Part 8
Disks

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From Infall to Rotation around Young Stars: The Origin of Protoplanetary Disks

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Abstract. The origin of disks surrounding young stars has direct implications for our understanding of the formation of planetary systems. In the interstellar clouds from which star form, angular momentum is regulated by magnetic fields, preventing the spin up of contracting cores. When ~ 0.03 pc-sized dense cores decouple from the magnetic field and collapse dynamically, $\sim 10^{-3}$ km s^{-1} pc of specific angular momentum is locked into the system. A viscous accretion disk is one of two possible mechanisms available for the necessary redistribution of angular momentum; the other one is the formation of a multiple stellar system. Recent observational results involving high-angular resolution observations are reviewed: the presence of disks deep inside collapsing envelopes; an accretion shock surrounding a disk; the velocity field in collapsing and slowly rotating envelopes; a possible transitional object, characterized as a large, contracting disk; and the velocity field in disks around T Tauri stars. Observational facilities becoming available over the next several years promise to offer significant progress in the study of the origin of protoplanetary disks.

1. Introduction

This contribution, the first in a series in this volume on the disks that surround many young stars (e.g., Beckwith & Sargent 1996), reviews our current understanding of the transition from infalling envelopes to rotating disks. It is based on recent theoretical and observational work, with an emphasis on high-resolution results. Time and space constraints limit the discussion to low-mass stars only, and the intriguing question of the presence and nature of disks around higher mass stars is left unaddressed (cf. Cesaroni et al. 1997; Norris et al. 1998; Zhang, Hunter, & Sridharan 1998; De Buizer 2003; Sandell, Wright, & Forster 2003).

The origin of a disk lies in the angular momentum of the cloud cores from which the star condensed. The evolution of the angular momentum during the star-formation process determines the properties of the disk that will form: its mass and size, and therefore its density. These disks are the likely birthplace of planets, and the surface density in the disk is an important parameter in

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planet-formation theories (e.g., Lissauer 1993; Ruden 1999). It is for this reason that the study of the origin of disks is so important.

The outline of this contribution is as follows. Section 2 describes the initial conditions: the angular-momentum distribution in dense cloud cores before collapse. Section 3 presents evidence for a characteristic length scale at which dense cores decouple from the surrounding cloud and start to collapse. Section 4 gives a brief overview of theoretical work on the collapse of rotating cloud cores. Section 5 provides a sampling of recent high-resolution observational work that addresses the origin of disks. Section 6 concludes this contribution with a short summary and an outlook to future developments in this area.

2. Initial Conditions: Rotation in Interstellar Clouds

Interstellar cloud complexes have a hierarchical structure, consisting of filaments, clumps, and dense cores (see, e.g., Blitz & Williams 1999; McKee 1999; Myers 1999). It is generally thought that magneto-hydrodynamic (MHD) turbulence provides the support of these clouds against collapse under their own gravity, because the widths of molecular emission lines are usually much larger than can be explained by thermal motions alone (e.g., Fuller & Myers 1992). The quasi-equilibrium nature of clouds was recently questioned by Hartmann, Ballesteros-Paredes, & Bergin (2001), who argue that at least the Taurus-Auriga cloud complex may have a much shorter life time than previously thought. This would obviate the need for a support mechanism, but disucssion about this interpretation is not yet settled.

In addition to random (turbulent) motions, cloud cores also exhibit organized motions (velocity gradients). Goodman et al. (1993) constructed a velocity-gradient vs. size plot for a large sample of dense cores, akin to the line-width vs. size relation first identified by Larson (1981). Goodman et al. finds that the rotation rate Ω increases at most moderately with decreasing core size, $\Omega \propto R^{-0.4}$, although the relation shows significant scatter. With assumptions about the mass distribution inside these cores, this relation corresponds to a relation between the specific angular momentum (=angular momentum per mass unit) $j \propto R^{1.6}$. Both relations show that smaller cores do not spin much faster, or, in other words, if smaller cores are the descendants through contraction of larger cores, they do not spin up much and must loose specific angular momentum. A likely explanation is that the magnetic field lines that permeate the core and that are coupled to the ions transfer angular momentum from the contracting to core to the surrounding cloud. This mechanism is known as magnetic braking and was studied in the context of weakly ionized media by Königl (1987). Another result of Goodman et al. (1993) is that the ratio of rotational energy to gravitational energy of the cores, β, is independent of size and ≈ 0.03. Since this value is $\ll 1$, it indicates that rotation is dynamically unimportant for cloud cores.

Recent theoretical work tries to reproduce the observed cloud characteristics through numerical simulations of MHD turbulence (e.g., Myers & Gammie 1999; Burkert & Bodenheimer 2000; Ostriker et al. 2001; Ossenkopf & MacLow 2002; contribution by Vázquez-Semadeni in this volume). Burkert & Bodenheimer (2000) find that the specific angular momentum and the ratio of rotational to gravitational energy on cloud-core scales in their simulations corresponds well to the values reported by Goodman et al. (1993). This supports the idea that MHD turbulence is the shaping mechanism of interstellar clouds and regulates the angular momentum distribution of their constituents.

3. Decoupling of Cloud Cores

Magnetic fields cannot support cloud cores against collapse indefinitely, because only the ions couple to the field lines while the neutrals can slip through. Through this process, called ambipolar diffusion, cloud condensations will slowly form. Because of the increased recombination rate in denser gas, the ionization degree in these cores will decrease, and dynamic collapse is inevitable. For a more detailed description see, e.g., Shu in this volume.

Goodman et al. (1998) show evidence of a transition around 0.03 pc, where the line widths (tracing random motions in the cores) become much smaller (close to thermal) and no longer depend on the size of the core. They interpret this as a cutoff scale for MHD turbulence. When these MHD waves can no longer penetrate, the motions inside the cores damp out rapidly.

Ohashi et al. (1997) find that around that same scale of 0.03 pc, the specific angular momentum of objects no longer decreases with size, as it did for cloud cores: infalling envelopes around Class 0/I objects and rotationally supported disks all have angular momenta of $\sim 10^{-3}$ km s^{-1} pc independent of size. This amount of specific angular momentum is comparable to the high end of values found in Solar-neighborhood binaries (Heacox 1998). This further supports the suspicion that when cores decouple from the magnetic field of the surrounding cloud around 0.03 pc, $\sim 10^{-3}$ km s^{-1} pc of specific angular momentum is locked into the nascent stellar system.

4. Theory of Collapsing and Rotating Cores

Since rotation is dynamically unimportant in cores, it can initially be treated as a perturbation to a non-rotating collapse solution. In the absence of angular momentum redistribution, the infalling material will spin up, and the perturbation approach is valid only outside the radius where the centripetal force grows to a significant fraction of the gravitational force (or, equivalently, where the stream lines of the infalling material start to deviate appreciably from the radial direction). Inside this rotational radius R_c a disk forms (see below). R_c evolves over time as material with different amounts of angular momentum falls in.

Terebey, Shu, & Cassen (1984) based such a perturbational procedure on the self-similar collapse solution of Shu (1977) and the assumption of initial solid-body rotation. Because of this assumption of solid-body rotation, the rotational radius grows rapidly with time, $R_c \propto t^3$, as material that falls in at later times originated from larger radii and carries more angular momentum.

For a magnetized core a different initial angular momentum profile is expected. Basu (1997) explores the slow contraction of a magnetized core by ambipolar diffusion, and finds that the core tends toward differential rotation. The outside of the core, where densities are low and the ionization degree significant, remains strongly coupled to the slow rotation of the surrounding cloud.

The contracting central region, less strongly coupled to the magnetic field, spins up, and is joined by a sharp gradient in rotation rate to the outside. As a result of this differentially rotating configuration, once dynamic collapse starts the rotational radius grows only linearly with time, $R_c \propto t$ (Basu 1998).

Whatever the rate of growth of R_c, within this radius material will form a disk. Stahler et al. (1994) explored this analytically in the Terebey et al. framework, and find that material piles up at $\frac{1}{3}R_c$. In their model an infinitely thin ring of infinitely high density is formed; in reality, viscosity will spread this ring and set up an accretion disk within this radius. Many authors have explored the formation of a disk numerically (e.g., Bodenheimer et al. 1990; Yorke, Bodenheimer, & Laughlin 1993, 1995; Nakamura 2000; Krasnopolsky & Königl 2002). Because of the difficulty of the problem (the order of magnitude of scales involved; the physics of magnetic fields; the poorly understood source(s) of viscosity) much of this work is limited in the range of modeled scales or ages, and few direct comparisons with observations have been made.

Other contributions in this volume discusses the structure of disks around young stars in detail (see the contributions by Dullemond, by Wardle, and by D'Alessio). Here it suffices to mention that disks offer mechanisms to redistribute angular momentum for the first time in the star-formation process since decoupling from the cloud magnetic field. In addition to viscosity, disk instabilities can transfer angular momentum, and photo-evaporated material can carry it away. Alternatively, angular momentum can be stored in a binary system, or carried away when objects are ejected from multiple systems.

5. A Sampling of Recent Observations

5.1. Disks Deeply Embedded in Collapsing Cores

Disks are formed inside collapsing cores, hampering direct observation of their formation process. Aperture-synthesis observations at (sub) millimeter wavelengths can reveal the presence of a distinct compact source inside an extended envelope from the distribution of detected flux as function of angular scale. Looney, Mundy, & Welch (2000, 2003) surveyed a number of deeply embedded young stellar objects (Class 0 YSOs) using the Berkeley-Illinois-Maryland Association (BIMA) array. They find that during this early evolutionary stage the disks are not more massive than during the later Class I and T Tauri stages, with derived masses of ≤ 0.12 $M_\odot$. This suggests that the disks funnel mass onto the star at a rate comparable to that with which the envelope material falls onto the star–disk system.

Looney et al. also report that $> 85\%$ of the millimeter flux originates from the extended envelope, illustrating the difficulty of distinguishing a disk from the envelope. This is further exacerbated by the fact that the envelopes are strongly centrally concentrated. When trying to determine the degree of central concentration from lower-resolution (e.g., SCUBA) data, the presence of a disks affects the derived density slope when unaccounted for (see, e.g, Harvey et al. 2003; Jørgensen et al. submitted to A&A.). Fig. 1 illustrates how interferometer data can separate envelope from disk emission.

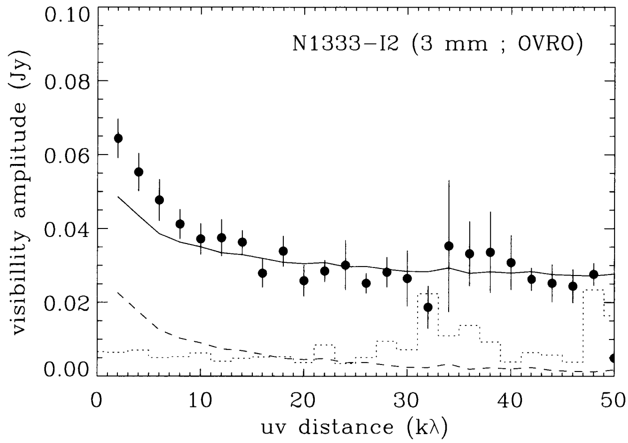

Figure 1. Visibility amplitude vs. projected *uv*-distance of the 3 mm emission from the embedded YSO NGC 1333 IRAS2, observed with OVRO. The upturn of the flux at short *uv* spacings reflects the emission from the resolved envelope. The constant flux level of $\sim$ 22 mJy at larger *uv* spacings corresponds to the flux of the unresolved disk. The dashed and solid curves show models without, respectively, with a point source included. From Jørgensen et al. (submitted to A&A).

5.2. An accretion shock

When material falls in from the collapsing envelope onto the rotationally supported disk, an accretion shock is expected. Recently, Velusamy et al. (2002) presented evidence for such a shock. Observations obtained with the Owens Valley (OVRO) Millimeter Array of the Class 0 object L1157 show CH_3OH emission surrounding the continuum disk, with respective sizes of 1210×640 AU and 800×590 AU. Since CH_3OH is usually only found when icy grain mantles evaporate, requiring temperatures higher than present in the collapsing envelope, its presence is taken as evidence for an accretion shock. This work illustrates how understanding the gas- and solid-state chemistry is an essential tool.

5.3. The velocity field in a Class 0 envelope

Infall is commonly detected in Class 0 envelopes (Gregersen et al. 1997; Mardones et al. 1997), while slow rotation is reported in flattened Class I envelopes (Ohashi, this volume). To date one of the best studied velocity fields of a Class 0 object is that of IRAM 04191+1522. Using molecular-line observations from the IRAM 30-meter telescope and the Plateau de Bure interferometer, Belloche et al. (2002) find two regimes of inward motions: slow contraction at $R > 3000$ AU and inside-out collapse at $R < 3000$ AU. They also identify two regimes of rotation: a steep fall off in rotation rate at $R > 3500$ AU and a much shallower or even constant profile at $R < 3500$ AU. They suggest that this 3000–3500 AU (0.015–0.017 pc) scale reflects the decoupling of the core from the magnetic field of the surrounding cloud, as expected in models of the contraction and collapse of magnetized cores (Basu 1997, 1998).

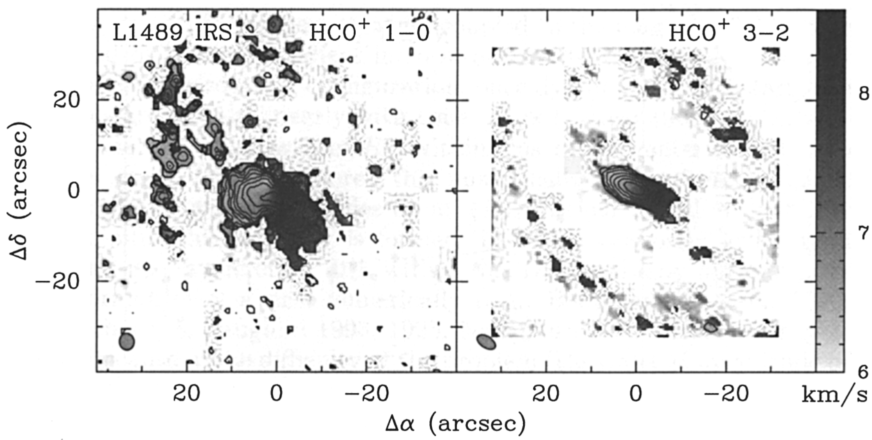

Figure 2. Aperture-synthesis images of HCO^+ J=1–0 (left) and 3–2 (right) emission of L1489 IRS obtained at OVRO and BIMA, from Hogerheijde (2001). The greyscale shows the velocity centroid of the emission; the contours show integrated intensity. The HCO^+ 3–2 image is one of the highest frequency line images ever obtained at BIMA.

5.4. L1489 IRS: A Transitional Object?

One of the most intriguing observational pieces of evidence on the transition from infall to rotation is offered by the object L1489 IRS. Millimeter and submillimeter data presented by Hogerheijde & Sandell (2000) and Hogerheijde (2001) show that this Class I object is surrounded, not by an infalling envelope with perhaps a small measure of rotation, but by a 2000 AU radius rotating disk. Unresolved, single-dish spectra of the dense-gas tracers HCO^+ J=1–0, 3–2, and 4–3 show the 'classic' infall signature (as explained in Evans 1999). High-resolution interferometric images of HCO^+ 1–0 and 3–2 emission obtained with OVRO and BIMA show a highly flattened circumstellar configuration and a velocity gradient clearly indicative of rotation (Fig. 2). The disk interpretation is further supported by HST/NICMOS data from Padgett et al. (1999) that shows light reflected off two flared surfaces, separated by a dark lane. With a mass of 0.02 $M_\odot$, this disk is no different than commonly found around T Tauri stars (e.g., Beckwith & Sargent 1996), but its size (2000 AU radius) is larger by a factor of at least 2–3 than other gas disks. This implies that its surface density is lower by an order of magnitude or more: a fact that would have consequences for its planet-forming capability.

Modeling the velocity field as observed in the interferometer beam in detail, Hogerheijde (2001) finds that it is well characterized by Keplerian rotation around a 0.65 $M_\odot$ object, but only if inward motions amounting to 10% of total magnitude of the velocity vector are included. These radial motions are required to explain the asymmetry of the HCO^+ position–velocity diagram and the clear collapse signatures in the single-dish HCO^+ line profiles. With such inward mo-

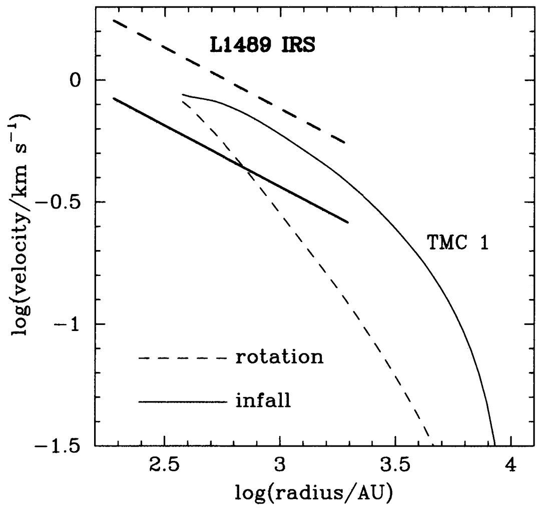

Figure 3. Comparison of the velocity fields around L1489 IRS and TMC 1. The former is dominated by rotation with a $\sim$ 10% contribution from infall; the latter is dominated by infall, with rotation dynamically unimportant. From Hogerheijde (2001).

tions, the lifetime of this 2000 AU disk is only 2×10^4 yr. This velocity field is radically different from those of Class I objects, where rotation does not account for more than a small fraction of the total velocity vector (Fig. 3).

The resolution of the HCO^+ interferometer images is $\sim 5''$ or 700 AU. Do the inward motions continue all the way to the star? These much smaller scales are sampled by the 4.65 μm Keck/NIRSPEC spectrum presented by Boogert, Hogerheijde, & Blake (2002) and reproduced here in Fig. 4. This spectrum shows a wealth of gas-phase CO absorption lines from the vibrational ground state into the first excited state, in addition to a prominent solid-state CO absorption band. The gas-phase lines from ^{12}CO, ^{13}CO, and C^{18}O originate in a wide range of rotationally excited levels, requiring kinetic temperatures as high as 250 K. Such temperatures are only expected close to the star, well within an AU. The excellent spectral resolution of NIRSPEC ($R \approx 25,000$) resolves the ^{12}CO absorption lines into a narrow line core plus a red wing extending to 100 km s^{-1} (Fig. 5). On the basis of the velocity model derived from the HCO^+ interferometer data, such inward motions are expected only within 0.1 AU. With a few minor adaptations (a change in the uncertain density profile of the disk, and the inclusion of a small amount of scattered light) this velocity model can provide an adequate fit to the ^{12}CO and ^{13}CO absorption lines. Apparently, inward motions continue from the 1000 AU scales sampled by the HCO^+ data to within 0.1 AU as traced by the Keck M-band spectrum.

This velocity field does pose some problems, however. If the entire disk participates in the inward motions, the implied accretion rate exceeds the observational limits (Muzerolle, Hartmann, & Calvet 1996) by more than an order of magnitude. Also, a viscous accretion disk model would predict subsonic flow, while the observed velocities are supersonic. A possible solution would be inflow

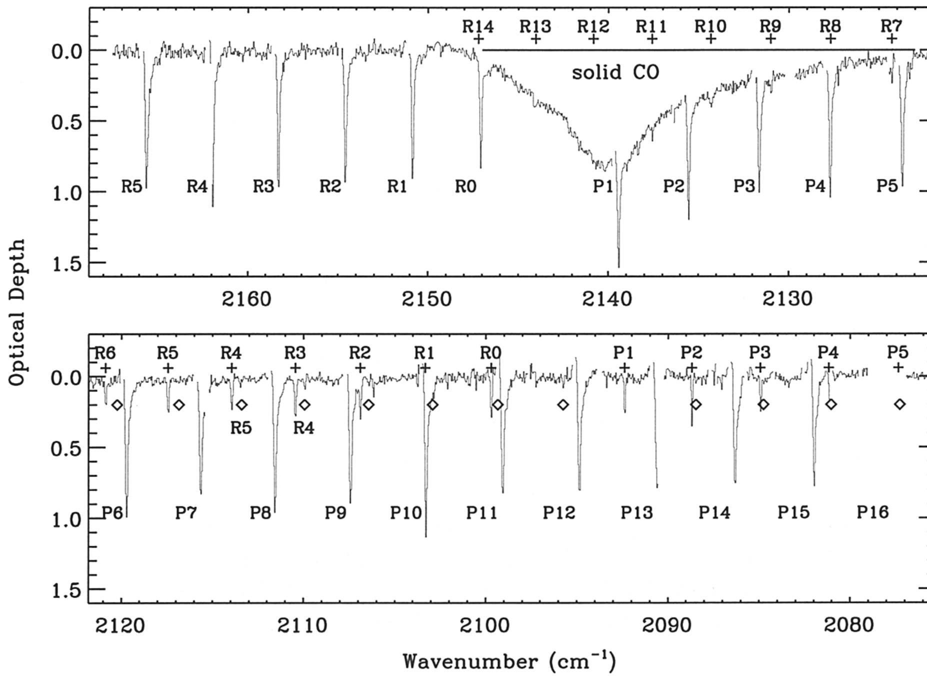

Figure 4. Keck/NIRSPEC M-band spectrum of L1489 IRS showing narrow absorption lines of ^{12}CO, ^{13}CO (marked by +), and $C^{18}O$ (marked by ◇), as well as a broad absorption feature of solid CO ice. From Boogert et al. (2002).

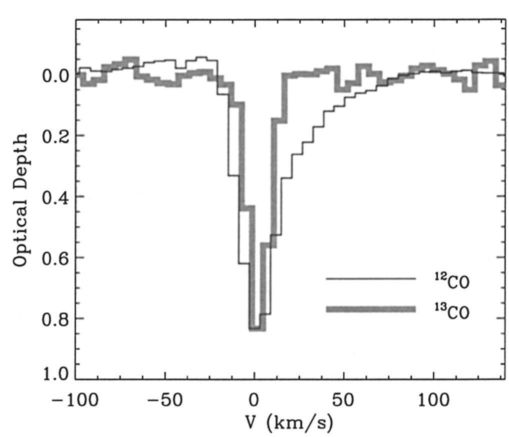

Figure 5. Comparison of the ^{12}CO (thin black line) and ^{13}CO (thick grey line) spectra of L1489 IRS, averaged over the ^{12}CO P(6)–P(15) and all ^{13}CO lines. The ^{13}CO lines are scaled to the same depth as the ^{12}CO lines, to bring out the different line shapes. From Boogert et al. (2002).

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in a thin surface layer only (reducing the amount of mass participating in the flow and hence the accretion rate). Another solution would be that the observations trace two regions if inflow: one in the outer disk ($\gtrsim$ 500 AU) probed by the HCO^+ interferometry where envelope material is settling onto the (unresolved) rotationally supported disk; and a second in the inner disk ($\lesssim$ 0.1 AU) where material accretes from the disk onto the star. The fact that the same velocity model fits both regions is not surprising, since it is determined by the gravitational potential well of the same star. Both explanations are supported by the failure of the velocity model to fit the core of the ^{12}CO absorption line, underestimating the amount of the material that is not moving radially. The alternative explanation of the ^{12}CO lines originating from two disks around the members of a binary system is ruled out by the NICMOS observations of Padgett et al. (1999) and lack of temporal changes in the line profiles (Boogert, priv. comm.).

In summary, L1489 IRS appears to represent a transitional object between Class I YSOs characterized by infalling envelopes with little rotation, and T Tauri stars surrounded by Keplerian disks. Inward motions are present throughout the large, rotating disk that surrounds L1489 IRS, but their exact nature remains elusive. Higher (both angular and spectral) resolution observations and the identification of additional object like it are required to correctly interpret the nature of this intriguing object.

5.5. Keplerian Disks around T Tauri Stars

Other contributions in this volume (e.g., Wilner, Dutrey) discuss observations of disks around T Tauri stars in detail. Here it only needs to be mentioned that their velocity fields are Keplerian (e.g., Simon, Dutrey, & Guilloteau 2000) with little indication for large radial motions. In viscous accretion disks, no such motions are expected. The presence of accretion signatures in the stellar spectra clearly shows that material does flow inward through these disks, however.

6. Summary and Outlook

Before collapse, the angular momentum in cloud cores is regulated by MHD turbulence. Through ambipolar diffusion, dense cores slowly grow, which have a decreasing ionization degree and which ultimately decouple from the magnetic field and collapse. The scale for this decoupling appears to be $\sim$ 0.03 pc. At the moment of decoupling, angular momentum is locked in the collapsing core, which will lead to the formation of a disk. Theoretical description of the disk-formation process are progressing, but detailed comparisons with observations are still lacking. Observationally, millimeter-interferometry can pick out disks deep inside envelopes. These disks are found to be no more massive than their counterparts during later evolutionary stages, indicating they funnel mass onto the star efficiently. The velocity fields of only a handful of YSOs have been studied in detail, but they appear to follow theoretical expectations for collapsing, magnetized cores. The object L1489 IRS may represent a short-lived, transitional object between these embedded YSOs and T Tauri stars. It is surrounded by a large (2000 AU radius), rotating disk, that has significant inward motions traced from $\gtrsim$ 700 AU to $\lesssim$ 0.1 AU with HCO^+ interferometry and CO M-band spectroscopy. While the exact nature of this object's velocity field remains unknown, L1489 IRS, and other possible objects like it, offer intriguing insight into the transition from infall to rotation.

The outlook for high-resolution observations is very promising, with numerous facilities coming online, being constructed, or being planned. (Sub) millimeter arrays such as the Combined Array for Research in Millimeter Astronomy (CARMA), the SubMillimeter Array (SMA), and ultimately the Atacama Large Millimeter Array (ALMA) will revolutionize our view of collapsing envelopes and circumstellar disks. The sensitivity and accuracy with which ALMA is designed to probe a wide range of spatial scales will prove essential in uncovering the birth of disks deep inside the collapsing envelopes. Our increased understanding of the chemistry that occurs during star formation will help us the select tracers that are as unambiguous as possible, even for unresolved observations.

At shorter wavelengths, the spectral resolution at infrared wavelengths is increasing incrementally, with the EXES instrument designed for the Stratospheric Observatory For Infrared Astronomy (SOFIA) surpassing the NIRSPEC data presented above by a factor of almost 4 (but with lower sensitivity). At these infrared wavelengths, interferometric facilities such as VLTI, Keck-I, and one day Darwin/TPF will uncover the processes occurring close to the star, such as accretion, outflow, and disk structure. Together, these observations will no doubt inspire more theoretical work, and direct comparisons between theory and observations. The prospects for uncovering the origin of disks, and thereby the initial conditions of planet formation, are excellent.

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