FROM PRE-STELLAR CORES TO PROTOSTARS: THE INITIAL CONDITIONS OF STAR FORMATION

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The last decade has witnessed significant advances in our observational understanding of the earliest stages of low-mass star formation. The advent of sensitive receivers on large radio telescopes such as the JCMT and IRAM 30m MRT has led to the identification of young protostars at the beginning of the main accretion phase ('Class 0' objects), and has made it possible to probe, for the first time, the inner density structure of pre-collapse cores. Class 0 objects are characterized by strong, centrally-condensed dust continuum emission at submillimeter wavelengths, very little emission shortward of $\sim 10\,\mu$m, and powerful jet-like outflows. Direct evidence for gravitational infall has been observed toward several of them. They are interpreted as accreting protostars which have not yet accumulated the majority of their final stellar mass. In contrast to protostars, pre-stellar cores have flat inner density profiles, suggesting the initial conditions for fast protostellar collapse depart sometimes significantly from a singular isothermal sphere. In the case of non-singular initial conditions, the beginning of protostellar evolution is expected to feature a brief phase of vigorous accretion/ejection which may coincide with Class 0 objects. In addition, submillimeter continuum imaging surveys of regions of multiple star formation such as Ophiuchus and Serpens suggest a picture according to which each star in an embedded cluster is built from a finite reservoir of mass and the associated IMF is primarily determined at the pre-stellar stage of evolution.

I. INTRODUCTION

The formation of low-mass stars is believed to involve a series of conceptually different stages (e.g. Larson 1969, Shu, Adams, & Lizano 1987). The first stage corresponds to the fragmentation of a molecular cloud into a number of gravitationally-bound cores which are initially supported against gravity by a combination of thermal, magnetic, and turbulent pressures (e.g. Mouschovias 1991, Shu et al. 1987). These pre-stellar condensations/fragments form and evolve as a result of a still poorly understood mechanism, involving ambipolar diffusion (e.g. Mouschovias 1991), the dissipation of turbulence (e.g. Nakano 1998), and/or an outside impulse (e.g. Bonnell et al. 1997). Once such a condensation becomes gravitationally unstable and collapses, the main *theoretical* features of the ensuing dynamical evolution have been known since the pioneering work of Larson (1969). During a probably brief initial phase, the released gravitational energy is freely radiated away and the collapsing fragment stays roughly isothermal. This "runaway" isothermal collapse phase tends to produce a strong central concentration of matter with a radial density gradient approaching $\rho \propto r^{-2}$ at small radii essentially independently of initial conditions (e.g. Whitworth & Summers 1985, Blottiau et al. 1988, Foster & Chevalier 1993). It ends with the formation of an opaque, hydrostatic protostellar object in the center (e.g. Larson 1969, Boss & Yorke 1995, Bate 1998). Numerical simulations in fact predict the successive formations of two hydrostatic objects, before and after the dissociation of molecular hydrogen respectively (see Boss & Yorke 1995), but we will not distinguish between them here. One then enters the main accretion phase during which the central object builds up its mass ($M_\star$) from a surrounding infalling envelope (of mass M_{env}) and accretion disk, while progressively warming up. In this chapter, we will refer to the system consisting of the central object, plus envelope and disk as an accreting protostar. The youngest accreting protostars have $\mathrm{M_{env}} >> \mathrm{M_\star}$, and radiate the accretion luminosity $L_{acc} \approx GM_\star \dot{M}_{acc}/R_\star$. In the 'standard' theory of isolated star formation (Shu et al. 1987, 1993), the collapse initial conditions are taken to be (static) singular isothermal spheroids ($\rho \sim (a^2/2\pi G)\, r^{-2}$, cf. Li & Shu 1996, 1997), there is no runaway collapse phase, and the accretion rate $\dot{M}_{acc}$ is constant in time $\sim a^3/G$, where a is the effective isothermal sound speed. With other collapse initial conditions, the accretion rate is generally time-dependent (see III–D below).

Observations have shown that the main accretion phase is always accompanied by a powerful ejection of a small fraction of the accreted material in the form of prominent bipolar jets/outflows (e.g. Bachiller 1996). These outflows are believed to carry away the excess angular momentum of the infalling matter (e.g. Königl & Pudritz, this volume). When the central object has accumulated most ($\gtrsim 90\%$) of its final, main-sequence mass, it becomes a pre-main sequence (PMS) star, which evolves approximately at fixed mass on the Kelvin-Helmholtz contraction timescale (e.g. Stahler & Walter 1993). (Note that, during the protostellar accretion phase, stars more massive than a few $0.1\,M_\odot$ start burning deuterium, while stars with masses in excess of $\sim 8\,M_\odot$ begin to burn hydrogen – see Palla & Stahler 1991.)

The details of the earliest stages outlined above are still poorly known. Improving our understanding of these early stages is of prime importance since to some extent they must govern the origin of the stellar initial mass function (IMF).

Observationally, it is by comparing the structure of starless dense cores with that of the envelopes surrounding the youngest stellar objects that one may hope to estimate the initial conditions for protostellar collapse. The purpose of this chapter is to review several major advances made in this field over the last decade, thanks mostly to ground-based (sub)millimeter continuum observations. We discuss results obtained on pre-stellar cores and young accreting protostars in Sect. II and Sect. III, respectively. We then combine these two sets of results and conclude in Sect. IV.

II. PRE-STELLAR CORES

A. Definition and Identification

The pre-stellar stage of star formation may be defined as the phase in which a gravitationally bound core has formed in a molecular cloud, and evolves toward higher degrees of central condensation, but no central hydrostatic protostellar object exists yet within the core.

A pioneering survey of isolated dense cores in dark clouds was carried out in transitions of NH_3 by Myers and co-workers (see Myers & Benson 1983, Benson & Myers 1989 and references therein), who catalogued about 90 cores. These were separated into starless cores and cores with stars (Beichman et al. 1986), on the basis of the presence or absence of an embedded source detected by IRAS. The starless NH_3 cores were identified by Beichman et al. as the potential sites of future isolated low-mass star formation. Other dense core surveys have been carried out by Clemens & Barvainis (1988), Wood et al (1994), Bourke et al (1995a,b), Lee & Myers (1999), and Jessop & Ward-Thompson (1999).

Using the 15 m James Clerk Maxwell Telescope (JCMT), Ward-Thompson et al. (1994) observed the 800-μm dust continuum emission from about 20 starless NH_3 cores from the Benson & Myers list, mapping 4 of the cores, and showed that they have larger FWHM sizes than, but comparable masses to the envelopes of the youngest protostars (Class 0 sources – see III below). This is consistent with starless NH_3 cores being pre-stellar in nature and the precursors of protostars (see also Mizuno et al. 1994). Ward-Thompson et al. also demonstrated that pre-stellar cores do not have density profiles which can be modelled by a single scale-free power law, but instead have flat inner radial density profiles, suggestive of magnetically-supported cores contracting by ambipolar diffusion (see Mouschovias 1991, 1995 and references therein). Recent molecular line spectroscopy of several pre-stellar cores (e.g. Tafalla et al. 1998 and Myers et al. this volume) appears to support the argument that they are contracting, but more slowly than the infall seen toward Class 0 protostars (e.g. Mardones et al. 1997 – see III–C).

The 800 μm study by Ward-Thompson et al. (1994) also suggests that wide-field submillimeter continuum imaging may be a powerful tool to search for new pre-stellar cores in the future (cf. Ristorcelli et al. 1998).

B. Spectral Energy Distributions and Temperatures

The advent of the Infrared Space Observatory (ISO) of the European Space Agency (ESA), has allowed pre-stellar cores to be studied in the far-infrared for the first time (Ward-Thompson et al. 1999a in prep), since these cores were not detected by IRAS. Likewise, the Submillimetre Common User Bolometer Array (SCUBA) camera on the JCMT has allowed pre-stellar cores to be observed in the submm with greater signal to noise than ever before (Ward-Thompson et al. 1999b in prep). Pre-stellar cores emit almost all of their radiation in the FIR/submm/mm regimes, so the combination of these two instruments provides a unique opportunity to study them.

As an illustration, Figure 1 shows a series of images of the L1544 pre-stellar core at 90 & 200 μm (from ISO), 850 μm (from SCUBA), and 1.3 mm (from IRAM). The core is clearly detected at 200–1300 μm, but is almost undetected at 90 μm. This shows that the core is very cold, and its dust temperature can be obtained from fitting a modified black-body to the observed emission. The spectral energy distribution (SED) of L1544 in the far-infrared and submillimeter wavelength regimes is shown in Fig. 2. The solid line is a grey-body curve of the form:

$$S_\nu = B_\nu(T_{dust})\,[1 - \exp(-\tau_\nu)]\,\Delta\Omega\,,$$

where $B_\nu(T_{dust})$ is the Planck function at frequency ν for a dust temperature T_{dust}, $\tau_\nu = \kappa_\nu\,\Sigma$ is the dust optical depth through a mass column density Σ (see below), and $\Delta\Omega$ is the source solid angle. In this simple modelling, the dust opacity per unit (gas + dust) mass column density, κ_ν, is assumed to scale as ν^β with $\beta = 1.5$–2 as usually appropriate in the submillimeter range (e.g. Hildebrand 1983). For L1544, a good fit to the SED is obtained with $T_{dust} = 13$ K and $\beta = 2$. Similar results are obtained in other starless cores. This confirms the lack of any warm dust in such cores, and consequently the lack of any embedded protostellar object. The (sub)millimeter data show a morphology similar to the ISO images, at much higher resolution, indicating that the same dust is being observed at all wavelengths. Consequently the temperature derived from the SED is representative of all the emitting dust and can be used to convert submillimeter fluxes into estimates of dust masses, and hence to gas masses.

C. Mass and Density Structure

Dust emission is generally optically thin at (sub)millimeter wavelengths, and hence is a direct tracer of the mass content of molecular cloud cores. For an isothermal dust source, the total (gas + dust) mass $M(r < R)$ contained within a radius R from the center is related to the submillimeter flux density $S_\nu(\theta)$ integrated over a circle of projected angular radius $\theta = R/d$ by:

$$M(r < R) \equiv \pi R^2 < \Sigma >_R = [S_\nu(\theta)\, d^2]/[\kappa_\nu\, B_\nu(T_{dust})],$$

where $< \Sigma >_R$ is the average mass column density. The dust opacity κ_ν is somewhat uncertain, but the uncertainties are much reduced when appropriate dust models are used (see Henning et al. 1995 for a review). For pre-stellar cores of intermediate densities ($n_{H_2} \lesssim 10^5\ cm^{-3}$), κ_ν is believed to be close to $\kappa_{1.3} = 0.005\,\mathrm{cm}^2\,\mathrm{g}^{-1}$ at 1.3 mm (e.g. Hildebrand 1983, Preibisch et al. 1993). In denser cloud cores and protostellar envelopes, grain coagulation and the formation of ice mantles make κ_ν a factor of ~ 2 larger, i.e., $\kappa_{1.3} = 0.01\ \mathrm{cm}^2\,\mathrm{g}^{-1}$ assuming a gas-to-dust mass ratio of 100 (e.g. Ossenkopf & Henning 1994). A still higher value, $\kappa_{1.3} = 0.02\ \mathrm{cm}^2\,\mathrm{g}^{-1}$, is recommended in protoplanetary disks (Beckwith et al. 1990, Pollack et al. 1994).

Following this method, FWHM masses ranging from $\sim 0.5\ M_\odot$ to $\sim 35\ M_\odot$ are derived for the 9 isolated cores mapped by Ward-Thompson, Motte, & André (1999 – hereafter WMA99).

Although observed pre-stellar cores are generally not circularly or elliptically symmetric (see, e.g., Fig. 1), one can still usefully constrain their radial density profiles by averaging the (sub)millimeter emission in circular or elliptical annuli.

Figure 3a shows the azimuthally-averaged radial intensity profile of the pre-stellar core L1689B at 1.3 mm, compared to the profile of a spherical isothermal core model with $\rho(r) \propto r^{-2}$. The model intensity profile results from a complete simulation taking into account both the observing technique (dual-beam mapping) and the reduction method (cf. André, Ward-Thompson, & Motte 1996). We see that L1689B exhibits the familiar radial profile of pre-stellar cores, with a flat inner region, steepening toward the edges (Ward-Thompson et al. 1994, André et al. 1996, WMA99). In this representative example, the radial density profile inferred assuming a constant dust temperature is as flat as $\rho(r) \propto r^{-0.4}$ (if the 3-D core shape is disk-like) or $\rho(r) \propto r^{-1.2}$ (if the core shape is spheroidal) at radii less than $R_{flat} \sim 4000$ AU, and approaches $\rho(r) \propto r^{-2}$ only between ~ 4000 AU and ~ 15000 AU.

More recently, it has been possible to constrain the outer density gradient of starless cores through *absorption* studies in the mid-infrared with ISOCAM (e.g. Abergel et al. 1996, 1998, Bacmann et al. 1998). It appears that isolated pre-stellar cores are often characterized by sharp edges, steeper than $\rho \propto r^{-3}$ or $\rho \propto r^{-4}$, at radii $R \gtrsim 15000$ AU.

These features of pre-stellar density structure, i.e., inner flattening and sharp outer edge, are qualitatively consistent with models of magnetically-supported cores evolving through ambipolar diffusion prior to protostar formation (e.g. Ciolek & Mouschovias 1994, Basu & Mouschovias 1995), although the models generally require fairly strong magnetic fields ($\sim 100\ \mu$G). Alternatively, the observed structure may also be explained by models of thermally supported self-gravitating cores interacting with an external UV radiation field (e.g. Falgarone & Puget 1985, Chièze & Pineau des Forêts 1987).

D. Lifetimes

Beichman et al. (1986) used the ratio of numbers of starless cores to numbers of cores with embedded IRAS sources to estimate their relative timescales. They found roughly equal numbers of cores with and without IRAS sources. They estimated the lifetime of the stage of cores with stars, based on T Tauri lifetimes and pre-main sequence HR diagram tracks (e.g. Stahler 1988). Based on this, they estimated the lifetime of the pre-stellar core phase to be a few times 10^6 yr.

However, the lifetime of a pre-stellar core depends on its central density. Figure 4 (taken from Jessop & Ward-Thompson 1999) shows the estimated lifetime of starless cores for each of six dark cloud surveys mentioned in II–A above, versus the mean volume density of cores in each sample. The lifespan of cores without stars in each sample was estimated from the fraction of cores with IRAS sources, using the same method as Beichman et al. (1986). An anti-correlation between lifetime and density is clearly apparent in Fig. 4. The solid line has the form $t \propto \rho^{-0.75}$, while the dashed line is of the form $t \propto \rho^{-0.5}$. These two forms are expected for cores evolving on the ambipolar diffusion timescale $t_{AD} \propto x_e$ (where x_e is the ionisation fraction – e.g. Nakano 1984), if the dominant ionisation mechanism is cosmic ray ionisation or UV ionisation, respectively (e.g. McKee 1989).

More details about the evolution of pre-stellar cores at higher densities can be inferred from the results of the submm continuum SCUBA survey of Ward-Thompson et al. (1999b). In this survey, 17 of the 38 NH_3 cores without IRAS sources from Benson & Myers (1989) were detected by SCUBA at 850μm. Ward-Thompson et al. (1999b) estimate that the 17 SCUBA detections all have central densities between $\sim 10^5$cm^{-3} and $\sim 10^6$cm^{-3}, whilst the 21 non-detections must have lower central densities, typically between $\sim 10^4$cm^{-3} and $\sim 10^5$cm^{-3} (see Benson & Myers 1989, Butner et al. 1995, and references therein). Consequently, they deduce that the lifetime of these two phases – central density increasing from $\sim 10^4$cm^{-3} to $\sim 10^5$cm^{-3} compared to central density of $\sim 10^5$cm^{-3} until the formation of a protostellar object at the center – must be roughly equal. This can be compared with the predictions of ambipolar diffusion models.

Figure 3b is taken from Ciolek & Mouschovias (1994) and shows the radial density profile predicted by an ambipolar diffusion model at different evolutionary stages (t_0 to t_6). The stage at which the central density is $\sim 10^4 \mathrm{cm}^{-3}$ corresponds to time t_1 and the stage at which the central density is $\sim 10^5 \mathrm{cm}^{-3}$ corresponds to time t_2. The time at which a protostellar object forms is effectively t_6. In this model the time taken to go from t_1 to t_2 ($\sim 2 \times 10^6$ yr) is six times longer than the time taken to go from t_2 to t_6. Some discrepancy could perhaps be accounted for by the statistical errors associated with our source number counting technique, but the ratio between the two timescales should be fairly robust: The model predicts that SCUBA should only have detected $\sim 1/7$ of the cores, whereas it detected half of the sample.

We are left with the conclusion that *cores at central densities of order $\sim 10^5 cm^{-3}$ evolve more slowly than ambipolar diffusion models predict* – i.e. the cores experience more support than a simple static magnetic field can provide. The extra support could perhaps be provided by turbulence which generates non-static magnetic fields (e.g. Gammie & Ostriker 1996, Nakano 1998, Balsara et al. 1998).

E. Pre-Stellar Condensations in Star-Forming Clusters

In regions of multiple star formation, submillimeter dust continuum mapping has revealed a wealth of small-scale cloud fragments, sometimes organized along filaments (e.g. Mezger et al. 1992, AWB93, Casali et al. 1993, Launhardt et al. 1996, Chini et al. 1997b, Johnstone & Bally 1999). Such fragmentation along filaments has not been observed in Taurus, but examples do exist in young embedded clusters forming primarily low-mass stars like ρ Ophiuchi (Motte, André, & Neri 1998). The individual fragments, which are denser ($< n > \gtrsim 10^6$–10^7 cm^{-3}) and more compact (a few 1000 AU in size) than the isolated pre-stellar cores discussed above, often remained totally undetected (in emission) by *IRAS* or ISO in the mid- to far-IR. Since molecules tend to freeze out onto dust grains at low temperatures and high densities, (sub)millimeter dust emission may be the most effective tracer of such condensations (e.g. Mauersberger et al. 1992).

The most centrally-condensed of these starless fragments have been claimed to be isothermal protostars, i.e., collapsing condensations with no central hydrostatic object (see I) (e.g. Mezger et al. 1992, Launhardt et al. 1996, Motte et al. 1998). Good examples are FIR 3 and FIR 4 in NGC 2024, OphA-SM1 and OphE-MM3 in ρ Oph, LBS 17-SM in Orion B, or MMS1 and MMS4 in OMC-3. This isothermal protostar interpretation remains to be confirmed, however, by observations of appropriate spectral line signatures (cf. Myers et al. this volume).

Furthermore, the advent of large-format bolometer arrays now makes possible systematic studies of the genetic link between pre-stellar cloud fragments and young stars. Figure 5 is a 1.3 mm continuum wide-field mosaic of the ρ Oph cloud (Motte et al. 1998) showing a total of 100 structures with characteristic angular scales of $\sim 15''$–$30''$ (i.e., $\sim$ 2000–4000 AU), which are associated with 59 starless condensations (undetected by ISO in the mid-IR) and 41 embedded YSOs (detected at IR or radio continuum wavelengths).

Comparison of the masses derived from the 1.3 mm continuum (from $\sim 0.05 M_\odot$ to $\sim 3 M_\odot$) with Jeans masses suggests that most of the 59 starless fragments are close to gravitational virial equilibrium with $M/M_{vir} \gtrsim$ 0.3–0.5 and will form stars in the near future. These pre-stellar condensations generally have flat inner density profiles like isolated pre-stellar cores, but are distinguished by compact, finite sizes of a few thousand AU. The typical fragmentation lengthscale derived from the average projected separation between condensations is $\sim$ 6000AU in ρ Oph. This is $\sim$ 5 times smaller than the radial extent of isolated dense cores in the Taurus cloud (see Gómez et al. 1993).

Figure 6 shows the mass distribution of the 59 ρ Oph pre-stellar fragments. It follows approximately $\Delta N/\Delta M \propto M^{-1.5}$ below $\sim 0.5 M_\odot$, which is similar to the clump mass spectrum found by large-scale molecular line studies (e.g. Blitz 1993 and Williams et al. this volume). The novel feature, however, is that the fragment mass spectrum found at 1.3 mm in ρ Oph appears to steepen to $\Delta N/\Delta M \propto M^{-2.5}$ above $\sim 0.5 M_\odot$. A similarly steep mass spectrum above $\sim 0.5 M_\odot$ was obtained by Testi & Sargent (1998) for compact 3 mm starless condensations in the Serpens core. These pre-stellar mass spectra resemble the shape of the *stellar* initial mass function (IMF), which is known to approach $\Delta N/\Delta M_\star \propto M_\star^{-2.7}$ for $1\,M_\odot \lesssim M_\star \lesssim 10\,M_\odot$ and $\Delta N/\Delta M_\star \propto M_\star^{-1.2}$ for $0.1\,M_\odot \lesssim M_\star \lesssim 1\,M_\odot$ (e.g. Kroupa et al. 1993, Tinney 1993, 1995, Scalo 1998, see also Meyer et al. this volume). Given the factor of ~ 2 uncertainty on the measured pre-stellar masses, such a resemblance is remarkable and suggests that *the IMF of embedded clusters is primarily determined at the pre-stellar stage of star formation* (see also IV below).

III. THE YOUNGEST PROTOSTARS

A. Class 0 Protostars and Other YSO Stages

1. Infrared YSO classes. In the near-/mid-infrared, three broad classes of young stellar objects (YSOs) can be distinguished based on the slope $\alpha_{\rm IR} = {\rm dlog}(\lambda F_\lambda)/{\rm dlog}(\lambda)$ of their SEDs between 2.2 μm and 10–25 μm, which are interpreted in terms of an evolutionary sequence (Lada & Wilking 1984, Lada 1987). Going backward in time, Class III ($\alpha_{\rm IR} < -1.5$) and Class II ($-1.5 < \alpha_{\rm IR} < 0$) sources correspond to

PMS stars ("Weak" and "Classical" T Tauri stars, respectively) surrounded by a circumstellar disk (optically thin and optically thick at $\lambda \lesssim 10$ μm, respectively), but lacking a dense circumstellar envelope (see André & Montmerle 1994 – hereafter AM94). The youngest YSOs detected at 2 μm are the Class I sources, which are characterized by $\alpha_{\rm IR} > 0$ (e.g. Wilking, Lada, & Young 1989 – WLY89), and the close association with dense molecular gas (e.g. Myers et al. 1987). Class I objects are now interpreted as relatively evolved protostars with typical ages ~ 1–2×10^5 yr (e.g. Barsony & Kenyon 1992, Greene et al. 1994, Kenyon & Hartmann 1995), surrounded by both a disk and a diffuse circumstellar envelope of substellar ($\lesssim$ 0.1–0.3 $M_\odot$) mass (Whitney & Hartmann 1993, Kenyon et al. 1993b, AM94, Lucas & Roche 1997). Their SEDs are successfully modeled in the framework of the "standard" theory of isolated protostars (e.g. Adams, Lada, & Shu 1987, Kenyon et al. 1993a), in agreement with the idea that they derive a substantial fraction of their luminosity from accretion (see also Greene & Lada 1996 and Kenyon et al. 1998).

2. Class 0 protostars. Several condensations detected in submillimeter dust continuum maps of molecular clouds (e.g. II–E) appear to be associated with formed, hydrostatic YSOs and have been designated "Class 0" protostars (André, Ward-Thompson, & Barsony 1993 – AWB93). Specifically, Class 0 objects are defined by the following observational properties (AWB93):

• (i) Indirect evidence for a central YSO, as indicated by, e.g., the detection of a compact centimeter radio continuum source, a collimated CO outflow, or an internal heating source.

• (ii) Centrally peaked but extended submillimeter continuum emission tracing the presence of a spheroidal circumstellar dust envelope (as opposed to just a disk).

• (iii) High ratio of submillimeter to bolometric luminosity suggesting the envelope mass exceeds the central stellar mass: $L_{smm}/L_{bol} > 0.5\%$, where L_{smm} is measured longward of 350 μm. In practice, this often means a SED resembling a single temperature blackbody at T $\sim$ 15–30 K (see Fig. 2).

Property (i) distinguishes Class 0 objects from the pre-stellar cores and condensations discussed in Sect. II. In particular, deep VLA observations reveal no compact radio continuum sources in the centers of pre-stellar cores (Bontemps 1996, Yun et al. 1996). Properties (ii) and (iii) distinguish Class 0 objects from more evolved (Class I and Class II) YSOs. As shown by AWB93, the L_{smm}/L_{bol} ratio should roughly track the ratio $M_{env}/M_\star$ of envelope to stellar mass, and may be used as an evolutionary indicator (decreasing with time), for low-luminosity ($L_{bol} \lesssim 50\,L_\odot$) embedded YSOs. Criterion (iii) approximately selects objects which have $M_{env}/M_\star > 1$, assuming plausible relations between L$_{bol}$ and $M_\star$ on the one hand and between L$_{\rm smm}$ and M_{env} on the other hand (see AWB93 and AM94). [A roughly equivalent criterion is $M_{env}/L_{bol} > 0.1\ M_\odot/L_\odot$.] *Class 0 objects are therefore excellent candidates for being very young accreting protostars in which a hydrostatic core has formed but not yet accumulated the majority of its final mass.* In practice, most of the confirmed Class 0 objects listed in Table 1 have L$_{smm}$/L$_{bol}$ >> 0.5% and are likely to be at the beginning of the main accretion phase with $M_{env} >> M_\star$ (see Fig. 7b).

3. Evolutionary diagrams for embedded YSOs. Combining infrared and submillimeter data, it is therefore possible to define a complete, empirical evolutionary sequence (Class 0 → Class I → Class II → Class III) for low-mass YSOs, which likely correspond to conceptually different stages of evolution: (early) main accretion phase, late accretion phase, PMS stars with protoplanetary disks, PMS stars with debris disks (see AM94). This sequence is quasi-continuous and may be parameterized by the "bolometric temperature", T_{bol}, defined by Myers & Ladd (1993) as the temperature of a blackbody having the same mean frequency as the observed YSO SED. Myers & Ladd proposed to use the L_{bol}–T_{bol} diagram for embedded YSOs as a direct analog to the H–R diagram for optically visible stars. As shown by Chen et al. (1995, 1997), YSOs with known classes have distinct ranges of T_{bol}: < 70 K for Class 0, 70–650 K for Class I, 650–2880 K for Class II, and > 2880 K for Class III (e.g. Fig. 7a). The evolution of T_{bol} and L_{bol} from the Class 0 stage to the zero-age main sequence has been modelled in the context of various envelope-dissipation scenarios by Myers et al. (1998).

A perhaps more direct approach to tracking the circumstellar evolution of YSOs is to use the circumstellar mass $M_{c\star}$ derived from (sub)millimeter continuum measurements of optically thin dust emission. Such measurements show that $M_{c\star}$ ($= M_{env} + M_{disk}$) is generally dominated by M_{env} in Class 0/Class I sources (e.g. Terebey et al. 1993) and decreases by a factor $\sim$ 5–10 on average from one YSO class to the next (AM94). In the spirit of the L$_{smm}$/L$_{bol}$ evolutionary indicator of AWB93, Saraceno et al. (1996a) proposed the L_{smm}–L_{bol} (or equivalently M_{env}–L_{bol}) diagram as an alternative evolutionary diagram for self-embedded YSOs. While L$_{smm}$ and M_{env} are well correlated with L$_{bol}$ for the majority of embedded YSOs (e.g. Reipurth et al. 1993), Class 0 objects clearly stand out from Class I sources in this diagram as objects with excess (sub)millimeter emission, i.e., excess circumstellar material (see Fig. 7b). Moreover, one may compare the locations of observed embedded sources in the M_{env}–L_{bol} diagram with simple protostellar evolutionary tracks (Saraceno et al. 1996a,b). Qualitatively at least, scenarios in which the mass-accretion rate decreases with time for a given protostar (Bontemps et al. 1996a, Myers et al. 1998 – see also III–D below) and increases with the mass of the initial pre-collapse fragment (e.g. Myers & Fuller 1993, Reipurth et al. 1993, Saraceno et al. 1996b) yield tracks in better agreement with observations than the constant-rate scenario discussed by Saraceno et al. (1996a). In particular, the peak accretion luminosity is reduced by a factor $\sim$ 2–4 compared to the constant-rate scenario (cf. Bontemps et al. 1996a, Myers et al. 1998, and Fig. 7b), which agrees better with observed luminosities (e.g. Kenyon & Hartmann 1995).

Inclination effects may a priori affect the positions of individual protostellar objects in these evolutionary diagrams. In particular, it has been claimed that some Class I sources may potentially look like Class 0 objects when observed at high inclination angles to the line of sight (e.g. Yorke, Bodenheimer, & Laughlin 1995, Sonnhalter, Preibisch, & Yorke 1995, Men'shchikov & Henning 1997). However, the fact that Class 0 objects are associated with an order of magnitude more powerful outflows than Class I sources (see III–D below) confirm that these two types of YSOs differ qualitatively from each other. Furthermore, some Class 0 sources are known to have small inclination angles (e.g. Cabrit & Bertout 1992, Greaves et al. 1997, Wolf-Chase et al. 1998). We also stress that existing (sub)millimeter maps of dust continuum and $C^{18}O$ emission provide direct evidence that both Class I and Class 0 objects are *self-embedded* in substantial amounts of circumstellar material distributed in spatially resolved, spheroidal envelopes (e.g. AM94, Chen et al. 1997, Ladd et al. 1998, Dent et al. 1998 – see also III–B below). This material has the ability to absorb the optical and near-IR emission from the underlying star/disk system and to reradiate it quasi-isotropically at longer far-IR and (sub)mm wavelengths. In such a self-embedded configuration, viewing-angle effects are minimized, as confirmed by radiative transfer calculations (e.g. Efstathiou & Rowan-Robinson 1991, Yorke et al. 1995). Physically, this is because the bulk of the luminosity emerges at long wavelengths where most of the emission is effectively optically thin. However, the short-wavelength emission from the inner star/disk remains very dependent on viewing angle, implying that T_{bol} estimates should be somewhat more sensitive to orientation effects than L_{bol} and L_{smm}/L_{bol}.

4. Protostar surveys and lifetime estimates. Based on the key attributes of Class 0 protostars (see 2. above), various strategies can be used to search for and discover new candidates: (sub)millimeter continuum mapping (e.g. Mezger et al. 1992, Casali et al. 1993, Sandell & Weintraub 1994, Reipurth et al. 1996, Launhardt et al. 1996, Chini et al. 1997ab, Motte et al. 1998, André et al. 1999), HIRES processing of the IRAS data (Hurt & Barsony 1996, O'Linger et al. 1999), deep radio continuum VLA surveys (e.g. Leous et al. 1991, Bontemps et al. 1995, Yun et al. 1996, Moreira et al. 1997, Gibb 1999), CO mapping (e.g. Bachiller et al. 1990, André et al. 1990, Bourke et al. 1997), and large-scale near-IR/optical imaging of shocked H_2 and [SII] emission (e.g. Hodapp & Ladd 1995, Yu, Bally, & Devine 1997, Wilking et al. 1997, Gómez et al. 1998, Stanke et al. 1998, Phelps & Barsony 1999).

Class 0 objects appear to be short-lived compared to both pre-stellar cores/fragments (see Sect. II above) and Class I near-IR sources. For example, in the ρ Oph main cloud where the IRAM 30 m mapping study of Motte et al. (1998) provides a reasonably complete census of both pre- and proto-stellar condensations down to $\lesssim 0.1\ M_\odot$, there are only two good Class 0 candidates (including the prototypical object VLA 1623 – AWB93), while there are $\sim$ 15–30 near-IR Class I sources (e.g. WLY89, AM94, Greene et al. 1994, Barsony & Ressler 1999, Bontemps et al. 1999).

Under the assumption that ρ Oph is representative and forming stars at a roughly constant rate, the lifetime of Class 0 objects should thus be approximately an order of magnitude shorter than the lifetime of Class I sources (see 1. above), i.e., typically $\sim$ 1–3 $\times 10^4$ yr. The jet-like morphology and short dynamical timescales of Class 0 outflows are consistent with this estimate (e.g. Barsony et al. 1998, see III–D below). A lifetime as short as a few 10^4 yr supports the interpretation of Class 0 objects as very young accreting protostars (see, e.g., Fletcher & Stahler 1994 and Barsony 1994).

Regions like the Serpens, Orion, or Perseus/NGC1333 complexes seem to be particularly rich in Class 0 objects, and this is probably indicative of fairly high levels of ongoing, likely induced star formation activity (e.g. Hurt & Barsony 1996, Chini et al. 1997b, Yu et al. 1997, Barsony et al. 1998). For instance, we estimate the current star formation rate in Orion-OMC-3 to be $\sim 2\times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$, which is 1–2 orders of magnitude larger than the star formation rates characterizing the Trapezium, NGC 1333, and IC 348 near-IR clusters when averaged over $\gtrsim 10^6$ yr periods (see Lada, Alves, & Lada 1996).

B. Density Structure of the Protostellar Environment

1. Envelope. In contrast to *pre-stellar* cores, the envelopes of low-mass Class 0 and Class I *protostars* are always found to be strongly centrally-condensed and do *not* exhibit any inner flattening in their (sub)millimeter continuum radial intensity profiles. In practice, this means that, when protostars are mapped with the resolution of the largest single-dish telescopes, the measured peak flux density is typically a fraction $\gtrsim 20\%$ of the flux integrated over five beam widths. For comparison, the same fraction is $\lesssim 10\%$ for pre-stellar cores. (Sub)millimeter continuum maps indicate that protostellar envelopes in regions of isolated star formation such as Taurus have radial density gradients generally consistent with $\rho(r) \propto r^{-p}$ with $p \sim 1.5$–2 over more than $\sim$ 10000–15000 AU in radius (e.g. Walker, Adams, & Lada 1990, Ladd et al. 1991, Motte 1998, Motte et al. 1999, see also Mundy et al. this volume). The estimated density gradient thus agrees with most collapse models which predict a value of p between 1.5 and 2 during the protostellar accretion phase (e.g. Whitworth & Summers 1985). Some studies have, however, inferred shallower density gradients ($p \sim 0.5$–1 – e.g. Barsony & Chandler 1993, Chandler, Barsony, & Moore 1998). In any case, the densities and masses measured for the envelopes around the bona-fide Class I objects of Taurus appear to be consistent within a factor of ~ 4 with the predictions of the "standard" inside-out collapse theory (e.g. Shu et al. 1993) for $\sim 10^5$ yr-old, isolated protostars (Motte 1998, Motte et al. 1999).

The situation is markedly different in star-forming clusters. In ρ Ophiuchi in particular, the circumstellar envelopes of Class I and Class 0 protostars are observed to be very compact: they merge with dense cores, other envelopes, and/or the diffuse ambient cloud at a *finite* radius $R_{out} \lesssim 5\,000$ AU (Motte et al. 1998). This is $\gtrsim$ 3 times smaller than the collapse expansion wavefront at a 'Class I age' of $\sim 2 \times 10^5$ yr in the standard theory of isolated protostars, emphasizing the fact that each YSO has a finite 'sphere of influence' in ρ Oph. Similar results were obtained in the case of the Perseus Class 0 sources NGC1333-4A, NGC1333-2, L1448-C, and L1448-N (e.g. Motte 1998). Moreover, the envelopes of these Perseus protostars are 3 to 10 times denser than the singular isothermal sphere for a sound speed $a = 0.2$ km s^{-1}. This suggests that, prior to collapse, the main support against gravity was turbulent and/or magnetic in origin rather than purely thermal (see also Mardones et al. 1997).

2. Disks and multiplicity. Many Class 0 protostars are in fact multiple systems, when viewed at sub-arcsecond resolution, sharing a common envelope and sometimes a circumbinary disk (e.g. Looney et al. 1999 – see also col. 11 of Table 1 and chapter by Mundy, Looney, & Welch). These protobinaries probably formed by dynamical fragmentation during (or at the end of) the isothermal collapse phase (e.g. Chapman et al. 1992, Bonnell 1994, Boss & Myhill 1995). Interestingly enough, only cores with inner density profiles as flat as $\rho \propto r^{-1}$ or flatter (like observed pre-stellar cores – see Sect. II), can apparently fragment during collapse (Myhill & Kaula 1992, Boss 1995, Burkert et al. 1997).

Despite the difficulty of discriminating between the disk and envelope components, existing (sub)millimeter continuum interferometric measurements suggest that the "disks" of Class 0 objects are a factor of $\gtrsim 10$ less massive than their surrounding circumstellar envelopes (e.g. Chandler et al. 1995, Pudritz et al. 1996, Looney et al. 1999, Hogerheijde 1998, Motte 1998, Wilner & Lay this volume).

C. Direct Evidence for Infall

Rather convincing spectroscopic signatures of gravitational infall have been reported toward several Class 0 objects, confirming their protostellar nature (e.g. Walker et al. 1986, Zhou et al. 1993, Gregersen et al. 1997, Mardones et al. 1997, see also col. 10 of Table 1). Inward motions can be traced by optically thick molecular lines which should (locally) exhibit asymmetric self-absorbed profiles skewed to the blue (see Myers, Evans, & Ohashi, this volume). The interpretation is often complicated by the simultaneous presence of rotation and/or outflow (e.g. Menten et al. 1987, Walker et al. 1994, Cabrit et al. 1996).

A comprehensive survey of a sample of 47 embedded YSOs in $H_2CO(2_{12}-1_{11})$ and CS(2–1) suggests that infall is more prominent in Class 0 than in Class I sources (Mardones et al. 1997): In these transitions, infall asymmetries are detected toward 40–50 % of Class 0 objects but less than 10 % of Class I sources. This is qualitatively consistent with a decline of infall/accretion rate with evolutionary stage (see III–D below). However, a more recent survey by Gregersen et al. (1999) using HCO^+(3–2) finds no difference in the fraction of sources with "blue profiles" between Class 0 and Class I sources. The HCO^+(3–2) line is more optically thick than $H_2CO(2_{12}-1_{11})$ and CS(2–1), hence a better tracer of infall at advanced stages. This result shows that some infall is still present at the Class I stage but remains consistent with a decline of the net accretion rate with time. The outflow is so broad in Class I sources that there often appears to be little transfer of mass to the inner $\sim$ 2000 AU radius region around these objects (e.g. Fuller et al. 1995b, Cabrit et al. 1996, Brown & Chandler 1999).

D. Decline of Outflow and Inflow with Time

1. Evolution from Class 0 to Class I. Most, if not all, Class 0 protostars drive powerful, "jet–like" CO molecular outflows (see, e.g., Bachiller 1996 and Richer et al., this volume, for reviews). The mechanical luminosities of these outflows are often of the same order as the bolometric luminosities of the central sources (e.g. Curiel et al. 1990, AWB93, Barsony et al. 1998). In contrast, while there is good evidence that some outflow activity exists throughout the accretion phase (e.g. Terebey et al. 1989, Parker et al. 1991, Bontemps et al. 1996a), the CO outflows from Class I sources tend to be much less powerful and less collimated than those from Class 0 objects.

In an effort to quantify the evolution of mass loss during the protostellar phase, Bontemps et al. (1996a – hereafter BATC) obtained and analyzed a homogeneous set of CO(2–1) outflow data around a large sample of low-luminosity ($L_{bol} < 50\ L_\odot$), nearby ($d < 450$ pc) self-embedded YSOs. Their results show that Class 0 objects lie an order of magnitude above the well-known (e.g. Cabrit & Bertout 1992) correlation between outflow momentum flux (F_{CO}) and bolometric luminosity ($L_{\rm bol}$) holding for Class I sources (see $F_{\rm CO}$ –$L_{\rm bol}$ diagram shown in Fig. 5 of BATC). Furthermore, BATC found that $F_{\rm CO}$ was well correlated with M_{env} in their *entire* sample (including both Class I and Class 0 sources). The same correlation was noted independently on other source samples by Moriarty-Schieven et al. (1994), Hogerheijde et al. (1998), and Henning & Launhardt (1998). As argued by BATC, this new correlation is independent of the $F_{\rm CO}$ –$L_{\rm bol}$ correlation and most likely results from a progressive decrease of outflow power with time during the accretion phase. This is illustrated in the normalized $F_{\rm CO}\, {\rm c}/{\rm L_{bol}}$ versus $M_{\rm env}/L_{\rm bol}^{0.6}$ diagram of Fig. 8, which should be essentially free of any luminosity effect.

Since magneto-centrifugal accretion/ejection models of bipolar outflows (e.g. Shu et al. 1994, Ferreira & Pelletier 1995, Fiege & Henriksen 1996, Ouyed & Pudritz 1997) predict a direct proportionality between accretion and ejection, BATC proposed that the decline of outflow power with evolutionary stage seen in Fig. 8 reflects a corresponding decrease in the mass-accretion/infall rate. The results of BATC indicate that $\dot{M}_{\rm jet}$ declines from $\sim 10^{-6}\,{\rm M_\odot\,yr^{-1}}$ for the youngest Class 0 protostars to $\sim 2\times10^{-8}\,{\rm M_\odot\,yr^{-1}}$ for the most evolved Class I sources, suggesting a decrease in $\dot{M}_{\rm acc}$ from $\sim 10^{-5}\,{\rm M_\odot\,yr^{-1}}$ to $\sim 2\times10^{-7}\,{\rm M_\odot\,yr^{-1}}$ if realistic jet model parameters are adopted ($\dot{M}_{\rm jet}/\dot{M}_{\rm acc} \sim 0.1$–$0.3$, $V_{\rm jet} \sim 100\,{\rm km\,s^{-1}}$). These indirect estimates of $\dot{M}_{\rm acc}$ for Class 0 and Class I protostars should only be taken as indicative of the true evolutionary trend. Nevertheless, it is interesting to note that they agree well with independent estimates of the rates of envelope dissipation based on circumstellar mass versus age arguments (Ward-Thompson 1996, Ladd, Fuller, & Deane 1998).

As illustrated by the evolutionary tracks of Fig. 7b, a decline of $\dot{M}_{\rm acc}$ with time does not imply a higher accretion luminosity for Class 0 objects compared to Class I sources because the central stellar mass is smaller at the Class 0 stage and the stellar radius is likely to be larger (see Henriksen, André, & Bontemps 1997 – hereafter HAB97).

2. Link with the collapse initial conditions. The apparent decay of $\dot{M}_{\rm acc}$ from the Class 0 to the Class I stage may be linked with the density structure observed for pre-stellar cores/condensations (Sect. II). (Magneto)hydrodynamic collapse models predict a time-dependent accretion history when the radial density profile at the onset of fast protostellar collapse differs from $\rho \propto r^{-2}$ (e.g. Foster & Chevalier 1993 – FC93, Tomisaka 1996, McLaughlin & Pudritz 1997, HAB97, Basu 1997, Safier, McKee, & Stahler 1997, Li 1998, Ciolek & Königl 1998). In particular, when starting from Bonnor-Ebert-like initial conditions resembling observed pre-stellar cores, these studies find that supersonic infall velocities develop prior to the formation of the central hydrostatic protostellar object at $t = 0$ (see, e.g., FC93). Observationally, this early collapse phase should correspond to 'isothermal protostars' (see II–E for possible examples). During the protostellar accretion phase ($t > 0$), because of the significant infall velocities achieved at $t < 0$, $\dot{M}_{\rm acc}$ is initially higher than the standard $\sim a^3/G$ value obtained for the inside-out collapse of a static singular isothermal sphere (Shu 1977, see also Sect. I). The accretion rate then converges toward the standard value of the Shu solution, and declines again below a^3/G at late times if the reservoir of mass is finite. By comparison with the rough estimates of $\dot{M}_{\rm acc}$ given above, it is tempting to identify the short period of energetic accretion ($\dot{M}_{\rm acc} \sim 10 \times a^3/G$) predicted by the models just after point-mass formation with the observationally-defined Class 0 stage (HAB97, see Fig. 8). In this view, the more evolved Class I objects would correspond to the longer period of moderate accretion/ejection when the accretion rate approaches the standard value ($\dot{M}_{\rm acc} \lesssim a^3/G \sim 2 \times 10^{-6}\,{\rm M_\odot\,yr^{-1}}$ for a cloud temperature of ~ 10 K). Using simple pressure-free analytical calculations (justified since the inflow becomes supersonic early on), HAB97 could indeed find a good overall fit to the empirical accretion history inferred by BATC on the basis of CO outflow observations (see Fig. 8).

In the absence of magnetic fields, FC93 have shown that the timescale for convergence to the standard accretion rate of Shu (1977) depends on the radius of the flat inner core (R_{flat}) relative to the outer radius of the initial pre-collapse condensation (R_{out}). They found that a phase of constant $\sim a^3/G$ accretion rate is achieved only when $R_{out}/R_{flat} \gtrsim 20$, typically after ~ 10 free-fall times of the flat inner region, for a period lasting ~ 15 free-fall times when $R_{out}/R_{flat} = 20$ and progressively longer as R_{out}/R_{flat} increases. Since observations suggest $R_{out}/R_{flat} \lesssim 3$ in Ophiuchus and $R_{out}/R_{flat} \gtrsim 15$ in Taurus (see II–C, III–B, and Motte et al. 1998), one may expect a marked time-dependence of $\dot{M}_{\rm acc}$ in Ophiuchus but a reasonable agreement with the constant accretion rate of the self-similar theory of Shu et al. (1987, 1993) in Taurus. Indeed, HAB97 note that there is a much better continuity between Class 0 and Class I protostars in Taurus than in Ophiuchus (see also André 1997).

Finally, we stress that the absolute values of $\dot{M}_{\rm acc}$ in the Class 0 and Class I stages are presently quite uncertain. An alternative interpretation of the evolution seen in Fig. 8 is that Class 0 protostars accrete at a rate roughly consistent with $\sim a^3/G$, while most Class I sources are in a terminal accretion phase with $\dot{M}_{\rm acc} \lesssim 0.1 \times a^3/G$, resulting from the finite effective reservoir of mass available to each object in clusters (e.g. Motte et al. 1998 and III–B) and/or from the effects of outflows dispersing the envelope (e.g. Myers et al. 1998, Ladd et al. 1998). Distinguishing between this possibility and that advocated above will require direct measurements of the mass accretion rates.

IV. CONCLUSIONS AND IMPLICATIONS

The observational studies discussed in Sect. II demonstrate that pre-stellar cores/fragments are characterized by flat inner radial density gradients. This, in turn, suggests the initial conditions for fast protostellar collapse are non-singular, i.e., the density profile at the onset of collapse is not infinitely centrally condensed. (Sub)millimeter observations also set strong constraints on protostellar evolution (Sect. III). The fact that young (Class 0) protostars drive more powerful outflows than evolved (Class I) protostars suggests that the mass accretion rate $\dot{M}_{\rm acc}$ decreases by typically a factor of $\sim$ 5–10 from the Class 0 to the Class I stage (III–D). Such a decline in $\dot{M}_{\rm acc}$ during the protostellar accretion phase may be the direct result of a flattened initial density profile (see III–D). Based on these observational constraints, we suggest that most protostars form in a dynamical rather than quasi-static fashion.

The results summarized in this chapter also have broader implications concerning, e.g., the origin of the IMF. As pointed out in Sect. II–E, the pre-stellar condensations observed in regions of multiple star formation such as ρ Ophiuchi are finite-size structures, typically a few 1000 AU in radius, which are clearly not scale-free. This favors a picture of star formation in clusters in which individual protostellar collapse is initiated in compact dense clumps resulting from fragmentation and resembling more finite-size Bonnor-Ebert cloudlets than singular isothermal spheres. Such condensations may correspond to dense, low-ionization pockets decoupling themselves from the parent molecular cloud as a result of ambipolar diffusion and/or the dissipation of turbulence (e.g. Mouschovias 1991, Myers 1998, Nakano 1998). They would thus be free to undergo Jeans-like gravitational instabilities and collapse under the influence of external disturbances, of which there are many types in regions of multiple star formation (e.g. Pringle 1989, Whitworth et al. 1996, Motte et al. 1998, Barsony et al. 1998). By contrast, the low-density regions of the ambient cloud, being more ionized, would remain supported against collapse by static and/or turbulent magnetic fields. The typical separation between individual condensations should be of order the Jeans length in the parent cloud/core, in rough agreement with observations (e.g. Motte et al. 1998).

In this observationally-driven scenario of fragmentation and collapse, stars are built from bounded fragments which represent finite reservoirs of mass. The star formation efficiency within these fragments is high: most of their 'initial' masses at the onset of collapse end up in stars. If this is true, it implies that the physical mechanisms responsible for the formation of pre-stellar cores/condensations in molecular clouds, such as turbulent fragmentation (e.g. Padoan, Nordlund, & Jones 1997), play a key role in determining the IMF of embedded clusters. Such a picture, which we favor for regions of multiple star formation, is consistent with some theoretical scenarios of protocluster formation (e.g. Larson 1985, Klessen, Burkert, & Bate 1998). It need not be universal, however, and is in fact unlikely to apply to regions of isolated star formation like the Taurus cloud. In these regions, protostars may accrete from larger reservoirs of mass, and feed-back processes such as stellar winds may be more important in limiting accretion and defining stellar masses (e.g. Shu et al. 1987, Silk 1995, Adams & Fatuzzo 1996, Velusamy & Langer 1998).

With the advent of major new facilities at far-IR and submillimeter wavelengths, the next decade promises to be at least as rich in observational discoveries as the past ten years. By combining the capabilities of space telescopes such as FIRST with those of large ground-based arrays such as the LSA/MMA, it will be possible to study the detailed physics of complete samples of young protostars and pre-collapse fragments, in a variety of star-forming clouds, and down to the brown-dwarf mass regime. This should tremendously improve our global understanding of the initial stages of star formation in the Galaxy.

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FIGURE CAPTIONS

Figure 1. Dust continuum images of L1544 at 90 μm (a) and 200 μm (b) from ISOPHOT, at 850 μm (c) from SCUBA, and at 1.3 mm (d) from IRAM 30 m. A polarization E-vector, perpendicular to the B field, is overlaid on the 850 μm image (c), as measured with the SCUBA polarimeter. The observed morphology is consistent with a magnetically-supported core that has flattened along the direction of the mean magnetic field.

Figure 2. Spectral energy distributions of the pre-stellar core L1544 and the Class 0 protostar IRAS 16293, along with grey-body fits (see text). The L1544 SED is based on ISOPHOT, JCMT, and IRAM data from Ward-Thompson et al. (1999a,b). The IRAS 16293 SED is based on IRAS, ISO-LWS (Correia, Griffin et al. 1999 in prep. – see also Ceccarelli et al. 1998), and JCMT data (Sandell 1994). Note that a simple grey-body model cannot account for the 25 μm emission of IRAS 16293 and that a two-component model is required (Correia et al. 1999).

Figure 3. (a) (left) Radial intensity profile of L1689B at 1.3 mm illustrating that pre-stellar cores have flat inner density profiles (from André, Ward-Thompson, & Motte 1996). For comparison, the dotted curve shows a spherical isothermal model with $\rho(r) \propto r^{-1.2}$ for $r < 4000$ AU and $\rho(r) \propto r^{-2}$ for $r \geq 4000$ AU. The dash-dotted curve shows a model with $\rho(r) \propto r^{-2}$ such as a singular isothermal sphere (SIS).

(b) (right) Typical density profiles expected for a magnetically supported core undergoing ambipolar diffusion at various times increasing from t_0 to t_6 (from Ciolek & Mouschovias 1994). The normalization values are $n_{n,c0} = 2.6 \times 10^3$ cm^{-3} and $R_0 = 4.29$ pc. Open circles mark the instantaneous radius of the uniform-density central region; starred circles mark the radius of the magnetically supercritical region (present only for $t \geq t_2$).

Figure 4. Plot of lifetime vs. mean density for six core samples compared with $t \propto \rho^{-0.75}$ and $t \propto \rho^{-0.5}$ as predicted by ambipolar diffusion models with different ionisation mechanisms (Jessop & Ward-Thompson 1999).

Figure 5. Dust continuum mosaic of the ρ Oph cloud taken at 1.3 mm with the IRAM 30m telescope and the MPIfR bolometer array (Motte, André, & Neri 1998).

Figure 6. Mass spectrum of the 59 pre-stellar fragments extracted from the ρ Oph 1.3 mm continuum mosaic shown in Fig. 5 (from Motte et al. 1998). For comparison, dotted and long-dashed lines show power laws of the form $\Delta N/\Delta M \propto M^{-1.5}$ and $\Delta N/\Delta M \propto M^{-2.5}$, respectively. This pre-stellar mass spectrum is remarkable in that it resembles the shape of the IMF.

Figure 7. (a) L_{bol}–T_{bol} diagram for 14 well-documented YSOs along with three model evolutionary tracks for various (final) stellar masses and cloud temperatures (from Myers et al. 1998). Four times t (Myr) since the start of infall are indicated, at log $t = -1.5, -1.0, -0.5$, and 0.0.

(b) M_{env}–L_{bol} diagram for a sample of Class I (filled circles) and confirmed Class 0 sources (open circles) mainly in Ophiuchus, Perseus, and Orion (adapted from AM94 and Saraceno et al. 1996a). Evolutionary tracks, computed assuming protostars form from bounded condensations of finite initial masses and have $L_{bol} = GM_\star \dot{M}_{acc}/R_\star + L_\star$, where $L_\star$ is the PMS birthline luminosity (e.g. Stahler 1988), are shown. $M_{\rm env}$ and $\dot{M}_{acc} = M_{env}/\tau$ (where $\tau = 10^5$ yr) have been assumed to decline exponentially with time (see Bontemps et al. 1996a). Small arrows are plotted on the tracks every 10^4 yr, big arrows when 50% and 90% of the initial condensation has been accreted. The dashed and dotted lines are two $M_\star$–L_{bol} relations marking the conceptual border zone between the Class 0 ($M_{env} > M_\star$) and the Class I ($M_{env} < M_\star$) stage; the dashed line has $M_\star \propto L_{bol}$ (cf. AWB93 and AM94) while the dotted line has $M_\star \propto L_{bol}^{0.6}$ as suggested by the accretion scenario adopted in the tracks.

Figure 8. Normalized outflow momentum flux, $F_{\rm CO}\,{\rm c/L_{bol}}$, versus normalized envelope mass, $M_{\rm env}/L_{\rm bol}^{0.6}$, for a sample of Class 0 (open circles) and Class I (filled circles) objects (from Bontemps et al. 1996a). $F_{\rm CO}\,{\rm c/L_{bol}}$ can be taken as an empirical tracer of the accretion rate $\dot{M}_{\rm acc}$, while $M_{\rm env}/L_{\rm bol}^{0.6}$ is an evolutionary indicator which decreases with time. This diagram should therefore mainly reflect the evolution of $\dot{M}_{\rm acc}$ during the protostellar phase. The solid curve shows the accretion rate history predicted by the simplified collapse model of Henriksen et al. (1997).