THE EARLIEST STAGES OF STAR FORMATION: PROTOSTARS AND DENSE CORES

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Abstract

Despite recent progress, both the earliest stages of individual protostellar collapse and the origin of the global stellar initial mass function (IMF) are poorly understood. Since pre-stellar condensations and young protostars have $T_{bol} \lesssim 30$ K and emit the bulk of their luminosity in the 80–350 μm band, a large far-infrared and submillimeter space telescope such as FIRST/Herschel is needed to make further advances in this area. In particular, FIRST will provide a unique probe of the energy budget and temperature structure of pre/proto-stellar condensations. With an angular resolution at 85-300 μm comparable to, or better than, the largest ground-based millimeter radiotelescopes, the two imaging instruments of FIRST (i.e., PACS and SPIRE) will make possible deep, unbiased surveys for such condensations in the nearby ($d \lesssim$ 0.5–1 kpc) molecular cloud complexes of the Galaxy. These surveys will provide, for the first time, the mass and luminosity functions of complete samples of cold pre-stellar condensations, comprising thousands of objects down to substellar masses. This should greatly help improve our understanding of the fragmentation origin of the IMF.

Key words: Molecular clouds – Stars: formation – Stars: mass distribution – Missions: FIRST/Herschel

1. Introduction

Although the formation of isolated low-mass stars is now reasonably well understood in outline (e.g. Larson 1969; Shu, Adams, Lizano 1987; Mouschovias 1991), the very first stages of the process, which bracket in time the onset of local protostellar collapse within molecular clouds, still remain poorly known, especially in star-forming clusters. These early stages are of crucial interest since they can differentiate between collapse models and, to some extent at least, must govern the origin of stellar masses.

1.1. Background

Qualitatively, low-mass star formation is thought to begin with the fragmentation of a molecular cloud into a number of gravitationally-bound condensations initially supported against gravity by a combination of thermal, magnetic, and turbulent pressures (e.g. Shu et al. 1987). These pre-stellar 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). At some point, a pre-stellar condensation becomes gravitationally unstable and quickly collapses to form a (possibly multiple) accreting protostar, which itself evolves into a pre-main sequence (PMS) star and eventually a main sequence star (e.g. Stahler & Walter 1993).

A large number of isolated pre-stellar cores have been observed, both in molecular line tracers of dense gas such as NH_3, CS, N_2H^+, HCO^+ (e.g. Jijina, Myers, & Adams 1999, Myers 1999), and in the (sub)millimeter dust continuum (e.g. Ward-Thompson et al. 1994, 1999 – see Figs. 1 & 2). Many examples of accreting protostars are also known, which are divided into two broad classes. Class 0 sources are young stellar objects (YSOs) characterized by very high ratios of submillimeter to bolometric luminosity and overall spectral energy distributions (SEDs) resembling 15–30 K blackbodies (see Figs. 3 and 4). With measured envelope masses exceeding their estimated central stellar masses ($M_{env} >> M_*$), Class 0 objects are believed to be young ($\gtrsim 10^4$ yr) protostars at the beginning of the main accretion phase (André, Ward-Thompson, & Barsony 1993, 2000). They drive powerful jet-like outflows (e.g. Bachiller 1996 – see Fig. 3b) and exhibit spectroscopic signatures of gravitational collapse (e.g. Gregersen et al. 1997, Mardones et al. 1997). By contrast, Class I objects are near-IR sources with rising SEDs from $\lambda \sim 2$ μm to $\lambda \sim 60$ μm (Lada 1987), and much weaker submillimeter continuum emission and outflows than Class 0 sources (e.g. André & Montmerle 1994 – AM94; Bontemps et al. 1996). They are interpreted as more evolved protostars approaching the end of the main accretion phase ($M_{env} < M_*$; typical age $\gtrsim 10^5$ yr).

Prior to the main accretion phase, but subsequent to pre-collapse fragmentation, theory (e.g. Larson 1969) predicts the existence of a third type of protostars, namely 'isothermal protostars'. Indeed, when collapse is initiated in a *non-singular* pre-stellar condensation (with a finite density at its center), the collapsing gas is expected to remain roughly isothermal until a central density of $n_{H_2} \sim 10^9$–10^{11}cm^{-3} is reached (see Bate 1998, Masunaga & Inutsuka 2000). This "isothermal" collapse phase ends with

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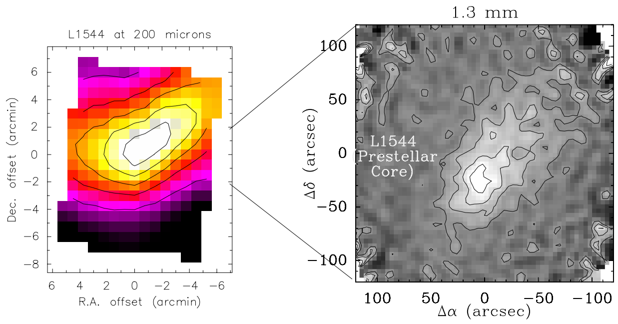

Figure 1. Dust continuum images of the pre-stellar core L1544 in Taurus at 200 μm (left) and 1.3 mm (right) taken with ISOPHOT and the IRAM 30 m telescope, respectively. The angular resolution is $\sim 2.8'$ *at 200 μm and* $13''$ *at 1.3 mm. (From Ward-Thompson et al. 1999, 2001).*

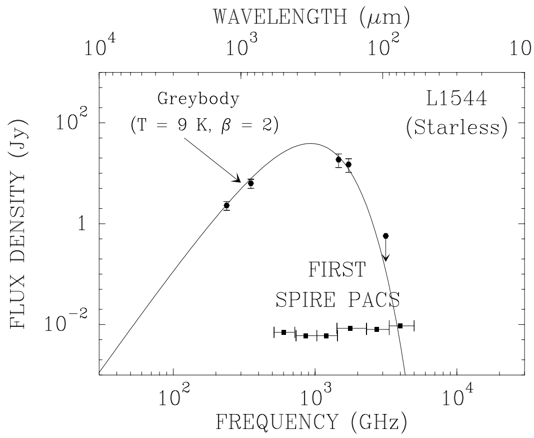

Figure 2. Spectral energy distribution of the starless core L1544 in Taurus (from Ward-Thompson, André, & Kirk 2001). The luminosity detected from this object ($L_{bol} \sim 0.2\,L_\odot$ *in a* $\sim$ *2.5'-diameter ISOPHOT aperture) is consistent with purely external heating from the local interstellar radiation field. The six photometric bands of the SPIRE and PACS instruments on FIRST are shown, along with their estimated (10σ, 1hr) sensitivities.*

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 (Larson 1969). First protostellar cores, or hydrostatic protostellar objects before the dissociation of molecular hydrogen, have been referred to as 'Class −I' objects by Boss & Yorke (1995), but have not yet been observed unambiguously. Evidence for significant collapse motions has recently been reported in a number of starless cores/condensations (e.g. Tafalla et al. 1998, Onishi et al. 1999, Gregersen & Evans 2000, Belloche et al. 2001), but the true nature of these sources remains uncertain. Some them may be 'isothermal protostars' or 'Class −I' objects in the previous sense. Note that the isothermal collapse phase is expected to be vanishingly short in the idealized scenario of Shu et al. (1987), which uses singular isothermal spheres as initial conditions. In practice, it is possible that a range of collapse regimes exists in nature: from highly dynamical protostellar core formation, with a dominant runaway isothermal collapse phase, in the case of induced (multiple) star formation (e.g. Henriksen et al. 1997), to quasi-static core formation, with virtually no such phase, in the case of self-initiated, 'isolated' star formation (e.g. Shu et al. 1987).

Inproving our knowledge of the pre-collapse phase and first collapse stages is of prime importance to get at a good understanding of phenomena occurring later on, in the PMS phase (corresponding to Class II and Class III objects – cf. Lada 1987 and AM94). It is during the early stages that the final stellar mass is determined, that close binary systems must form (e.g. Bonnell 1994), and that any protoplanetary disk must begin to grow.

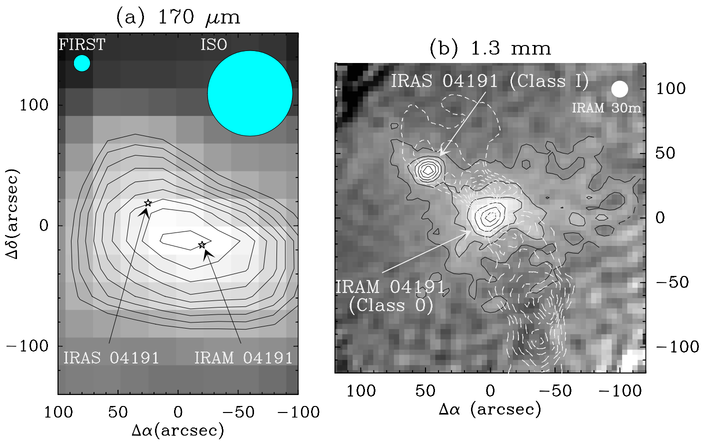

Figure 3. Dust continuum map of IRAM 04191 at 170 μm (a) and 1.3 mm (b) taken with ISOPHOT and the IRAM 30 m telescope, respectively (from André, Motte, & Bacmann 1999). The collimated CO(2–1) bipolar flow emanating from IRAM 04191 is superposed as dashed contours in (b).

1.2. Need for a large submm space telescope

So far, the observational study of the earliest stages of protostellar collapse has been seriously hindered by two main factors: the associated timescales are short ($\lesssim 10^4$-10^5 yr) and the corresponding SEDs peak around $\lambda \sim 100$–$300\,\mu$m (see Figs. 2 & 4), i.e., in the primary wavelength range of FIRST which has been inaccessible with good resolution and sensitivity up to now. While IRAS, ISO, and ground-based infrared studies have provided a fairly complete census of evolved protostars and pre-main sequence objects (i.e., Class I, Class II, and Class III near-IR sources) in nearby clouds (e.g. Wilking et al. 1989, Prusti 1999, Bontemps et al. 2001), no such census exists yet for (Class 0) young accreting protostars, 'isothermal' collapsing protostars, and cold pre-collapse condensations. Only about

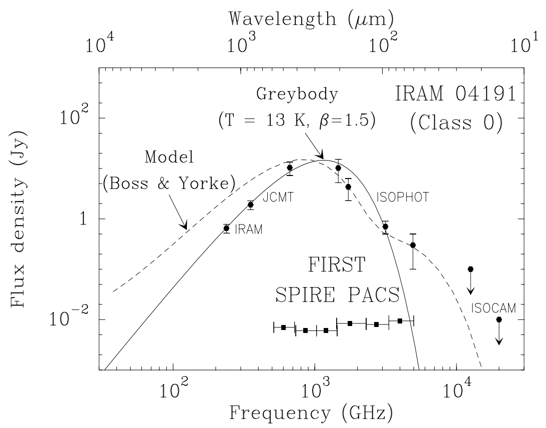

Figure 4. Spectral energy distribution of the Class 0 protostar IRAM 04191 (cf. André et al. 1999). This object is at d = 140 pc and has $L_{bol} \approx 0.15\,L_\odot$, $T_{bol} \approx$ 18 K, and $M_{env} \approx 0.5\,M_\odot$ (in a 1'-diameter aperture). The six photometric bands of SPIRE and PACS on FIRST are shown, along with their (10σ, 1hr) sensitivities. The solid curve is a greybody dust spectrum which fits the SED longward of 90 μm; the dashed curve shows the model SED computed by Boss & Yorke (1995) for a single "first protostellar core" seen along its rotational axis. FIRST is ideally suited for detecting and characterizing all such cold protostars to $M_{proto} \sim$ 0.03–0.1 $M_\odot$ and $d \sim 1$ kpc in the Galaxy.

thirty Class 0 protostars are known to date (André et al. 2000), which all are relatively massive ($M \gtrsim$ 0.5-1 $M_\odot$) and were discovered either serendipitously (e.g. Chini et al. 1997, Cernicharo et al. 1998) or through their powerful outflows (see Bachiller 1996). With present ground-based (sub)-millimeter telescopes, systematic surveys for pre-collapse condensations and cold protostars are possible only down to $\sim 0.1\,M_\odot$ in nearby ($d \sim 150$ pc) clouds such as the ρ Ophiuchi cloud (cf. Motte, André, & Neri 1998). Even in the Taurus cloud complex where stars are known to form in relative isolation, the angular resolution of ISO around ∼ 100–200 μm was barely sufficient to probe the emission from individual pre-stellar cores and protostars (e.g. Fig. 3). Furthermore, the recent millimeter discoveries of the Class 0 object IRAM 04191+1522 (André, Motte, & Bacmann 1999 – see Figs. 3 to 4) and of the cold $H^{13}CO^+$ condensation MC 27 (Onishi, Mizuno, & Fukui 1999) clearly show that the current census of protostars in Taurus is incomplete and that there may exist a significant, as yet unknown, population of cold protostars with $L_{bol} \lesssim 0.1\,L_\odot$ in this cloud. These examples (see also Ristorcelli et al. 1998) emphasize the need for unbiased surveys of molecular clouds in the submillimeter band. Because of source clustering and cirrus noise, *high resolution* is a prerequisite for *deep surveys* (see § 3 below).

2. Wide-field Surveys of Molecular Clouds

Equipped with the PACS and SPIRE bolometer arrays, FIRST/Herschel will have the ability to carry out deep, wide-field imaging surveys of nearby molecular clouds at 90–180 μm and 250–500 μm, respectively. These surveys should tremendously improve our knowledge of the first phases of protostellar collapse, on both individual (§ 2.1) and global (§ 2.2) scales in the Galaxy.

2.1. Formation of Individual Protostars

Unbiased submillimeter continuum surveys with SPIRE and PACS will detect large, *complete samples of young protostars and pre-collapse condensations*, down to much smaller masses ($M \lesssim$ 0.03 $M_\odot$) than is possible from the ground. This will provide, for the first time, reliable statistical estimates for the *lifetimes* of the isothermal, Class −I, and Class 0 protostellar phases in a variety of star-forming regions, and for the whole spectrum of stellar masses. Color-color diagrams based on combined SPIRE and PACS photometry in six bands around $\lambda \sim 200$ μm, i.e., around the peak of the SEDs (see, e.g., Figs. 2 & 4), will help solve one of the difficulties, namely distinguishing between the various types of objects (see, e.g., Boss & Yorke 1995). Follow-up spectroscopic observations with FIRST (see § 4) and millimeter interferometers such as the Atacama Large Millimeter Array (ALMA – e.g. Wootten 2001) will also be very useful to identify those condensations that are collapsing.

Second, coordinated surveys with SPIRE and PACS will yield *accurate bolometric luminosities* (down to low values $\lesssim 0.01\,L_\odot$) for cold protostellar sources, thanks to a good sampling of the SEDs with six photometric bands between ∼ 75 μm and ∼ 500 μm (see, e.g., Figs. 2 & 4). The much better angular resolution of FIRST ($\lesssim$ 7" at 90 μm with PACS) compared to IRAS, ISO, or SIRTF in the far-IR will be sufficient to separate the main individual members of nearby ($d \lesssim 900$ pc) embedded clusters (which all have stellar surface densities < 2000 stars pc^{-2}, except the Trapezium). For the first time, the energy output of many individual protostars will thus be measurable in the key 90–400 μm range (see Figs. 2 and 4). In particular, this will allow us to fully exploit the potential of the M_{env}–L_{bol} and L_{bol}–T_{bol} diagrams (e.g. AM94, Saraceno et al. 1996, Myers et al. 1998) as practical evolutionary diagrams for embedded protostars.

Third, using combined SPIRE and PACS images to construct 75–500 μm SED maps for at least the nearest (spatially resolved) sources, it will be possible to derive the *temperature distribution* within both pre-stellar condensations/cores and protostellar envelopes. This is important because most existing models of cloud collapse *assume* an isothermal equation of state with $T \sim 10$ K (e.g. Larson 1969, Shu et al. 1987, Mouschovias 1991, Foster & Chevalier 1993). Isothermality is known to be a valid approxi-

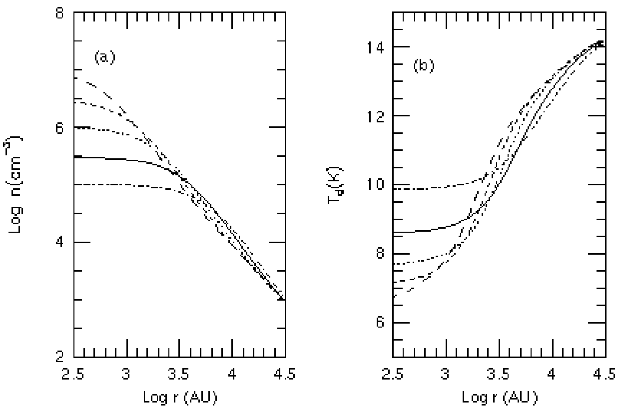

Figure 5. Predicted evolution of the radial temperature distribution (on the right) for a sequence of self-gravitating spherical cloud cores with radial density profiles as shown on the left (from Evans et al. 2001). Note that these model pre-collapse cores are not strictly isothermal and that the densest models have the lowest central temperatures.

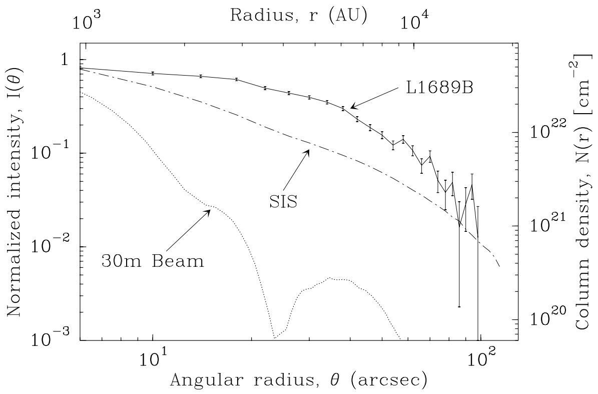

Figure 6. Radial intensity profile of the starless core L1689B derived from 1.3 mm continuum observations with the 30 m telescope (from André, Ward-Thomspon, & Motte 1996). For comparison, the dash-dotted curve shows the simulated profile of a model singular isothermal sphere (SIS) with $\rho \propto r^{-2}$. Such 1.3 mm data imply that typical pre-stellar cores have flat density gradients ($\rho \sim$ constant) in their central few 1000 AUs, assuming their dust (temperature and emissivity) properties are roughly independent of radius. With FIRST/Herschel, it will be possible to check the validity this assumption and to derive accurate radial temperature profiles across nearby cloud cores.

mation until the end of the so-called 'isothermal collapse phase' (e.g. Hayashi 1966 and § 1.1), as a rough equilibrium is maintained between molecular/dust cooling on the one hand and heating by cosmic rays, the interstellar radiation field, and gravitational compression (if present) on the other hand. However, recent modelling of the thermal energy balance suggests that starless cloud cores are significantly colder in their central regions (with T as low as $\sim$ 5–7 K) than in their outer parts (Masunaga & Inutsuka 2000; Evans et al. 2001; Zucconi, Walmsley, & Galli 2001 – see Fig. 5). FIRST/Herschel will allow us to directly measure the magnitude of this effect and to determine the extent to which the envelopes of the youngest accreting (Class 0) protostars are already internally heated.

Coupled with complementary ground-based dust continuum observations at longer submillimeter wavelengths, the *column density structure* of the same sources will also be measurable with unprecedented accuracy. Promising results have been obtained in this area using JCMT/IRAM 800–1300 μm emission maps and ISOCAM mid-IR absorption maps (e.g. Ward-Thompson et al. 1994, 1999; André et al. 1996; Bacmann et al. 2000 – see Fig. 6). However, the only way to reach unambiguous conclusions is to constrain the temperature and the column-density gradient simultaneously through multi-band imaging from the Rayleigh-Jeans part of the emission spectrum up to and beyond the peak of the SED.

Comparison between the structure of pre-stellar condensations and that of the envelopes surrounding the youngest protostars will give insight into the *initial conditions of individual protostellar collapse*. These initial conditions hold the key to understanding early protostellar evolution and, in particular, determine the history of the mass accretion rate at the Class 0 and Class I stages (e.g. Foster & Chevalier 1993; Henriksen, André, & Bontemps 1997).

2.2. Origin of the Stellar Initial Mass function

On a more global level, wide-field submillimeter imaging of both active and quiescent regions with FIRST will also allow us to better understand the origin of stellar masses and the *nature of the fragmentation process in molecular clouds*, for which we still have no satisfactory theory (e.g. Elmegreen 2001). Sensitive submillimeter dust emission maps have the remarkable property that they can probe cloud structure, pre-collapse condensations, collapsing/accreting protostars, and post-collapse circumstellar envelopes/disks, *simultaneously*.

This point is illustrated by the results of recent ground-based dust continuum surveys around 1 mm. In particular, Motte, André, & Neri (1998 – MAN98) obtained a $\sim$ 480 arcmin^2 mosaic of the ρ Oph main cloud ($d \approx$ 150 pc) at 1.3 mm with the MPIfR bolometer array on the IRAM 30 m telescope. Using a multi-resolution wavelet analysis, they could identify a total of 100 compact 'condensations' with characteristic angular scales of $\sim 15'' - 30''$ (i.e., $\sim$ 2500–5000 AU) in their mosaic. These small-scale condensations consist of 59 starless fragments (undetected by ISOCAM in the mid-IR – cf. Bontemps et al. 2001) and 41 circumstellar envelopes/disks around embedded YSOs (detected at mid-IR and/or radio continuum wavelengths). Comparison of the masses derived from the 1.3 mm continuum with the virial masses estimated from follow-up molecular-line observations (e.g. Fig. 8 below) indicates that most of the starless fragments are gravitationally bound (with $M_{1.3}/M_{vir} \gtrsim 0.5$ – Belloche et al.

2001) and will form stars in the near future. The mass distribution of these 59 compact pre-stellar condensations, complete down to $\sim 0.1\,M_\odot$, is remarkable in that it mimics the shape of the stellar IMF (see Fig. 7a). Above $m \sim 0.3-0.5\ M_\odot$ it follows approximately the Salpeter power-law, i.e., $N(>m) \propto m^{-1.35}$ in cumulative form, but flattens out to $N(>m) \propto m^{-0.5}$ at lower masses. This is very similar in shape to the YSO mass function recently determined down to $\sim 0.06\,M_\odot$ for the Class II sources of the ρ Oph cluster from ISOCAM 7 μm and 15 μm observations (Bontemps et al. 2001, see Fig. 7a). Interestingly, the position of the break point at $\sim 0.3-0.5\,M_\odot$ is comparable to the typical Jeans mass in the dense DCO^+ cores of the ρ Oph cloud (cf. Loren et al. 1990). Such a resemblance to the IMF suggests that *the starless condensations detected in the (sub)millimeter dust continuum on the same spatial scales as protostellar envelopes are the direct progenitors of individual stars or systems.* In agreement with this view, some of the condensations show spectroscopic evidence of collapse (Fig. 8).
By contrast, recall that the typical clump mass spectra found by large-scale molecular line studies ($N(>m) \propto m^{-0.5}$ in integral form – e.g. Williams et al. 2000) are much shallower than both the stellar IMF and the pre-stellar mass distributions of Fig. 7 above $\sim 0.5\,M_\odot$. The difference presumably arises because, up to now, line studies have been primarily sensitive to transient unbound structures (cf. Kramer et al. 1998) which are not immediately related to star formation.

Other studies have found pre-stellar mass spectra consistent with the IMF. Using the OVRO interferometer at 3 mm to mosaic the inner $5.5' \times 5.5'$ region of the Serpens cloud core, Testi & Sargent (1998) detected 26 starless condensations above $\sim 0.5\,M_\odot$ and measured their mass spectrum to be $N(>m) \propto m^{-1.1}$, i.e., close to the Salpeter IMF. With SCUBA at 850 μm, Johnstone et al. (2000) surveyed approximately the same ρ Oph cloud region as MAN98 did (see above) and found essentially similar results. Motte et al. (2001 – MAWB01) also used SCUBA in the scan-map mode on JCMT to image a $30' \times 17'$ field at 450 μm and 850 μm around the NGC 2068/2071 protoclusters in Orion B (see Figs. 9 & 10). Their images reveal a total of ~ 70 compact starless condensations whose mass spectrum is again reminiscent of the IMF between $\sim 0.6\,M_\odot$ and $\sim 5\,M_\odot$ (see Fig. 7b).

These recent findings on the mass spectrum of protocluster condensations are very encouraging because they support scenarios according to which *the low-mass end of the IMF is at least partly determined by turbulent fragmentation at the pre-stellar stage of star formation* (see Larson 1999 and Elmegreen 2001). It is nevertheless clear that present studies are limited by small-number statistics due to insufficient sensitivity. Surveys with FIRST can probe much deeper into the mass distributions of pre-stellar condensations and young protostars than ground-based (sub)millimeter observations (see § 3). Furthermore,

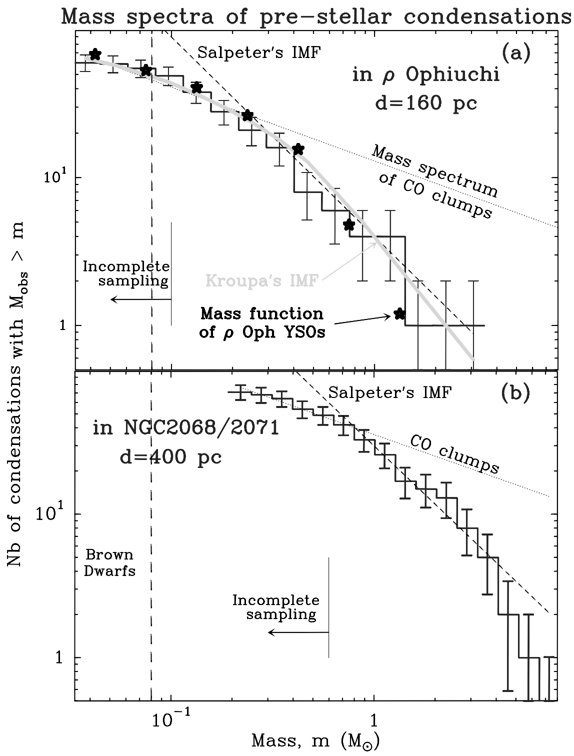

Figure 7. Cumulative mass distributions of the pre-stellar condensations found by MAN98 and MAWB01 in the ρ Oph (**a**) *and NGC 2068/2071* (**b**) *protoclusters. The dotted and dashed lines show power-laws of the form $N(>m) \propto m^{-0.5}$ (mass spectra of CO clumps, see Williams et al. 2000) and $N(>m) \propto m^{-1.35}$ (Salpeter's IMF), respectively. The solid curve in* (**a**) *shows the shape of the field star IMF (Kroupa et al. 1993), and the star markers represent the mass function of ρ Oph YSOs derived from an extensive mid-IR survey with ISOCAM (Bontemps et al. 2001; Olofsson et al. 2000).*

the mass uncertainties will be much reduced since coordinated SPIRE and PACS observations between $\sim 80\,\mu$m and $\sim 500\,\mu$m will strongly constrain the temperature and emissivity of the dust, as well as the nature of the objects (see § 2.1 above).

3. Feasibility and Uniqueness of FIRST Surveys

The potential sites of star formation in the Galaxy are known from large-scale CO observations (e.g. Dame et al. 1987, 2001). There are about 20 large molecular complexes within 1 kpc of the Sun, the closest and most famous of which are the ρ Ophiuchi, Taurus, Chamaeleon, Corona Australis, Serpens, Perseus, and Orion dark clouds. These giant complexes harbor several compact embedded clusters which contain large, homogeneous samples of dense cores, protostars, and YSOs, and thus provide ideal laboratories for star formation studies (e.g. Zinnecker, McCaughrean, & Wilking 1993; Jijina et al. 1999; Meyer et al. 2000). Based on current estimates of the local star formation rate ($\sim 7.5\,M_\odot$ pc^{-2} Gyr^{-1} per unit area of

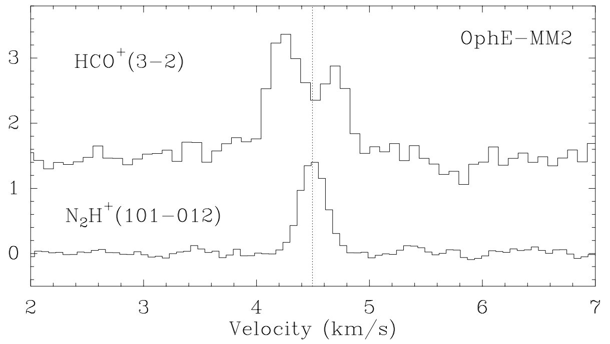

Figure 8. HCO^+ (3–2) and N_2H^+ (101-012) spectra observed at the IRAM 30 m telescope toward the starless 1.3 mm continuum condensation E-MM2 identified by MAN98 in the ρ Oph protocluster. The optically thick HCO^+ line is self-absorbed and skewed to the blue, which is the classical signature of collapse (e.g. Evans 1999), while the optically thin N_2H^+ line is narrow ($\Delta V \lesssim 0.3$ km s^{-1}) indicating small levels of turbulence. (From Belloche et al. 2001.)

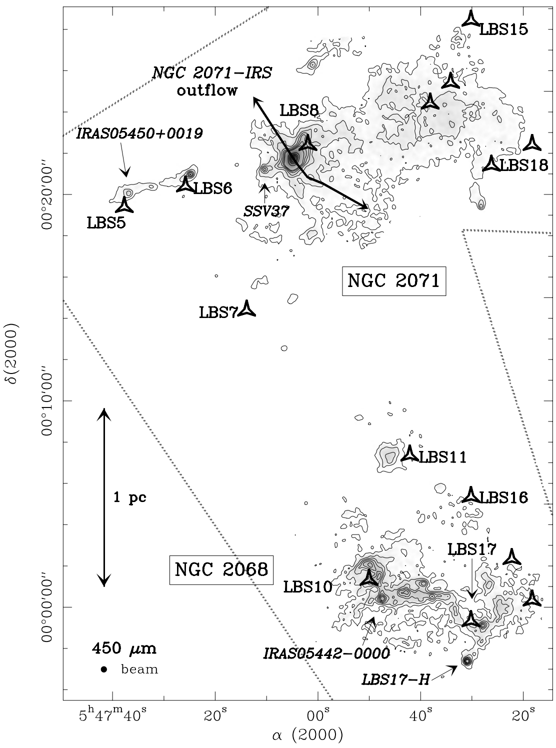

Figure 9. SCUBA 450 μm dust continuum mosaic of the NGC2068/2071 protoclusters in Orion B (Motte, André, Ward-Thompson, & Bontemps 2001). The effective angular resolution is 18″. Contour levels go from 1.2 to 9.6 Jy/beam with steps of 1.2 Jy/beam and from 20 to 50 Jy/beam by 10 Jy/beam. The mean rms noise level is ∼ 0.4 Jy/18″-beam. FIRST will easily provide deeper images by ∼ 1–2 orders of magnitude over much wider fields.

the Galactic disk, implying a value $\sim$ 0.02 $M_\odot yr^{-1}$ in an area of $d \leq 1$ kpc around the Sun – e.g. McKee & Williams 1997), the above-mentioned clouds should harbor $\gtrsim 500$ low-mass young protostars and several thousand pre-stellar condensations, i.e., an order of magnitude more at least than those already identified from the ground (see § 1.2 above).

Since the details of the star formation process appear to depend on environmental factors, it is crucial to study a large number of these complexes in order to build a complete observational and theoretical picture. In particular, the typical Jeans mass is likely to differ from cloud to cloud, which may lead to a break in the mass spectrum of pre-stellar condensations at different characteristic masses (see Fig. 7). Besides cluster-forming clouds, more *quiescent* regions, such as high-latitude starless clouds (e.g. Falgarone et al. 1998, Heithausen 1999, Falgarone & Pety 2001), should also be mapped in order to investigate the factors that control the efficiency of dense core and star formation. As one of the main goals is to understand how protostellar condensations form out of the diffuse ISM, it is also essential that the FIRST surveys span a wide range of column densities and physical conditions from cirrus-like regions with $N_{\rm H2} \lesssim 10^{21}$ cm^{-2} (e.g. Bernard et al. 1999, Heithausen 1999) to dense cores with $N_{\rm H2} > 10^{22}$ cm^{-2}. The detailed definition of the fields to be imaged with FIRST will greatly benefit from the results of earlier missions like SIRTF, ELISA (Ristorcelli et al., this volume), and ASTRO-F (Nakagawa, this volume).

Such Galactic surveys will be limited by the confusion arising from small-scale cirrus/cloud structure. Previous work with, e.g., *IRAS*, *COBE*, *ISO* has established that the spatial fluctuations of the cirrus infrared background emission have a steep power spectrum [$P(k) = P_0\,(k/k_0)^{-3}$] (e.g. Gautier et al. 1992, Herbstmeier et al. 1998, Abergel et al. 1999). The shape of this power spectrum is apparently universal but its normalization varies from region to region, scaling roughly as $P_0 \propto < B >^3$ where $< B >$ is the mean brightness in the sky region (Gautier et al. 1992). The origin of the fluctuations, still poorly understood, is presumably related to the turbulent, fractal nature of the ISM (e.g. Elmegreen & Falgarone 1996). An important consequence of the steep cirrus power spectrum is that the confusion limit at a given wavelength improves quite dramatically with angular resolution, scaling roughly as $D^{-2.5}$ where D is the telescope diameter (cf. Eq. (4) of Herbstmeier et al. 1998). Thus, *the cirrus confusion limit will be a factor ∼ 35-55 lower with FIRST/Herschel than with SIRTF and ASTRO-F.* Furthermore, there is a growing body of evidence (e.g. Larson 1999, Williams et al. 2000) that the self-similarity of the ISM breaks down below $\sim 5000 - 15000$ AU within gravitationally-bound dense cores. Investigating the underlying physics cannot be done with SIRTF or ASTRO-F and requires surveys with the angular resolution of FIRST.

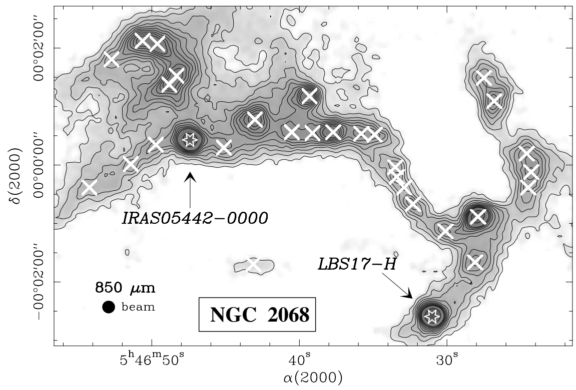

Figure 10. Blow-up 850 μm continuum map extracted from the SCUBA mosaic of NGC 2068/2071 by Motte, André, Ward-Thompson, & Bontemps (2001). The mean rms noise level is ∼ 22 mJy/13″-beam. A total of 30 compact starless condensations (cf. crosses) are detected in this field.

Assuming conservative detector-array performances, one would need only ~ 15 days to survey 100 deg^2 with SPIRE down to the estimated cirrus confusion limit ($\sigma_{250\mu} \sim$ 10 mJy/18″-beam) in a region like the Taurus cloud complex. Such a sensitivity is sufficient to detect and spatially resolve proto-brown dwarfs of temperature $T_{proto} = 10K$ and mass $M_{proto} \geq 0.03\ M_\odot$ at the 5σ level in the nearest clouds ($d = 150$ pc).

In the Orion A & B Giant Molecular Clouds (GMCs) ($d = 450$ pc), the cirrus noise is expected to be somewhat higher than in Taurus; a SPIRE survey of the whole ~ 50 deg^2 extent of these GMCs (e.g. Maddalena et al. 1986) down to $\sigma_{250\mu} \sim 15$ mJy/18″-beam ($\sim$ half the estimated cirrus noise) could be completed in ~ 4 days and would be sensitive to $\sim 0.1\ M_\odot$, 10 K protostellar condensations at the 5σ level. (For comparison, in the same region, SIRTF and ASTRO-F will be limited by confusion to the detection of $\gtrsim 5\ M_\odot$ condensations.) In total, about 1 month of FIRST/SPIRE time should be sufficient to image ~ 500 deg^2 in nearby cloud complexes ($d < 1$ kpc) to the cirrus confusion limit at 250 μm. With its better angular resolution, PACS will be less affected by confusion but cannot be used to search for the coldest starless condensations. Imaging the densest ~ 30 deg^2 portion of the Orion A & B GMCs with PACS down to the cirrus confusion limit ($\sigma_{110\mu} \sim 5$ mJy/8″-beam) would take only ~ 15 days. This sensitivity would make possible spatially resolved studies of $\gtrsim 0.03\ M_\odot$, 15 K protostars and proto-brown dwarfs above the 5σ level. The temperature distribution within many starless condensations would also be constrained.

For this type of molecular cloud surveys, Herschel will be $\sim$ 2–3 orders of magnitude faster than SCUBA at 850 μm or SOFIA at 100–200 μm (cf. Becklin 1997), and somewhat faster than ALMA at 1.3 mm. ALMA and Herschel will be highly complementary: while the former will give access to the small-scale structure and kinematics of protostellar condensations, the latter will provide unique information about luminosities and temperatures, as well as on the medium- to large-scale structure (which cannot easily be retrieved with an interferometer such as ALMA).

4. Follow-up Detailed Spectroscopic Studies

Follow-up spectroscopy at high resolution ($R \sim 10^6$–10^7) with the HIFI heterodyne instrument (and at medium/low resolution with the PACS and SPIRE spectrometers) will give quantitative constraints on the velocity fields (e.g., infall, rotation, outflow, turbulence) and chemical evolutionary states of the most interesting protostars and pre-stellar condensations identified in the photometric surveys (see Ceccarelli et al. and van Dishoeck in this volume). The water lines falling in the HIFI range (e.g. $H_2O(3_{12}$–$3_{03})$ at 273 μm, $H_2O(2_{02}$–$1_{11})$ at 303 μm, and $H_2O(5_{32}$–$4_{41})$ at 483 μm) are particularly promising since they should probe the physical conditions in the inner ~ 100 AU region of protostellar envelopes where the water abundance should be greatly enhanced (Ceccarelli et al. 1996). These water lines will be easily resolved at the $\lesssim 0.1$ km s^{-1} resolution of HIFI providing, for the first time, valuable diagnostics of the mass accretion rate *close the central object* (Ceccarelli et al. 1996, and this volume).

5. CONCLUSIONS

The far-IR/submm is clearly the most appropriate wavelength range for studying the earliest stages of star formation. Large-scale, multi-band surveys of molecular clouds at $\lambda \sim 75$–500 μm with the PACS and SPIRE imaging instruments on Herschel should revolutionize our understanding of both the pre-collapse and collapse phases of star formation (see § 2 and § 3). They will allow us:

- to obtain a complete census of pre-stellar condensations, isothermal collapsing protostars, and young accreting protostars in the nearby ISM, setting direct constraints on the lifetimes of the various phases;
- to measure the associated temperature distributions and luminosity functions;
- to relate the mass spectrum of pre-stellar condensations to that of young stars, thereby giving insight into the fragmentation process and the origin of the IMF.

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