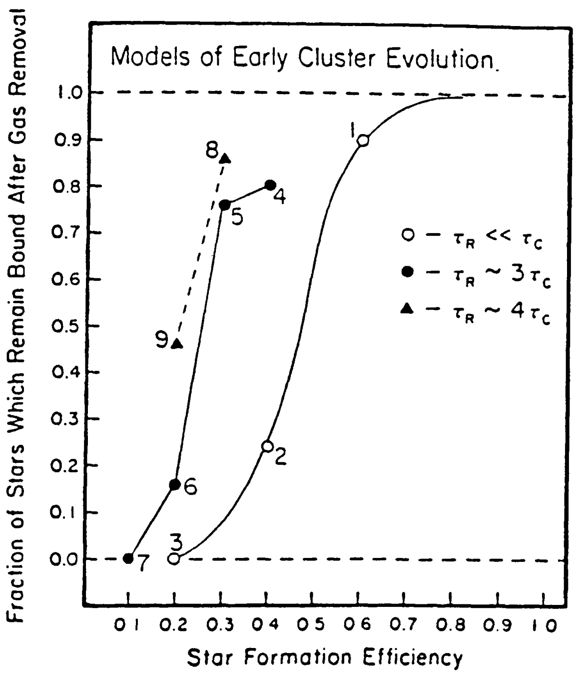

Figure 7. The fraction of stars in an embedded cluster which remain bound after gas removal plotted as a function of star formation efficiency for a series of N-body calculations. (from Lada, Margulis and Dearborn 1984)

revirialization. To date we have no examples of an embedded cluster with an SFE as high as 50%. Typically, embedded clusters are found to be characterized by values of SFE which are less than 50% (e.g., Table 1). Rapid gas dispersal from these systems will lead to the emergence of unbound clusters. Consequently clusters that form O stars are unlikely to evolve into bound exposed clusters, since a single O star can completely disrupt a core within one dynamical time scale.

Yet bound exposed clusters exist in sufficient numbers that at least some must have been formed from protoclusters characterized by SFEs less than 50%. Clusters with efficiencies between 20-50% can evolve into bound groups with more gentle gas dispersal. For long gas removal times clusters even with low SFEs can adiabatically adjust to new states of virial equilibrium and remain bound. However to produce a bound group which is stable against galactic tides and the tidal forces of its parental GMC places severe restrictions on the initial conditions prevailing in the protocluster cloud core and on the nature of the gas disruption (Lada, Margulis and Dearborn 1984). To evolve to bound open clusters, embedded clusters must have gas removal time scales on the order of a few million years. Numerical calculations show that low SFE systems which do evolve to bound clusters undergo significant expansion as they emerge from the cloud and may expand for a long time before they reach a new state of virial equilibrium. Indeed, observationally, the spatial appearances of bound emerging clusters and unbound emerging clusters are indistinguishable for clusters with ages less about 10^7 years. Consequently, it is extremely difficult to determine whether or not a specific young visible cluster will evolve into a bound system from knowledge of its stellar mass density alone. Calculations also indicate that even clusters that can survive as bound systems may lose 10% to 80% of their original members during the expansion phase which accompanies their emergence from a molecular cloud. This is illustrated in Figure 7 which plots the results of N-body calculations for various combinations of cluster SFE and gas removal times and shows the fraction of stars which remain bound as various model clusters emerge from molecular clouds. Clearly to produce a bound cluster from a dense core requires very special initial conditions and constraints on the gas dispersal mechanisms. This must be a rare occurrence. The observed low SFEs of the known embedded clusters can easily account for the dearth of predicted visible (bound) clusters. We expect that most embedded clusters emerge from molecular clouds as unbound clusters. Thus, although most stars may form in rich embedded clusters, these stellar groups evolve to become the cores of unbound associations, not bound open clusters.

CONCLUDING REMARKS

Embedded clusters are important laboratories for the study of star formation and early stellar evolution in our galaxy. The development of infrared array detectors has finally enabled the first systematic investigations of embedded clusters to be made. Initial results of such studies have found embedded clusters to be surprisingly numerous. In the only GMC (L1630) to be thoroughly surveyed to date, four embedded infrared clusters have been discovered buried in the cloud. Moreover, these clusters were found to account for almost all the stars formed so far in the cloud! To the south of L1630 is the well known Orion molecular cloud (L1641). Although it has not yet been systematically imaged at near-infrared wavelengths, existing optical and infrared observations show that this cloud contains the most densely populated young cluster known in the galaxy (i.e., the Trapezium cluster). This partially obscured and embedded cluster accounts for the bulk of all star forming activity so far uncovered throughout the entire cloud (Lada, Strom and Myers 1991). In addition, other embedded or partially embedded clusters also have been identified in the cloud (i.e., NGC 1981, NGC 1977 and L1641N). The extent to which the cluster-rich Orion complex typifies star formation in other clouds is unclear. However, it is possible that most stars in the galaxy were formed in embedded clusters which did not survive their emergence from their molecular clouds as bound systems. If so, the formation of most stars occurred in an environment quite different than that normally assumed in existing theories of star formation (e.g., Shu, Adams and Lizano 1987; Lada and Shu 1990). The extent to which this should alter our current understanding of star formation physics is not known. Clearly, a more thorough census of the population of embedded clusters in the galaxy is desirable. Whether or not embedded clusters turn out to be as numerous as suggested by initial investigations, detailed study of their members and associated molecular cloud cores is extremely important. Such observations will provide crucial information concerning the nature of the star formation process in an environment quite different than that which gives rise to single, isolated stars. Given the observational nature of star formation research, understanding the process of stellar formation in differing astrophysical environments is the only way to obtain fundamental and independent tests of our theories.

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REFERENCES

Adams, F. C., Lada, C. J. and Shu, F. H. 1987 *Ap.J.*, **321**, 788.

Adams,M. T., Strom K. M. and Strom S. E. 1983 *Ap.J.Suppl.*, **53**, 893.

Barnes, P. J., Crutcher, R. M., Bieging, J. H., Storey, J. W. V. and Willner, S. P. 1989 *Ap.J.*, **342**, 883.

Beetz, M. Elsasser, H., Poulakos, C. and Weinberger, R. 1976 *Astr. Ap.*, **50**, 41.

Blaauw, A. 1964 *Ann.Rev.Ast.Ap.*, **2**, 213.

Blitz, L. 1980 *Giant Molecular Clouds in the Galaxy*, ed. P. M. solomon and M. G. Edmunds, (Pergamon Press), pg. 1.

Chini, R. 1981 *Astr. Ap.*, **99**, 346.

Chini, R., Elasasser, H., Hefele, H. and Weinberger, R. 1977 *Astr. Ap.*, **56**, 323.

Elmegreen, B. 1983 *M.N.R.A.S.*, **203**, 1011.

Elmegreen, B. G. and Clemmens, C. 1985 *Ap.J.*, **294**, 523.

Grasdalen, G. 1974 *Ap.J.*, **193**, 373.

Grasdalen, G. L., Strom. K. M. and Strom, S. E. 1973 *Ap.J.(Lett.)*, **184**, L53.

Herbig, G. H. 1960 *Ap.J.*, **131**, 516.

Herbig, G. H. and Terndrup, D. M. 1986 *Ap.J.*, **307**, 609.

Hills J. 1980 *Ap.J.*, **235**, 986.

Kenyon, S. J. and Hartmann, L. W. 1987 *Ap.J.*, **323**, 714.

Lada, C. J. 1987 *I. A. U. Symposium No. 115: Star Forming Regions*, ed. M. Peimbert and J. Jugaku, (Reidel Press), pg. 1.

Lada, C. J. and Elmegreen, B. G. 1979 A.J., **84**, 336.

Lada, C. J. and Wilking, B. A. 1984 *Ap.J.*, **287**, 610.

Lada, C. J., Margulis, M. and Dearborn, D. 1984 *Ap.J.*, **285**, 141.

Lada, C. J. and Shu, F. H. 1990 *Science*, **1111**, 1222.

Lada, C. J., DePoy, D. L., Merrill, M. and Gatley, I. 1991 *Ap.J.*, in press. Lada, E. A. 1990 Ph. D. Thesis, University of Texas at Austin.

Lada, E. A., Bally, J. and Stark, A. A. 1991 *Ap.J.*, in press.

Lada, E. A., DePoy, D. L., Evans, N. J. and Gatley, I. 1991 *Ap.J.*, in press.

Lada, E. A., Strom, K. M., and Myers, P. C. 1991 in *Protostars and Planets III*, eds. J. Lunine and G. Levy, University of Arizona Press, in press.

Leisawitz, D., Bash, F. N. and Thaddeus, P. 1989 *Ap.J.Suppl.*, **70**, 731.

Lynden-Bell, D. and Pringle, J. 1974 *M.N.R.A.S.*, **168**, 603.

Maddalena, R.J., Morris M., Moscowitz, J. and Thaddeus, P. 1986 *Ap.J.*, **303**, 375.

Margulis, M., Lada, C. J. and Young, E. T. 1989 *Ap.J.*, **345**, 906.

Mathieu, R. D. 1983 *Ap.J.(Lett.)*, **267**, 97.

McCaughrean, M., Zinnecker, H., Aspin, C. and McLean I. 1991 Proc. Workshop on *Astophysics with Infared Arrays* ed. R. Elston, in press.

Roberts, M. S. 1957 *Pub.A.S.P.*, **69**, 59.

Rucinski, S. M., 1985 A.J., **90**, 2321.

Rydgren, A. E., and Zak, D. 1987 *Pub.A.S.P.*, **99**, 141.

Salpeter, E. E. 1955 *Ap.J.*, **121**, 161.

Shu, F. H., Adams, F. C. and Lizano, S. 1987 *Ann.Rev.Ast.Ap.*, **25**, 23.

Spitzer, L. 1958 *Ap.J.*, **127**, 17.

Strom, K. M., Margulis, M., and Strom, S. E. 1989 *Ap.J.(Lett.)*, **346** L33.

Verschueren, W. and David, M. 1989 *Astr. Ap.*, **219**, 105.

Verschueren, W. 1990 *Astr. Ap.*, **234**, 156.

Vrba, F. J., Strom, K. M., Strom, S. E. and Grasdalen, G. L. 1975 *Ap.J.*, **197**, 77. Walker, M. F. 1956 *Ap.J.Suppl.*, **2**, 365.

Walter, F. M. 1987 *Pub.A.S.P.*, **99**, 31.

Wilking, B. A. and Lada, C. J. 1983 *Ap.J.*, **274**, 698.

Wilking, B. A., Lada, C. J. and Young, E. T., 1989 *Ap.J.*, **340**, 823.