Early Protostellar Evolution and Disk Formation

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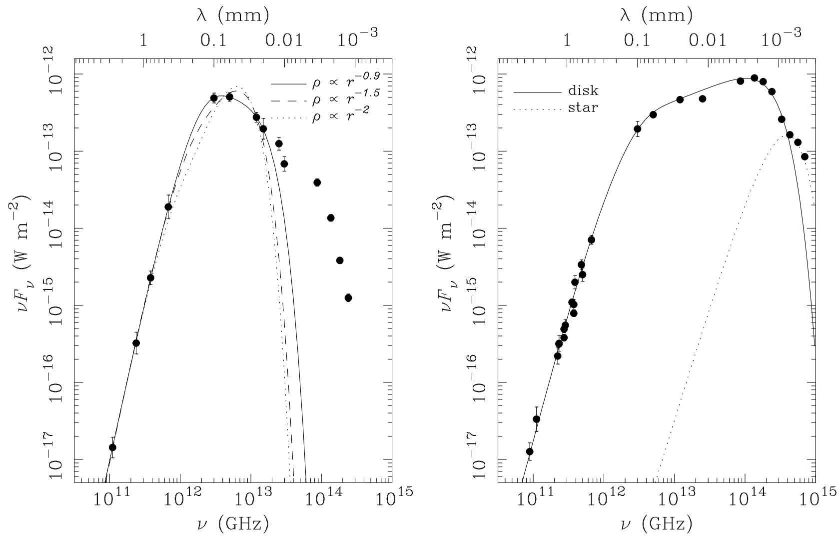
Abstract The physical and chemical properties of envelopes around low-mass protostars define the initial conditions for the formation of the solar nebula. Recent high-resolution observations of circumstellar material enable detailed comparisons to be made with predictions from star formation theory, and kinematic signatures of rotation and gravitational collapse on scales $\lesssim$ 1000 AU have been identified in a number of sources. The composition of the dust and gas in protostellar envelopes is different from quiescent molecular cloud cores, consistent with grain processing at high densities (e.g., particle growth), and the freezing-out of molecules from the gas phase onto grain surfaces. Both direct and indirect evidence suggests that disks form in the earliest observable phases of star formation.

1 Introduction

The formation of solar-type stars takes place within the dense cores of molecular clouds, such as those found in the nearby star-forming complexes of Taurus, Ophiuchus, and Orion [38]. Conservation of angular momentum during the gravitational collapse of a rotating dense core results in a protostar surrounded by an accretion disk [13]. The protostar/disk system is initially embedded in an extended, infalling envelope of gas and dust — the remnant of the cloud core — and the protostar gains mass by accreting this material through the disk. A highly-collimated, energetic, bipolar wind emerges from the protostar/disk, and is detected through high-velocity emission from molecular gas swept up by the wind [7]. The origin of the wind is not yet understood, but most popular models include disks as a means of accelerating the outflowing material to velocities of several 100 km s^{-1} [25]. In early phases the envelope obscures the star and disk at optical and infrared wavelengths, but it gradually dissipates as material is accreted onto the star or is dispersed by the accompanying outflow. After a few $\times\ 10^5$ yr, a pre-main sequence, solar mass (T Tauri) star, surrounded by a disk, is revealed optically. The dust and gas in dense cloud cores therefore constitute the raw material from which stars, disks, and planetary systems are made, and recent measurements of the physical and chemical environments of protostellar envelopes and disks are beginning to define the initial conditions for the formation of the solar nebula.



(a) SED for TMC1

(b) SED for DO Tau

Figure 1: (a) SED for the Class I protostar TMC1, with models of envelope emission fitted to the far-infrared and millimetre data [19]. The best fit, $\rho \propto r^{-0.9}$, is somewhat flatter than is predicted by models of cloud collapse. (b) SED for the Class II T Tauri star DO Tau. Once the envelope has dispersed, the spectrum can be fitted by the emission from the central star, plus a long-wavelength component due to a circumstellar disk [9].

2 Protostellar dust spectra

The spectral appearance of a protostar is determined by the amount and distribution of dust in its immediate environment. Dust in a disk contributes a component at infrared through to millimetre wavelengths, while dust in a surrounding envelope reprocesses the ultraviolet, optical, and near-infrared emission from the star and disk to far-infrared and submillimetre wavelengths. If the partitioning of circumstellar material between the disk and envelope is a function of age, SEDs might therefore be used as a means of assessing the evolutionary state of the forming star. The scheme initially proposed by Lada [26] uses the near- to mid-infrared spectral index, $\alpha = d\log(\lambda F_\lambda)/d\log(\lambda)$, to separate sources into Class I ($\alpha > 0$), Class II ($-2 < \alpha \leq 0$), and Class III ($\alpha \leq -2$). An additional Class 0 has also been introduced to accommodate objects not detected in the near-infrared, whose luminosity is largely radiated at wavelengths longer than 100 μm [4]. In terms of an evolutionary sequence, objects with particularly cold spectra, signifying a considerable amount of material in an extended envelope, are the youngest (Classes 0 and I: Figure 1a). Pre-main sequence T Tauri stars, whose dust SEDs are well modelled by circumstellar disks, fall into Classes II and III (Figure 1b). Images of the dust emission from protostars and T Tauri stars confirm this interpretation, with most of the circumstellar material in Class 0 protostars residing in extended envelopes resolved on scales of several 1000 AU, while T Tauri stars exhibit compact dust components [5].

3 Physical properties of protostellar envelopes

Spatial distribution

Both the long lifetimes of dark clouds and the low star formation rate observed in the Galaxy indicate that some form of support against gravitational collapse is needed in molecular clouds [38]. Magnetic fields are extremely good candidates for providing this support, in which case the timescale for collapse and star formation is dictated by ambipolar diffusion [20]. Observations of starless cores are beginning to confirm this picture, showing density structures similar to models of magnetically-mediated collapse [6]. However, once magnetic support is lost and a hydrostatic protostar develops at the centre of the cloud, theory suggests that the surrounding envelope takes on a density distribution $\rho \propto r^{-2}$. This density profile can be attained either quasi-statically [37], or dynamically, so that when the r^{-2} distribution is established the material is already moving inwards towards the centre at a few times the sound speed [22]. In both models, a region of free-fall with $\rho \propto r^{-3/2}$ then spreads outwards from the centre.

For a protostar $\sim 10^5$ yr old in the Taurus complex ($D \sim 140$ pc) the infall region is predicted to be ~ 30 arcsec in radius, requiring high spatial resolution and sensitivity for the density distribution to be measured directly. Only a small number of protostellar envelopes have therefore been studied, but several do exhibit the $\rho \propto r^{-3/2}$ expected for free-fall collapse in their inner regions [27, 15]. However, others have been found with density profiles as flat as $\rho \propto r^{-0.5}$, from comparisons of submillimetre continuum emission with dust radiative transfer models [4, 8]. The width of the spectrum is a measure of the relative amounts of dust at different temperatures, implying that SEDs can constrain the density distribution of envelopes. Figure 1 illustrates the dependence of the SED on the density profile for a Class I protostar in Taurus: spectra for $\rho \propto r^{-3/2}$ and r^{-2} are too narrow to explain the far-infrared data, and the best fit is for $\rho \propto r^{-0.9}$ [19]. Even after a protostar is well established at the centre of a collapse flow some form of support, such as rotation or magnetic fields, may still be present in the envelope.

Dynamics

Rotation or infall velocities of 1 km s^{-1} are established only on scales $\lesssim 10$ arcsec for solar-mass protostars in nearby star-forming regions, so millimetre interferometry has been essential for spatially resolving the kinematics of circumstellar material. Collapse is typically identified from redshifted absorption due to cool, infalling, foreground gas, which causes a characteristic asymmetry in optically thick emission lines [46]. The Class 0 protostar B335 ($D \sim 250$ pc) is an excellent example of the detection of infall, where the orientation of its outflow in the plane of the sky makes the interpretation of images of the envelope particularly straightforward. Single-dish observations suggest that material within a radius of ~ 30 arcsec is infalling [47], and millimetre interferometry of ^{13}CO and C^{18}O J=1–0 emission shows that the collapse can be traced to within $\lesssim 5$ arcsec (1000 AU) of the protostar [15]. Similar measurements demonstrate that infall motion dominates the envelope kinematics in the Class 0 protostars L1527 and L1157 [48, 32, 23].

In slightly older objects, where much of the low specific angular momentum material has already accreted onto the protostar, the kinematics of the envelope may become dominated by rotation. Figure 2 shows that emission from the same molecular lines used to detect infall in B335 now trace motion consistent with Keplerian rotation about

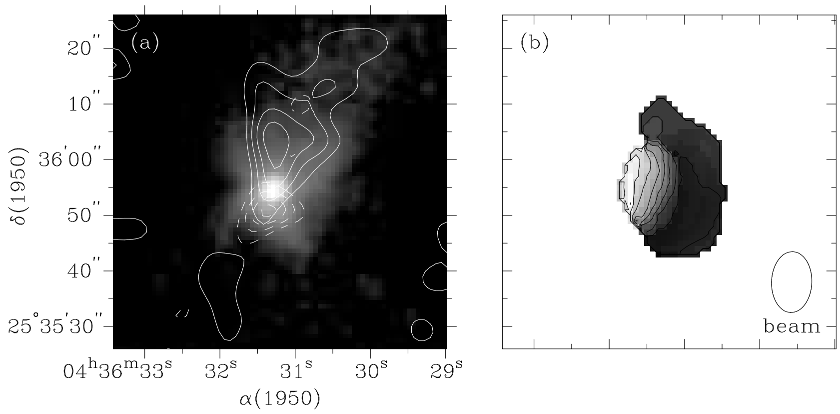


Figure 2: The dynamics of circumstellar material around the Class I protostar TMC1A observed using the Owens Valley millimetre array. (a) The molecular outflow is traced by blueshifted ^{12}CO J=1–0 emission (solid contours) and redshifted emission (dashed contours). The greyscale shows 2 μm reflection nebulosity following the evacuated outflow cavities [18]. (b) The intensity-weighted mean velocity of ^{13}CO J=1–0 emission from the rotating disk and envelope [14]. The isovelocity contours are spaced by 0.2 km s^{-1} and the corresponding greyscale runs from blueshifted (white) to redshifted (black).

a 0.7 M$_\odot$ star for the Class I source TMC1A in Taurus [14]. Figure 2 also illustrates how the kinematics detected depend on the molecular tracer used. The more optically-thick ^{12}CO J=1–0 line delineates a collimated redshifted and blueshifted bipolar outflow, perpendicular to the velocity gradient in ^{13}CO emission. Combinations of infall, rotation, and outflow have now been observed for a number of protostars.

4 Chemical composition of envelopes

Dust

Dense cloud cores are too cold for the diagnostic infrared dust bands to be detectable, so the dust properties of protostellar envelopes must be inferred from millimetre and submillimetre dust emission. The long-wavelength dust opacity is typically written as a power law function of frequency, $\kappa_\nu \propto \nu^\beta$, where β lies in the range 0 to 2. The value of β depends on the grain size, with small grains predicted to have $\beta = 2$ and large particles having $\beta = 0$, and also on the grain shape (e.g., spheres, rods), structure (e.g., fluffy, solid), and composition [35, 1, 2]. In diffuse clouds values of $\beta = 2$ are observed [21], while in T Tauri disks β is generally found to be 0 to 1 [10]. Such low values measured for T Tauri stars may indicate grain growth in their disks [30], but at present too little is known about the dust opacity to distinguish between an increase in particle size and changes in β caused by some other form of processing. Nevertheless, an intermediate evolutionary phase for the dust appears to have been identified in the dense cores of the NGC 2024 molecular ridge in the Orion B cloud [43]. The value of β in the dense cores containing embedded protostars is in the range 1.2 to 1.6, compared with 1.8 to 2.1 in

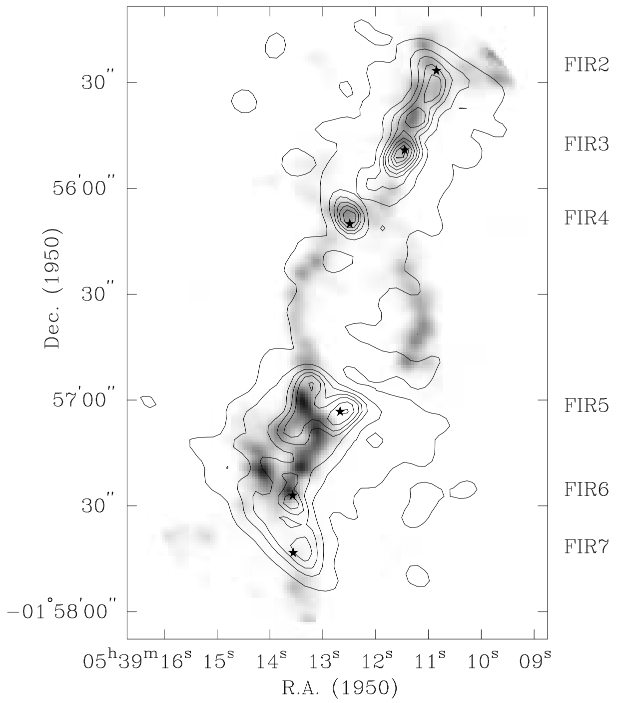


Figure 3: 450 μm dust emission (contours) and integrated CS J=2–1 emission (greyscale) from the NGC 2024 star-forming ridge. At the location of embedded protostars there is a large discrepancy between the column density implied by each tracer. One possibility is that the abundance of CS is low compared with the surrounding cloud [17, 43].

the surrounding cloud. These initial results suggest that the properties of the dust grains in the protostellar envelopes may represent an intermediate evolutionary phase for the dust, prior to further coagulation or processing in protostellar disks.

Gas

There is evidence that not only the dust is affected by the high densities found in protostellar envelopes, but that significant chemical processing of the gas phase also takes place. Several studies have shown that the abundances of many molecules in dense cores can be much lower than is generally observed in quiescent molecular clouds [31, 12, 42]. This is illustrated in Figure 3, where the 450 μm dust emission from NGC 2024 is overlaid on an interferometer image of the CS J=2–1 emission, which is normally expected to trace high densities. Although the dust and CS follow each other very closely at some locations, the dust cores containing the embedded protostars lack molecular line emission. This effect has also been observed in $C^{18}O$ emission and $C^{34}S$ [45, 44], and while differences in excitation temperatures in the protostellar cores compared with the other cores cannot yet be ruled out, one plausible explanation is that these molecules are underabundant in the gas phase by factors of ~ 10. Chemical models predict that the molecules could be freezing out onto the surface of the dust grains [11], which suggests that the evolution of gas phase composition and the formation of ices on dust grains may be linked to the change in β observed in the dust opacity.

5 Evidence for disks in young protostellar systems

Once the circumstellar envelope has dispersed disks around pre-main sequence stars can be identified from their dust spectra, and single-dish surveys demonstrate that $\sim 50\%$ of T Tauri stars have circumstellar disks [9]. Unfortunately, the presence of the envelope in protostellar systems confuses the interpretation of both SEDs and single-dish measurements. Single-dish imaging is well-matched to extended structure, and the millimetre fluxes detected from embedded protostars are usually consistent with arising from the envelope rather than a disk [40]. Interferometry has therefore proved essential for studying protostellar disks, providing the high resolution needed to examine the disk structure and acting as a spatial filter in order to isolate any compact dust components [24].

The first direct measurement of a protostellar dust disk used submillimetre interferometry to obtain a radius of 80 AU for the Class I protostar L1551-IRS5 in Taurus [28]. Disks now seem to be relatively common during the protostellar phase, and compact dust components have been detected in several Class 0 protostars, with measurements or upper limits on their radii of 100 to 200 AU [29, 16, 36, 23, 41]. For objects which are so deeply embedded, most of the mass of the protostar/disk/envelope system resides in the envelope, and the compact disk represents only 10% to 20% of the circumstellar material. However, the absolute value of the disk mass in these young protostars can be similar to that observed in T Tauri stars.

Further indirect evidence that disks form in the earliest phases of protostellar evolution arises from the association of more than 70% of young stellar objects, and all Class 0 protostars, with energetic winds and jets [34, 7]. If disks are the means by which the winds are driven then disks must be present throughout the life of the protostar. Indeed, the wind may be an important mechanism for removing angular momentum from infalling material, allowing accretion to take place through the disk [33].

6 Conclusions and future work

Millimetre and submillimetre measurements of embedded protostars are beginning to establish the physical and chemical conditions associated with star formation, but many problems remain to be solved. One of the most important questions is the nature of energetic mass-loss, which seems to be essential for star formation and yet is not understood. Large samples of Class 0 protostars are needed as a basis for expanding the study of the earliest stages of protostellar evolution and the properties of young outflows, which will require complete surveys of clouds for submillimetre dust emission using the new array cameras just becoming available. The role of magnetic fields in star formation must be established, and the detection of polarised emission from dust grains aligned by a B-field will be essential — one or two protostellar envelopes have been studied using millimetre interferometers [3], but more measurements with high resolution and sensitivity are needed to determine the relationship between magnetic fields and disks.

Many of the observations have been compared with models of the formation of single stars, and yet more than 50% of pre-main sequence stars are binary or multiple systems

[39]. The spatial resolution used for identifying visible binaries is not yet available at millimetre wavelengths, although some protostellar multiple systems with separations of ~ 1 arcsec can now be measured [29]. The future expansion of existing millimetre arrays and the building of the large arrays proposed by Europe, the US, and Japan, will therefore be extremely important for answering these questions.

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