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Observations of Protobinary Systems

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Abstract. High resolution images at millimeter wavelengths are providing new insights into the formation of binary and multiple star systems. These wavelengths are particularly useful in studying the earliest stages of multiplicity because they trace the bulk material distribution in the circumstellar environment and can penetrate 1000's of magnitudes of visual extinction. Current millimeter wavelength observations are finding a high incidence of multiplicity among young systems and that multiplicity begins at birth, or before. While the statistics are poor, the types of systems found (independent envelope, common envelope, and common disk systems) follow theoretical ideas about binary and multiple star formation. Systems can be identified which exhibit the characteristics of prompt initial collapse, central fragmentation during collapse, and fragmentation in high angular momentum scenarios. Expansion of this work to more systems and to more detailed studies of the structure and kinematics of individual systems will provide valuable insights into the formation of multiple systems.

1. Introduction

Multiplicity begins early in the history of stellar systems. This is evident from pre-main sequence stars in Taurus and other young regions which show multiplicity fractions as high or higher than main sequence systems (Simon et al. 1992; Ghez et al. 1997; Patience et al. 1998). In fact, a number of the long studied "classic" young stellar systems in Taurus such as T Tauri, GG Tau, and L1551 IRS5 are multiple systems. The question is how and when does this multiplicity begin?

Millimeter and submillimeter wavelengths provide a window into the early stages of stellar formation. Observations at these wavelengths provide an opportunity to see the formation of multiplicity because the early stages of star formation occur deep within molecular cloud cores where the extinction is 10's

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to 1000's of visual magnitudes. Optical observations can typically penetrate extinctions of 5 to 10 magnitudes, corresponding to column densities of around 0.03 gm cm^{-2}; near infrared observations can penetrate to visual extinctions of 15 to 30 magnitudes corresponding to around 0.1 gm cm^{-2}. On the other hand, dust continuum observations at millimeter and submillimeter can probe column densities from 0.1 gm cm^{-2} to 100's of gm cm^{-2}. For typical dust opacities, an optical depth of unity at a frequency of 230 GHz occurs at a visual extinction of roughly 4×10^4 magnitudes. This dust, which causes optical extinction, emits thermal radiation which peaks at far infrared to millimeter wavelengths. Thus, the dust continuum emission can be used to study the highest column density regions of the stellar birth environment, the dense envelope right down to the circumstellar accretion disk.

Molecular emission lines at millimeter and submillimeter wavelengths provide a second probe of these young stellar environments. High abundance molecules such as ^{12}CO and ^{13}CO trace the gas component down to column density as low as a few magnitudes of visual extinction. Rarer species such as $C^{18}O$, CS or N_2H^+ trace higher column density regions. Molecular lines provide information about the gas column density and physical density distribution, the gas kinematics, and the chemistry occurring within the system. Millimeter and submillimeter observations complement optical and near infrared observations, and together they provide a full picture of the young circumstellar environment.

The following sections will concentrate on what we are learning about the multiplicity of young low-mass systems from millimeter and submillimeter wavelength observations. For the purposes of this discussion we will employ a broader definition of multiplicity than is typical of optical systems. We will define a multiple system as any system in which the components compete significantly for material during their formation. There are a number of motivations for this definition. First, if the forming stars are depriving each other of material, the outcome of formation will presumably be different from what would occur in complete isolation. Thus their fates are influenced by the presence of companions. Second, forming multiple systems are dynamically young and buried in larger scale molecular cores so it is extremely difficult to formulate a strict test of multiplicity. And third, except for the closest separations in more mature systems, for example GG Tau or L1551 IRS5, it is difficult to predict which systems will go on to become main sequence binary systems. Even if they are bound now, they could become unbound depending on how the surrounding gas is dispersed, or if interactions occur with other systems or single stars. Thus, any strict definition of multiplicity which "guarantees" the final outcome leaves out many systems where the forming members are profoundly affected by the presence of others.

2. The Morphology of Embedded Low Mass Systems

Wide-field continuum maps of portions of the Perseus cloud NGC 1333 (Sandell and Knee 2001) and the main ρ Ophiuchi cloud (Motte et al. 1998) provide good examples of the structure of active star formation regions. These submillimeter wavelength maps show a variety of sources. The brightest dust emission is closely linked to regions of embedded star formation and these regions are often not isolated. In ρ Ophiuchi, Motte et al. (1998) estimate a separation scale of $\sim$6000 AU between star forming cores. A similar estimate for the Taurus cloud suggests a value five times larger (Motte et al. 1998). The brightest cores in NGC 1333 are similarly clumped in a small fraction of the map area. The scale of typical separation is a suggestion of the beginning of binarity since this is the scale on which the cores would likely have overlapped in their early, uncondensed state.

The resolution possible with millimeter arrays enables more detailed studies of the material distribution and kinematics of young and forming systems. One example of such work is provided by Looney et al. (2000). That paper presents 0.5" resolution images of the λ=2.7mm dust continuum emission from 11 fields containing 24 young stellar objects. A number of the objects are in the NGC 1333 cloud mapped by Sandell and Knee (2001). With high resolution, the extended or partially resolved sources in the Sandell and Knee map cleanly become separate sources, and some of these break-up further at arcsecond resolution. Figure 1 shows the multiplicity of the NGC 1333 IRAS4 system which is at a distance of 350 pc. Figure 2 shows the L1448 IRS3 system which shows a similar scale of multiplicity. Even Bok globules, once held-up as simple isolated laboratories for single star formation, are revealing evidence of early multiplicity (Launhardt et al. 2001). Launhardt et al. (2001) find at least 40% multiplicity in their sample when observed with 10" resolution.

What is it that the millimeter wavelength continuum emission is tracing? Primarily circumstellar envelopes: the inner dense portions of the cores inside which the stars are forming. The stars are invisible because they have too little surface to contribute significant emission. Detailed studies of systems (Looney et al. 2000, 2001) have shown that deeply embedded systems are dominated by the emission from the surrounding material on scales from 100's to 1000's of AU – and not by material in a circumstellar disk. In many systems, the disk, which is likely there, cannot be uniquely isolated from the envelope emission. With the current observations, we can only say that the disks in the embedded phase are not significantly more massive than disks in the later T Tauri phase (Mundy et al. 2000).

One major result of the high resolution work is simply stated: multiplicity is common in the formation era. It is common over a variety of cloud conditions. While it is too early to make statistical estimates of how common, the finding of more multiple objects than single objects in the sub-arcsecond resolution studies of embedded objects completed to date points to a high frequency of occurrence.

3. Fragmentation and Multiplicity

Based on morphology, we can divide embedded multiple systems into three major groups: independent envelope, common envelope, and common disk systems. The divisions are defined by the distribution of the circumstellar material. Independent envelope systems exhibit clearly distinct centers of gravitational concentration with separations of $\geq$6000 AU; the components are within a larger surrounding core of low density material but that material has a secondary role in the formation. Example systems are NGC 1333 IRAS2A & 2B or NGC 1333 SVS13 A, B, & C. Common envelope systems have one primary core of gravi-

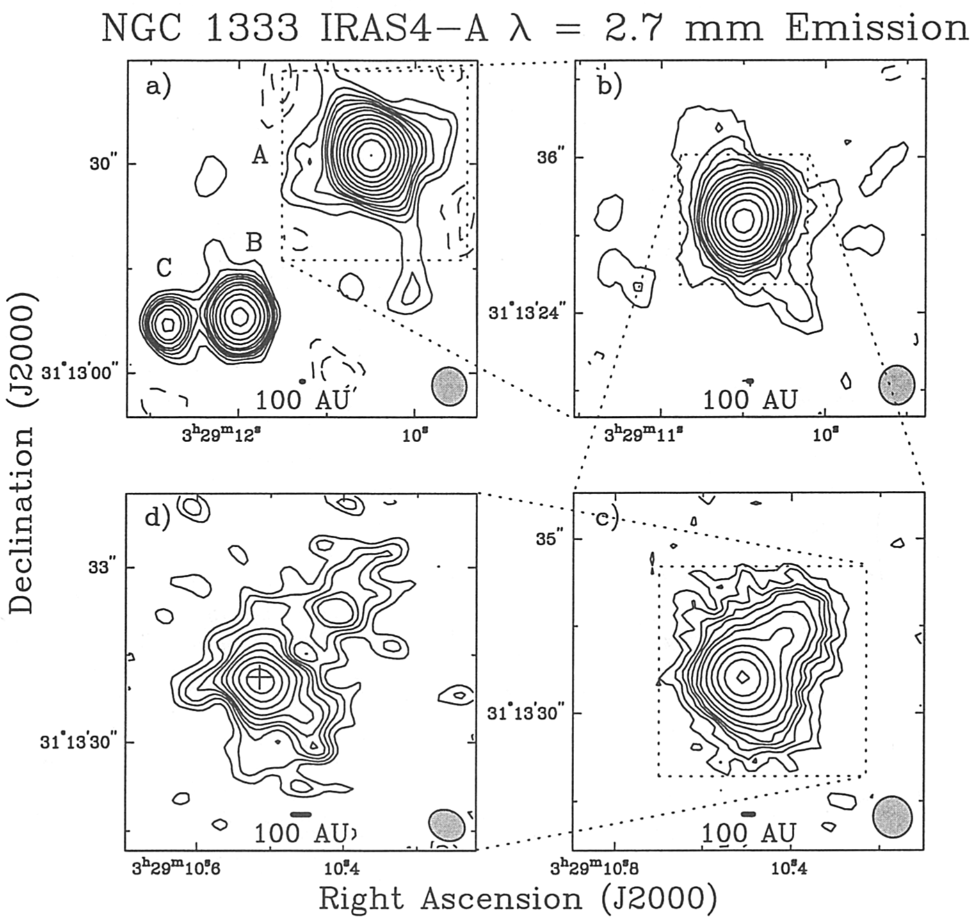

Figure 1. Maps of the $\lambda = 2.7$ mm continuum emission from NGC 1333 IRAS4 (Looney et al. 2000). Panel (a) shows the A, B, C system which is embedded in an overall lower column density envelope seen in ^{13}CO. The contours are (-4 -3 -2 2 3 4 5 6 8 10 14 20 28 40) × the rms noise of 3.1 mJy/beam. The beam is 5.5" × 5.0". Panels (b) through (d) show progressively higher resolution images of the IRAS 4A component of the system. Note that in going from panel b to c to d IRAS4A breaks into two sources which are separated by approximately 470 AU. More than half of the flux of the 4A system arises from the envelope that surrounds the two sources. The resolutions in panels b, c, and d are 3.0" × 2.8", 1.2" × 1.1", and 0.65" × 0.51", respectively. The contours are are (-4 -3 -2 2 3 4 5 6 8 10 14 20 28 40 56) × the rms noise of 2.9 mJy/beam.

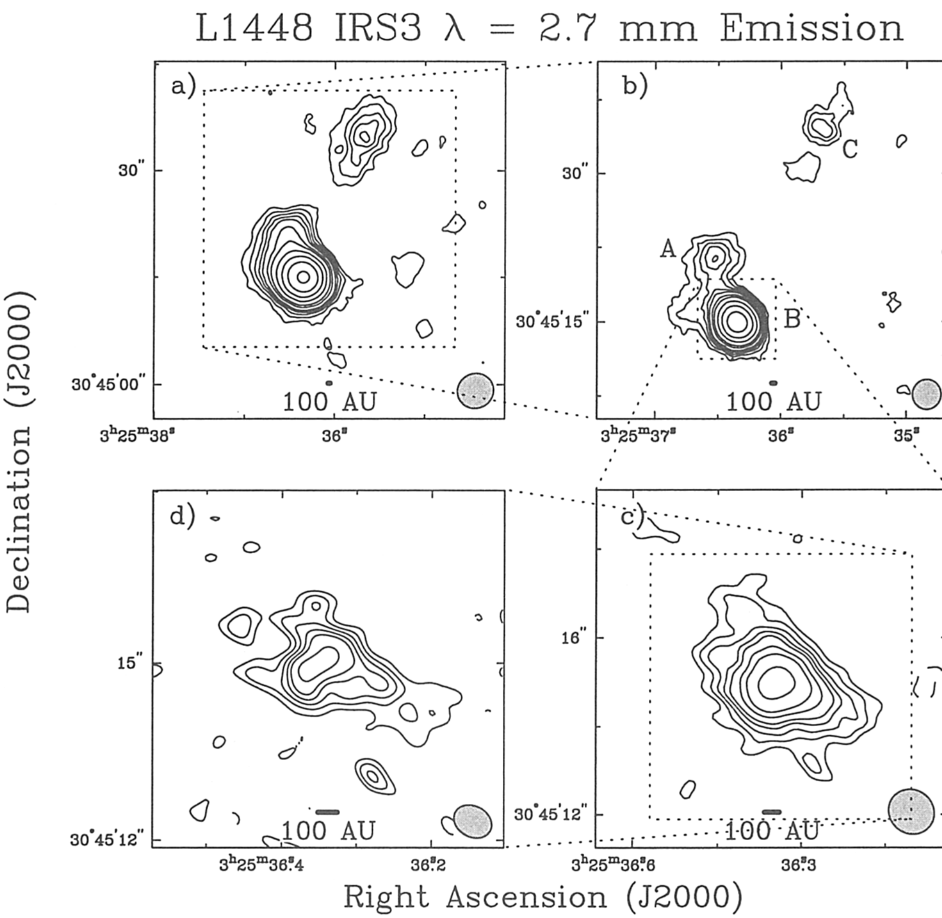

Figure 2. The $\lambda = 2.7$ mm continuum emission from the L1448 IRS3 system (Looney et al. 2000). Panel a shows the overall system with two primary components separated by about 6000 AU. In panel b, the southern component breaks into two components separated by about 2700 AU. Panels c and d show close-ups of component B. In this source the majority of emission in the A-B regions appears to be associated with the separate sources rather than surrounding the two sources. At sub-arcsecond resolution, IRS3B appears extended in a roughly south-east - northwest direction. This could be evidence of a flattened envelope or further multiplicity on the few hundred AU scale. It is unlikely to be a single stellar disk since the implied linear size is much larger than expected based on continuum disk sizes in Taurus systems (Mundy et al. 2000). Higher resolution images are needed to distinguish between the possibilities. The beams in panels a, b, c, and d are 5.2" × 4.9", 3.1" × 3.0", 1.1" × 1.0", and 0.68" × 0.52", respectively. All panels are contoured at (-4 -3 -2 2 3 4 5 6 8 10 14 20 28 40 56) × 2.3 mJy/beam (roughly the rms noise in each map).

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tational concentration which breaks into multiple objects at separations of 250–3000 AU. The common envelope is the reservoir that feeds material into the multiple system. NGC 1333 IRAS 4A is a good example of this type. Common disk systems have separations of $\leq$ 100 AU and typically have circumbinary disk-like distributions of material. L1551 IRS5 is an example of such a system which is still partially embedded and GG Tau is a more evolved example.

There are clear connections between these morphological distinctions and the origins of the systems. A study of the separation distribution of optical binaries by Larson (1995) found a knee in the distribution at 0.04 pc (8250 AU) which was posited to correlate with the Jeans size. Larson suggested that systems on that scale and larger formed by fragmentation of pre-stellar cores and separate collapse; this is exactly the structure found in the independent envelope systems. This scenario of prompt initial fragmentation has a history (Larson 1978; Pringle 1989; Bonnell et al. 1991; Bonnell et al. 1997). The critical requirement is that the collapse be initiated in a system which contains multiple Jeans masses in a weakly condensed configuration, for example a prolate Gaussian distribution with several Jeans masses along the long axis and one Jeans mass across the short axis. The collapse then proceeds more quickly within the individual Jeans mass than across the whole structure.

The common envelope systems can be linked to models following the fragmentation of moderately centrally condensed spherical systems (Burkert and Bodenheimer 1993; Boss 1995; Boss 1997; Bodenheimer et al. 2000). In this case, fragmentation occurs in the dense central region within an overall single core. The primary requirement for fragmentation is that the central region has a fairly flat distribution. Finally, the common disk systems are similar to models of high angular momenta systems (Artymowicz and Lubow 1994; Bate and Bonnell 1997). Close stellar systems then arise from the fragmentation of early disks. The distribution of material between circumstellar and circumbinary structures depends on the angular momentum of the infalling material.

4. The Density Structure of Cores with YSO's

To understand more about how multiplicity arises, we need to understand the detailed structure of the molecular cores in which stars are forming. Following from the theoretical ideas in the previous section, the density structure and kinematics of the material are of central importance. Magnetic fields and turbulence are also likely to be important factors in their own right and through their influence on the density and kinematic structure. Unfortunately, the observations are not yet up to the challenge of addressing all of these factors. This section will look at what can be said about the density structure; the next section will address kinematics.

Standard spherical collapse models for star formation in the literature are gravity driven with Shu (1977) inside-out collapse models and the Larson-Penston uniform collapse models (Larson 1969; Penston 1969) representing ends of a range of collapse scenarios (Foster and Chevalier 1993; Hunter 1977; Whitworth and Summers 1985). The common features of the range of models are that the density in the outer core tends to $\rho \propto r^{-2}$ and the inner density profile approaches $\rho \propto r^{-3/2}$ some time after the star begins forming. These are all, of

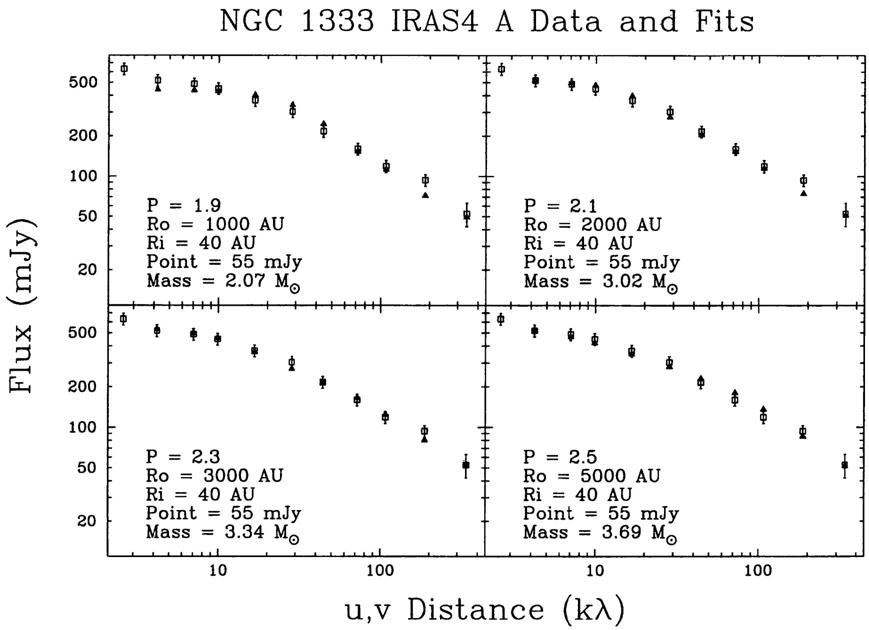

Figure 3. Fits to the λ=2.7 mm emission for NGC 1333 IRAS 4A in the *u,v* plane (Looney et al. 2001). The open boxes are the *uv* data binned in annuli; solid triangles are fit values. The four panels show fits using power-law envelopes with different density index P ($\rho \propto r^{-P}$). R_o and R_i are outer and inner radii. "Point" is a point source flux which represents a disk. "Mass" is the total mass of the envelope.

course, models for forming single-stars but numerical models with core rotation, magnetic fields, or asymmetric morphologies find broadly similar density profiles in dynamically active regions (Galli & Shu 1993; Fiedler & Mouschovias 1993; Li & Shu 1997; Basu & Mouschovias 1995).

Observations of cores covering a wide range of masses broadly find $\rho \propto r^{-3/2}$ to r^{-2} density profiles (Hatchell et al. 2000; Motte et al. 2001; Mundy et al. 2000). And, in particular, high resolution observations of embedded low-mass systems show $\rho \propto r^{-3/2}$ to r^{-2} profiles around the individual sources in the independent envelope systems, as expected in the fragmentation-collapse scenario. For the common envelope systems, the overall envelopes follow $r^{-3/2}$ to r^{-2} profiles down to scale comparable to the component separation; but the data do not have sufficient resolution to dissect the individual source envelopes. Since the intrinsic asymmetries which caused the multiplicity are dominating on this scale, these small scale envelopes may have a more complicated structure.

Figure 3 shows an example of fitting models to millimeter wavelength interferometer continuum data that cover size scales from 60" down to 0.5" (Looney et al. 2001). The models are simple envelopes with an inner radius, an outer radius, a power-law density gradient ($\rho \propto r^{-P}$), and a dust temperature distribution which is determined by radiative equilibrium with the YSO luminosity. At the center of the envelope is assumed to be a compact disk which creates a fitted amount of flux. As shown by the panels, this type of model can fit the data for a range of density power-laws, with compensating values for the other parameters. In many of the cases studied by Looney et al. (2001) values of P from 1.5 to a little more than 2 could fit the data. NGC 1333 IRAS 4A, shown in Figure 3, actually fits best for P=1.9-2.5. It is unfortunate that it is not easier to determine P to higher accuracy as this would be a valuable test of theoretical models.

A second interesting result of detailed studies of cores is the finding that they are finite in size (Looney et al. 2001; Motte & André 2000). That seems obvious and natural but it also leads to the questions of what sets that scale and is there a range of sizes corresponding to the mass range of stars and binary systems. The typical size seems to be 3000 to 5000 AU in Perseus but of order 10,000 AU in Taurus. The separation scale of cores in Taurus was also found to be significantly larger than in Perseus (Motte et al. 1998). Both differences may be indicative of a difference in the Jeans mass in the regions due to the temperature and density conditions in the cloud.

Finally, at very early times, before the star is formed, the inside-out collapse model has $\rho \propto r^{-2}$ all the way to the center while other models have the density flattening in the center. Models with magnetic fields, rotation, non-symmetric initial conditions tend to form oblate or prolate three dimensional structure with shallow density gradients in the center (Bodenheimer et al. 2000; Li & Shu 1997; Basu & Mouschovias 1995). The presence of a shallow central density gradient is argued to be essential to fragmentation models for multiplicity. The observations of pre-stellar cores (cores that will, but have not yet, formed stars) find evidence for such shallow density gradients in their centers (André et al. 2000). Thus, fragmentation appears to be a viable mechanism for forming common envelope multiplicity.

5. The Kinematics of Cores

The detailed kinematics of cores should reveal additional information about the binary formation process, and especially reveal insights into the influences of magnetic fields, rotation, and turbulence on the collapse. In the simple spherical infall scenario, the infall velocity structure can be determined from studying the profiles of selected molecular tracers. This has been done in detail for a couple of sources (Choi et al. 1995) and a number of surveys have shown that line profiles toward embedded YSO's statistically support general collapse motions (Lee et al. 1999, Choi et al. 1999; Mardones et al. 1997). However, studies of the kinematics of most embedded sources are much more difficult than one would like. The key complicating issues are: the depletion of tracer molecules from the gas resulting in little or no molecular emission from selected regions and hence no kinematic information for that gas; the enhancement of selected molecular abundances in shocked or heated gas resulting in the over representation of selected regions and misleading information about the kinematics of the undisturbed gas; the creation of cavities within the cores by the outflows.

Unfortunately, the observations of detailed kinematics are more promise than product at this point. Low resolution observations have provided evidence for rotational angular momentum in cores (Goldsmith & Arquilla 1985; Goodman et al. 1993; Barrandco & Goodman 1998), but as pointed out by Burkert and Bodenheimer (2000), the simple interpolation of line-of-sight velocity gradients is problematic. The observed line widths of cores support the presence of turbulent motions but only give few insights into the structure of the turbulence. The future is however bright as the body of detailed observations expands. Worthy observational goals for the near future include studying the variations in the velocity field on a broad range of scales to look at the structure function of the turbulence, looking at the specific angular momentum distributions of cores, and mapping infall regions around early YSO's.

6. Summary and the Future

The evidence from studies of embedded star formation is that multiplicity starts early, is common, and occurs on a range of scales. Most stars form in an environment in which they are competing for mass with their siblings. The structure of multiplicity being uncovered within molecular cores supports the broad theoretical picture in which distant multiplicity ($>$ 6000 AU separation) arises from early fragmentation of multiple Jeans mass condensations. Intermediate separation multiplicity (250–3000 AU) originates as fragmentation within the central high-density region of a core, and close multiplicity ($<$ 150 AU) is likely the signature of high angular momentum systems.

With the next breath, it must be acknowledged that the current observations of embedded systems do not have the resolution needed to probe separations typical of optical binary systems. The best observations are approaching 50 AU linear resolution, but 100–200 AU is more typical since most studied clouds are at distances of 200–350 pc. Thus, there must be significant undiscovered binarity within the studied systems. Among the embedded systems, it may be the unusual star that is not a part of multiple system at birth, but many such systems may not survive to the main sequence.

The next big steps in studies of embedded systems are to quantify the frequency and separation in a significant number of systems, covering a range of cloud/star-formation conditions. This will involve major time and effort. The work on the detailed density and kinematic structure of cores is just beginning to achieve the resolution and sensitivity necessary to answer questions. Further progress in these studies will provide the best insights in the binary formation process but the challenges of quantifying and interpreting what we see are significant.

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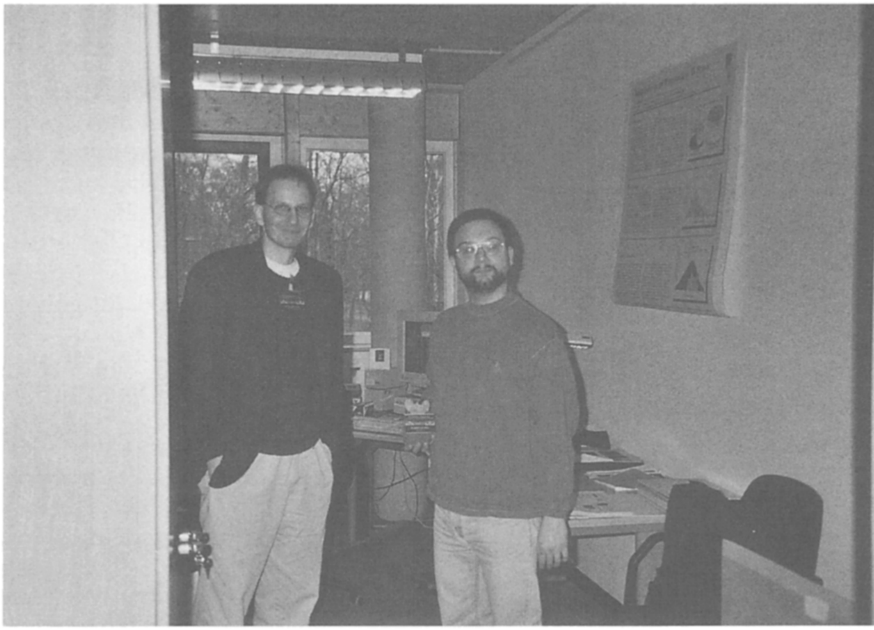

Wolfgang Brandner visiting Rainer Köhler in his office at the AIP to prepare their joint talk (top)
Mark McCaughrean instructing his friends to pose like the Trapezium stars in the Orion Nebula Cluster (bottom)

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