Part 1

Star Formation

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Observations of Star Formation

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Abstract. Star formation is a continuous ongoing process occurring over the lifetime of our Galaxy and the universe. However understanding how stars form from their pre-natal clouds of gas and dust remains a mystery. During the last two decades we have made remarkable progress toward unraveling this mystery mainly due to advances in observational technology especially at infrared and millimeter wavelengths which allow direct observation of the sites of star birth. Such observations suggest that embedded clusters may be the fundamental units of star formation in molecular clouds. Low star formation efficiency and rapid gas dispersal make these clusters disperse to provide the field star population. Consequently embedded clusters provide important laboratories for investigating fundamental issues of star formation within our Galaxy.

1. Introduction

Stars are the most basic objects in the universe and how stars and subsequently their planets form is one of the most fundamental unsolved mysteries of astrophysics. Unraveling the process of stellar birth is not only of fundamental importance for understanding the origins of stars themselves, but also the origin and evolution of planets, life and even galaxies. For example, stellar formation and evolution are the engines that drive galaxy evolution and any progress toward understanding galaxy formation and evolution will ultimately be tied to our theoretical understanding of the basic physical processes which govern the star formation process.

Our observational understanding of star formation has undergone a radical change over the past 15 years. Two decades ago, we worked toward unraveling the processes of star formation by concentrating our studies on regions and objects that were thought to be the paradigm for the formation of sun-like stars, mainly isolated, low mass molecular cores forming only one or a few low mass stars. Much progress was made in this endeavor both observationally and theoretically and has provided an important foundation for understanding the star forming process. However our focus has dramatically changed. This is mainly due to the discovery of large numbers of embedded clusters by the use of

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infrared array cameras, and the subsequent realization that these young clusters are responsible for a significant fraction of all star formation currently occurring in the Galaxy. Indeed, embedded clusters may be the fundamental units of star formation in giant molecular clouds.

2. The Importance of Embedded Clusters

Observations at infrared wavelengths are necessary to identify embedded clusters because many, if not all, of their members are heavily obscured. The first deeply embedded cluster in a molecular cloud was found almost thirty years ago by near-infrared surveys of the Ophiuchi dark cloud using single channel photometers (Grasdalen, Strom & Strom 1974; Wilking & Lada 1983). However, it was not until near-infrared imaging arrays were available for astronomical use in the late 1980s, that large numbers of embedded clusters were discovered and studied. Searches of the astronomical literature over this time period by Lada & Lada (2003) and by Porras et al. (2003) have revealed that well over a hundred such clusters have been found both nearby the Sun (e.g., Eiroa & Casali 1992) and at the distant reaches of the galaxy (e.g., Santos et al. 2000). To date, embedded clusters have been discovered using three basic observational approaches: 1) case studies of individual star forming regions, such as for example, NGC 281 (Megeath & Wilson 1997), NGC 2282 (Horner, Lada & Lada 1997), Orion (McCaughrean & Stauffer 1994), W49A (Alves & Homeier 2003), and NGC 2316 (Teixeira et al. 2003); 2) systematic surveys of various signposts of star formation, such as outflows (Hodapp 1994), luminous IRAS sources (e.g., Carpenter et al. 1993), and Herbig AeBe stars (Testi, Natta & Palla 1998); and 3) systematic surveys of individual molecular cloud complexes (e.g., Lada et al. 1991b; Carpenter Snell & Schloerb 1995; Phelps & Lada 1997; Carpenter, Heyer & Snell 2000; Carpenter 2000). In the past, most known embedded clusters have been found in surveys of star formation signposts (2), in particular Hodapp (1994) was particularly successful at finding embedded clusters. Surveys conducted using the data generated by the all sky near-infrared surveys (i.e., DENIS and 2MASS) will likely provide the the most systematic and complete inventory of the embedded cluster population of the Galaxy. Indeed very recent work by Bica et al. (2003) and Dutra et al (2003) using the 2MASS database has increased the number of known embedded clusters by more than 50%.

While the discovery of such large numbers of embedded clusters has emphasized their importance for understanding Galactic star formation, it does not allow us to estimate the actual fraction of stars born in embedded clusters. This is best derived from systematic, large scale surveys of individual giant molecular clouds. The first systematic attempt to obtain an inventory of high and low mass YSOs in a single GMC was made by Lada et al. (1991b) who performed an extensive near-infrared imaging survey of the central regions ($\sim$1 square degree) of the L1630 GMC in Orion. Their survey produced the unexpected result that the vast majority (60-90%) of the YSOs and star formation in that cloud occurred within a few (3) rich clusters, with little activity in the vast molecular cloud regions outside these clusters. A subsequent survey by Carpenter (2000) using the 2MASS database to investigate the distribution of young stars in 4 nearby molecular clouds, including L1630, produced similar results with estimates of

50-100% of the clouds' embedded populations being confined to embedded clusters. In both studies the lower limits were derived with no correction for field star contamination, which is substantial. Consequently, it is likely that the fraction of stars formed in clusters is very high (70-90%). Subsequent near-infrared surveys of L1630 (Li, Evans & Lada 1997), as well as other molecular clouds such as Mon OB1 (Lada, Young & Greene 1993), the Rosette (Phelps & Lada 1997), Gem OB1 (Carpenter, Snell & Schloerb 1995) and W49 GMC (Alves & Homeier 2003), have yielded similar findings suggesting that formation in clusters may be the dominant mode of formation for stars of all masses in GMCs and that embedded clusters may be the fundamental units of star formation in GMCs. Since GMCs account for almost all star formation in the Galaxy, most field stars in the Galactic disk may also have originated in embedded clusters.

3. Global Properties of Embedded Clusters

Since clusters now appear to be the fundamental unit of star formation rather than individual stars, it is important to study the integrated or ensemble properties of young clusters in order to understand how star formation proceeds on the Galactic scale. Determining quantities such as the embedded cluster mass function, cluster birthrate and global star formation efficiency allow us to investigate the origin and evolution of clusters and hence lay a foundation for understanding galaxy evolution.

3.1. Embedded Cluster Mass Function

Lada & Lada (2003) derived an embedded cluster mass distribution function (ECMDF) using their embedded cluster catalog compiled from the literature and including clusters having more than 35 stars and at a distance less than 2.4 kpc (Figure 1). Their derived mass distribution function reveals two potentially significant features. First, the function is relatively flat over a range spanning at least an order of magnitude in cluster mass (i.e., $50 \leq M_{ec} \leq 1000$ $M_\odot$). This indicates that, even though rare, 1000 $M_\odot$ clusters contribute a significant fraction of the total stellar mass, the same as for the more numerous 50–100 $M_\odot$ clusters. Moreover, more than 90% of the stars in clusters are found in clusters with masses in excess of 50 $M_\odot$ corresponding to populations in excess of 100 members. A similar result has been reported by Porras et al. (2003), who find that although the majority of clusters in their catalog are small with fewer than 30 members, most stars ($\sim$ 80%) form in clusters having $>$ 100 members. The flat mass distribution corresponds to an embedded cluster mass spectrum (dN/dM_{ec}) with a spectral index of -2 over the same range. This value is quite similar to the spectral index (-1.7) typically derived for the mass spectrum of dense molecular cloud cores (e.g. Lada, Bally & Stark, 1991). The fact that the embedded cluster mass spectrum closely resembles that of dense cloud cores is very interesting and perhaps suggests that a uniform star formation efficiency characterizes most cluster forming dense cores. The index for the mass spectrum of embedded clusters is also essentially the same as that (-1.5 to -2) of classical open clusters (e.g., van den Berg & Lafontaine 1984; Elmegreen & Efremov 1997).

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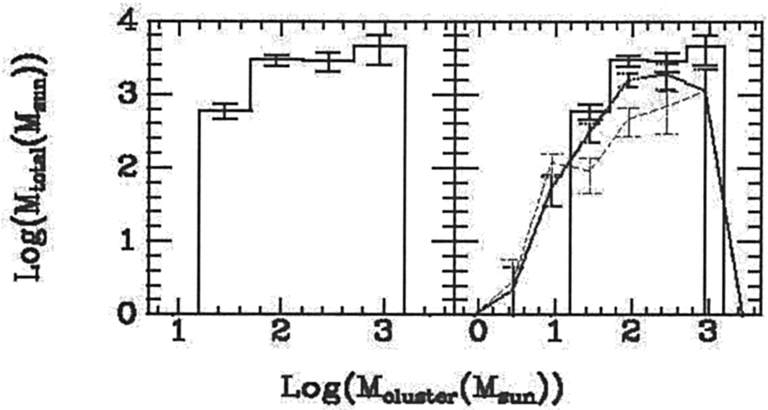

Figure 1. The embedded cluster mass distribution function (ECMDF) from Lada & Lada (2003). On the left the ECMDF is plotted for clusters with N>35 stars and located within $2kpc$ from the entire LL catalog. The right panel compares the ECMDF with those derived for two cluster subsamples which are believed to be more complete at the lowest masses. The dotted line is the Hodapp outflow sample and the dashed line the sample of all known embedded clusters within 500 pc of the Sun. The ECMDFs all appear to decline below 50 $M_\odot$.

The second important feature in the ECMDF is the apparent drop off in the lowest mass bin ($\sim$ 20-50 $M_\odot$). Given that the Lada & Lada cluster catalog only included clusters with more than 35 stars, it is likely that it is considerably more incomplete for clusters in the 20 to 50 $M_\odot$ range than for the higher mass clusters. To test the significance of this fall off to low cluster masses they also derived the mass distribution functions for subsets of clusters drawn from 3 homogeneous samples and from this analysis concluded that the drop off in the ECMDF at masses less than 50$M_\odot$ is significant. Apparently, there appears to be a characteristic cluster mass (50 $M_\odot$) above which the bulk of the star forming activity in clusters is occurring.

3.2. Cluster Birthrate

Early estimates of the embedded cluster birthrate, based primarily on the number of clusters in the Orion cloud complex, found the rate to be extremely high compared to the birthrate of classical open clusters, suggesting that only a small fraction of embedded clusters survived emergence from molecular clouds to become classical open clusters (Lada & Lada 1991). Using their more extensive embedded cluster catalog, Lada & Lada (2003) estimate a lower limit of the formation rate for clusters within 2kpc to be between 2-4 clusters Myr^{-1} kpc^{-2} for assumed average embedded cluster ages of 2 and 1 Myrs, respectively. Although this rate is a lower limit, it is a factor of 8–17 times that (0.25 Myr^{-1} kpc^{-2}) estimated for classical open clusters by Elmegreen & Clemens (1985) and 5-9 times that (0.45 Myr^{-1} kpc^{-2}) estimated by Battinelli & Capuzzo-Dolcetta

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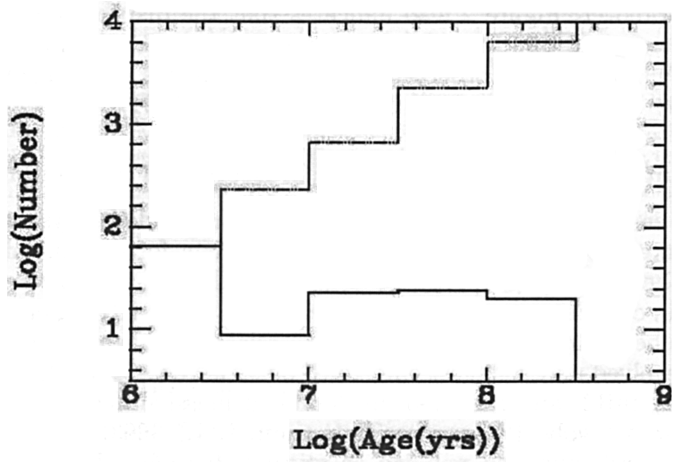

Figure 2. Observed frequency distribution of ages for open and embedded clusters within 2 Kpc of the Sun (solid line) compared to that (dotted line) predicted for a constant rate of star formation adjusted for cluster luminosity evolution. All embedded clusters fall into the first bin. The large discrepancy between the predicted and observed numbers indicates a high infant mortality rate for protoclusters. Taken from Lada & Lada (2003)

(1991) for a more complete open cluster sample within 2 kpc of the Sun. This difference in birthrates between embedded and open clusters represents an enormous discrepancy and is of fundamental significance for understanding cluster formation and evolution.

Figure 2 shows the observed distribution of ages of all known clusters both embedded and open within 2 kpc, produced from the combined catalogs of Lada & Lada (2003) and Battinelli & Capuzzo-Dolcetta (1991). Embedded clusters populate the lowest age bin. The number of clusters is found to be roughly constant as a function of age for at least 100 Myr. Also plotted in this figure is the predicted cluster age distribution, assuming a constant rate of star formation and adjusting for cluster luminosity evolution. There is a large and increasing discrepancy between the expected and observed numbers. These distributions clearly confirm earlier speculations that the vast majority of embedded clusters do not survive emergence from molecular clouds as identifiable systems for periods even as long as 10 Myr. *Figure 2 suggests an extremely high infant mortality rate for clusters.*

Less than $\sim$ 4–7% of the clusters formed in molecular clouds are able to reach ages beyond 100 Myr in the solar neighborhood, less than 10% survive longer than 10 Myr. Indeed, most clusters may dissolve well before they reach an age of 10 Myr. It is likely that only the most massive clusters are candidates for long term survival. Roughly 7% of embedded clusters in the Lada & Lada (2003) catalog have masses in excess of 500 $M_{\odot}$, and this likely represents a lower limit to the mass of an embedded cluster that can evolve to a Pleiades-like system. Moreover, Figure 2 also indicates that the disruption rate for bound clusters between 10–100 Myrs of age is significant, probably due to encounters with GMCs. Many of the observed open clusters in this age range may also not be presently bound (Battinelli & Capuzzo-Dolcetta 1991).

3.3. Relation Between Embedded Clusters and Molecular Gas

A defining characteristic of embedded clusters is their close physical association with the interstellar gas and dust from which they form. Embedded clusters can either be partially (i.e., $A_V \sim$ 1–5 mag.) or deeply (i.e., $A_V \sim$ 5–100 mag.) immersed in cold dense molecular material or hot dusty HII regions. The degree of their embeddedness in molecular gas is related to their evolutionary state. The least evolved and youngest embedded clusters (e.g., NGC 2024, NGC 1333, Ophiuchi, MonR2, and Serpens) are found in massive dense molecular cores, while the most evolved (e.g., the Trapezium, NGC 3603, IC 348) are within HII regions and reflection nebulae or at the edge of molecular clouds. Our current understanding of the relationship between embedded clusters and the cores from which they form is largely a result of studies of clouds such as L1630 (Orion B), Gem OB1 and the Rosette (Mon OB2), for which the most systematic and complete surveys for both embedded clusters and dense molecular material exist (Lada 1992; Carpenter, Snell & Schloerb 1996; Phelps and Lada 1997). These studies all show that embedded clusters are physically associated with the most massive (100–1000 $M_\odot$) and dense ($n(H_2) \sim 10^{4-5}$ cm^{-3}) cores within the clouds. These cores have sizes (diameters) typically on the order of 0.5-1 pc. The typical star formation efficiencies range between 10-30% for these systems. The gas densities correspond to mass densities of 10^{3-4} $M_\odot$ pc^{-3}, suggesting that clusters with central densities of a few times 10^3 $M_\odot$ pc^{-3} can readily form from them.

Typically less than 10% of the area and mass of a GMC is in the form of dense gas. This gas is non-uniformly distributed through the cloud within numerous discrete and localized cores. These cores range in size from about 0.1 - 2 pc and in mass from a few solar masses up to a thousand solar masses. The largest cores are highly localized and occupy only a very small fraction (a few %) of the area of a GMC. Numerous studies have indicated that the mass spectrum ($\frac{dN}{dm}$) of dense molecular cloud cores is a power-law with an index of $\alpha \sim$ -1.7 (e.g, Lada, Bally & Stark 1991, Blitz 1993, Kramer et al. 1998). For such a power-law index, most of the mass of dense gas in a cloud will be found in its most massive cores, even though low mass cores outnumber high mass cores. Stars form in dense gas and it is not surprising, therefore, that a high fraction of all stars form in highly localized rich clusters, since most of a cloud's dense gas is contained in its localized massive cores. Moreover, as discussed earlier, the mass spectrum of cores is very similar to that of both embedded and classical open clusters.

The star formation efficiency, defined as, SFE = $M_{stars}/(M_{gas} + M_{stars})$, is a fundamental parameter of both the star and cluster formation processes. Since the measurement of the SFE requires a reliable and systematic determination of *both* the gaseous and stellar mass within a core, accurate estimates of the SFE are only available for a small number of cluster forming regions. Existing estimates of the SFEs for embedded clusters range from approximately 10-30%

(Lada & Lada 2003; 1992; Lada 1992) and are significantly higher than the global SFEs estimated for entire GMCs, which are typically only 1-5 % (e.g., Duerr, Imhoff & Lada 1982). The clusters exhibiting the lowest SFEs appear to be among the youngest clusters, as indicated by their comparatively high fraction of near-infrared excess sources, outflows and association with high extinction and nebulosity. This suggests that the SFE of a cluster may increase with time and reach a maximum value of typically 30% by the time the cluster emerges from its parental cloud core. Whether all clusters can reach SFEs as high as 30% before emerging from a molecular cloud is unclear, however, it does seem apparent that clusters rarely achieve SFEs much in excess of 30% before emerging from molecular clouds.

3.4. The Fate of Embedded Clusters

The evolution of embedded clusters as they emerge from their parent molecular clouds has been well studied theoretically, both by analytical (e.g., Hills 1980; Elmegreen 1983; Verschueren & David 1989) and numerical (Lada, Margulis & Dearborn 1984; Goodwin 1997; Geyer & Burkert 2001; Kroupa, Aarseth & Huley 2001; Kroupa & Boily 2002) methods and has been shown to sensitively depend on the evolution of the gas from which the clusters form. Embedded clusters form in dense, massive molecular cloud cores, and as such are strongly gravitationally bound systems. However, the star forming efficiencies of these systems are low ($< 30\%$) and the gravitational binding energy is mostly provided by the gas. Consequently, the fate of an emerging embedded cluster critically depends on how quickly the gas is removed from the cluster or the gas dispersion timescale.

The timescale for gas removal is even less well constrained by empirical data than the SFE. If the gas is removed quickly, on timescales shorter than or comparable to the dynamical time of the system, then a cluster will remain bound only if the stars contain more than 50% of the original mass of the system (Wilking & Lada 1983). Mechanisms such as the formation of O stars or outflows from a population of low mass stars (e.g. Matzner & Mckee 2000) are both capable of disrupting molecular cloud cores on such short timescales. Consequently, the fact that the SFEs of embedded clusters are always observed to be less than 50% is critically important for understanding their dynamical evolution. Apparently, it is very difficult for embedded clusters to evolve to bound open clusters, particularly if they form with O stars.

The observed low SFEs for embedded clusters can account for the high infant mortality rate of clusters inferred from the relatively large numbers and high birthrates of embedded clusters compared to classical open clusters. Most ($\sim$ 90-95%) embedded clusters must emerge from molecular clouds as unbound systems. Only the most massive ($M_{EC} > 500$ $M_\odot$) embedded clusters survive emergence from molecular clouds to become open clusters. Thus, although most stars form in embedded clusters, these stellar systems evolve to become the members of unbound associations, not bound clusters. However, bound classical clusters form at a sufficiently high rate that on average, each OB association (and GMC complex) probably produces one such system (Elmegreen & Clemens 1985) accounting for about 10% of all stars formed within the Galaxy (Roberts 1957; Adams & Myers 2001).

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4. Role of Embedded Clusters in Understanding Star and Planet Formation

If embedded clusters are indeed the fundamental units of star formation in the Galaxy, then the properties of the stars within such clusters should determine the properties of the field stars in the Galaxy as a whole. Embedded clusters individually and collectively contain statistically significant numbers (hundreds) of young stellar objects (YSOs), providing a meaningful sampling of essentially the entire stellar mass function. Clusters can be characterized by the mean age of all its members, which statistically is a reliable indicator of age, and a sample of clusters can be observed which span a significantly wider range of age than is typical of stars formed in any individual star-forming region. Consequently, embedded clusters provide important laboratories for determining the initial mass function (IMF), binarity, origin of brown dwarfs, the origin and evolution of circumstellar disks and the likelihood of planet formation. There is not enough space to discuss each of these issues here and the reader is referred to the review by Lada & Lada (2003). Here we will discuss the role that embedded clusters play in determining the frequency and evolution of circumstellar disks and the implications for planet formation.

4.1. Protoplanetary, Circumstellar Disks

Knowledge of the frequency distribution of circumstellar disks in clusters is key to understanding the processes involved in the formation and evolution of circumstellar disks and any planetary systems. For example, in the youngest embedded clusters, determination of the disk frequency is a measure of the probability of disk formation around newly formed stars. In addition, the investigation of the variation of disk frequency with cluster age, provides a direct measure of the lifetimes of circumstellar disks and hence the duration for planet building.

Recently, Haisch, Lada, & Lada (2001) performed the first systematic and homogeneous observational survey for circumstellar disks in young clusters. They used JHKL imaging observations to determine the circumstellar disk frequencies in six clusters whose ages ranged from 0.2 - 30 Myr. These observations reveal that clusters are characterized by a very high initial disk frequency ($\geq$ 80%) which then sharply decreases with cluster age (Figure 3). Half the disks in a cluster population are lost in only about 3 Myr, and the timescale for essentially all the stars to lose their disks appears to be about 6 Myrs (Haisch, Lada, & Lada 2001; hereafter HLL01). Such short disk lifetimes, combined with the fact that many of the extrasolar planets discovered to date are in very close proximity to their central stars as a result of migration (e.g., Marcy & Butler 1999), would appear to support models which can accommodate rapid planetary formation (e.g., Boss 1998, 2000). Near-infrared observations, however, only probe the *inner* disk ($\lesssim$ 0.25 AU) via reflected light or hot (900K) dust emission. The lifetime for the *outer* disk regions ($\gtrsim$ 1 AU), which contain the bulk of the mass available to form planets, may be different from that for the inner disk. For example, if disks evolve large inner holes as they age, then circumstellar disk lifetimes determined from NIR observations, which are sensitive to the inner portions of the disk, could be much shorter than those derived from observations of the outer disk. If the outer disk is not coupled to the inner disk

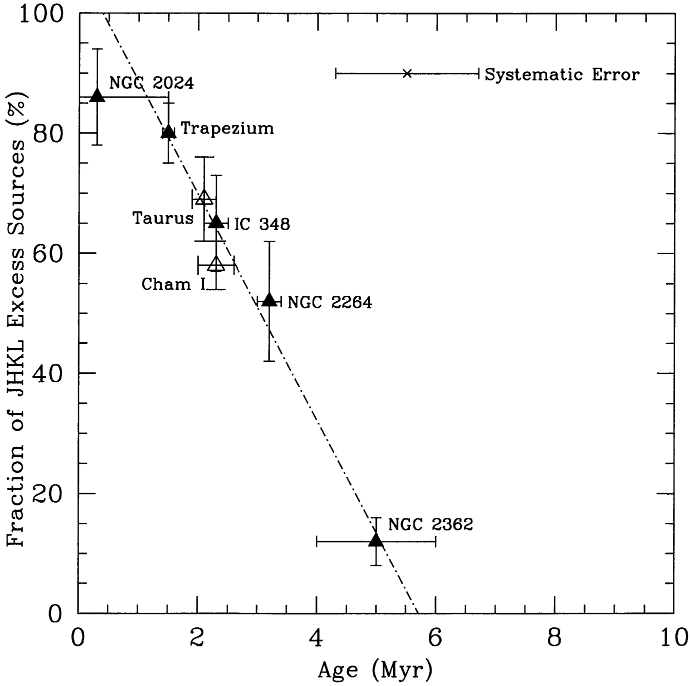

Figure 3. Disk Fraction as a function of cluster age for a sample of young clusters with consistently determined mean ages. The disk fraction is initially very high, but then rapidly drops with cluster age, suggesting maximum disk lifetimes of less than 6 Myrs in young clusters (Haisch et al. 2001)

and its lifetime is longer than that which we measure for the inner disk, models which predict a longer giant planet formation timescale could be accommodated (Thi et al. 2001; Lissauer 2001)

Millimeter wavelength observations provide direct probes of the masses and lifetimes of circumstellar disks in regions of the disks which are of interest for planet formation. Such observations trace the emission from cool dust which traces the bulk mass in the disk systems (Beckwith & Sargent 1993; Beckwith 1999). The unprecedented sensitivity and spatial resolution of existing large, millimeter-wave telescopes and sensitive bolometers allows the detection of thermal emission from circumstellar disks with total masses equal to that of Jupiter (or less under ideal observing conditions). Hence, it is only at millimeter wavelengths that the masses and planet forming capabilities of the putative disk systems can really be assessed. To date, the most comprehensive millimeter continuum surveys for circumstellar disks have been conducted at 1.3 millimeters in the closest ($<$ 150pc) star forming regions such as Taurus (Beckwith et al. 1990; Osterloh & Beckwith 1995) and ρ Oph (André & Montmerle 1994). These studies have shown that a large fraction of stars in these nearby regions have

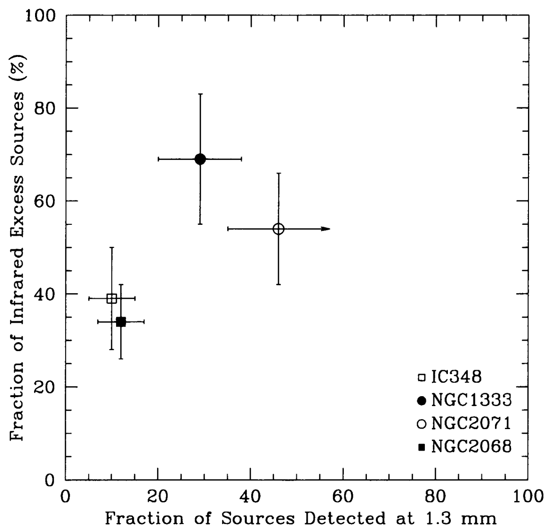

Figure 4. Disk Fraction as a function of cluster age for a sample of young clusters with consistently determined mean ages. The disk fraction is initially very high, but then rapidly drops with cluster age suggesting maximum disk lifetimes of less than 6 Myrs in young clusters (Haisch et al. 2001)

disks massive enough to form planets. Only a few attempts have been made to survey young rich clusters, other than ρ Oph, at millimeter wavelengths with sensitivities sufficient to detect circumstellar disks capable of forming planets. For example the very young Trapezium cluster has been surveyed at $\sim$ 3 mm with both the BIMA (Mundy, Looney, & Lada 1995) and OVRO (Bally et al. 1998) interferometers. Neither study detected any massive disks greater than 0.015 $M_\odot$. IRAM interferometer continuum observations (Lada et al. 2000; Lada 1998)) obtained at 1.3 and 2.7 mm of this cluster reveal emission from $\sim$ 10% of the NIR sources in the fields observed. The masses for these circumstellar disks are estimated to be only $\sim$ 0.01 $M_\odot$. In addition, Carpenter (2002) surveyed 95 stars in the 2.3 Myr old, IC 348 cluster in 3 mm continuum using the OVRO interferometer. Again no massive disks were detected. Taken at face value, these results could imply that it is very difficult to form massive, planet forming disks in clusters or alternatively that disks are quickly destroyed in such environments.

Lada & Haisch (2003) have carried out a sensitive, systematic 1.3 mm continuum survey of four embedded clusters; NGC 1333, NGC 2071, NGC 2068 and IC 348. Figure 4 summarizes their results. The high occurrence of massive outer disks in the NGC 1333 and NGC 2071 clusters implies that these disks are common in young clusters. However, there is a clear variation in the outer disk fraction among the clusters studied. Comparison of their observations with near-IR observations of the same clusters reveal that the variation in the fraction of detected millimeter sources from cluster to cluster is similar to the variation in the fraction of near-IR excess sources for these clusters. This implies that the inner disk and the outer disk are coupled and indicates that the decrease in the outer disk fraction is a result of evolution. Further, the very low occurrence of massive disks in the IC 348 cluster strongly suggests that the outer disks in this cluster dissipate in less than 3 million years.

The short disk evolution timescales ($<$ 3–6 Myr) suggested by both the millimeter and near-infrared observations discussed above, place important constraints on the timescale for building gas giant planets in cluster environments. Typical timescales derived from the accepted model of planet formation, the core accretion model are roughly 10 Myrs or greater depending on the mass accretion rate of solid material, the disk surface density of solid material and atmospheric dust abundance (Bodenheimer, Hubickyj & Lissauer 2002; Lissauer 2001). It may be very difficult to both build and then migrate planets (Lin, Bodenheimer, & Richardson 1996) on such short timescales with standard core accretion models, if the gas depletion time scale is as short. Indeed, evidence of short gas dissipation times may be indicated from studies of CO fundamental emission in the inner disks of young low mass stars (Najita 2003). The disk lifetimes measured would be sufficient for giant planets to form via models of Boss (1998, 2000) which invoke gravitational instabilities within relatively massive ($M_{disk} \sim 0.1\ M_\odot$ within a radius of 20 AU) protoplanetary disks to form giant planets. These models can produce giant planets on a much shorter ($\sim 10^3$ yr) timescale. However, more theoretical investigation is required to determine whether such models are really viable (Boss 2000).

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