FIRST AND THE EARLIEST STAGES OF STAR FORMATION

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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 (to be launched by ESA in 2007) 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/protostellar 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 all the nearby ($d \lesssim 1$ kpc) molecular cloud complexes of the Galaxy. These surveys are already considered among the top scientific priorities of the SPIRE and PACS core observing programmes. They 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. In addition, follow-up spectroscopy at high resolution with the HIFI heterodyne instrument (and at medium resolution with the PACS and SPIRE spectrometers) will give quantitative constraints on the dynamical and chemical states of the most interesting condensations identified in the photometric surveys.

Key words: Molecular clouds – Stars: formation – Stars: mass distribution – Satellites: FIRST

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, they 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 which are 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 eventually evolves into a pre-main sequence (PMS) star and a main sequence star (e.g. Stahler & Walter 1993). A large number of pre-stellar cores/condensations have been observed, both in molecular line tracers of dense gas such as NH_3, CS, N_2H^+, HCO^+ (e.g. Benson & Myers 1989, Myers 1999), and in the (sub)millimeter dust continuum (e.g. Ward-Thompson et al. 1994, 1999, André, Ward-Thompson, Motte 1996 – see Figs. 1 to 3). Many examples of accreting protostars have also been observed, 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. 4 to 6). Since their measured envelope masses exceed their estimated central stellar masses ($M_{env} >> M_*$), Class 0 objects are excellent candidates for being young ($\sim 10^4$ 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. 5) and exhibit spectroscopic signatures of gravitational collapse (e.g. 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

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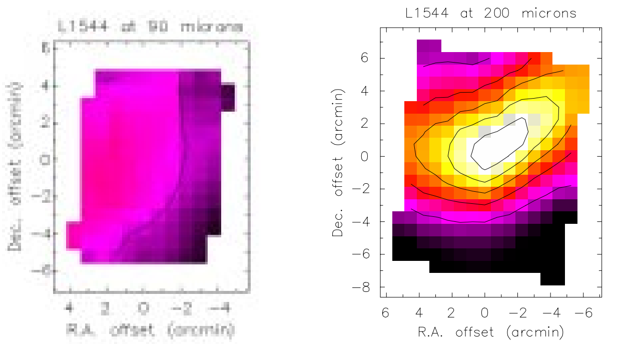

Figure 1. ISOPHOT dust continuum images of the pre-stellar core L1544 in Taurus at 90 μm and 200 μm (from Ward-Thompson & André 2000). The angular resolution is ~ 2.8′ at 200 μm. Note that the core is too cold to be detected at 90 μm.

accretion phase (typical age $\sim 10^5$ yr), and surrounded by both a disk and a residual circumstellar envelope of substellar mass.

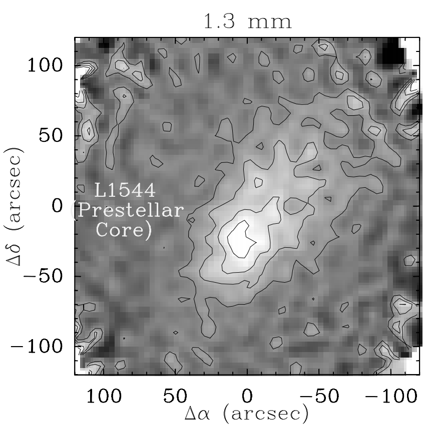

Figure 2. Dust continuum image of L1544 at 1.3 mm taken at the IRAM 30 m telescope in the on-the-fly scanning mode (from Ward-Thompson, Motte, & André 1999). Effective angular resolution: 13″; base contour and contour step: 20 mJy/beam.

Prior to the main accretion phase, theory (e.g. Larson 1969) predicts the existence of a third type of protostars, namely 'isothermal protostars', which have never been unambiguously observed up to now. 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 $n_{H_2} \sim 10^9$–$10^{11}\mathrm{cm}^{-3}$ is reached (see Masunaga, Miyama, & Inutsuka 1998, Bate 1998, Masunaga & Inutsuka 2000). This "runaway" isothermal collapse phase ends with the formation of an opaque, hydrostatic protostellar object in the center (e.g. Larson 1969, Boss & Yorke 1995, Bate

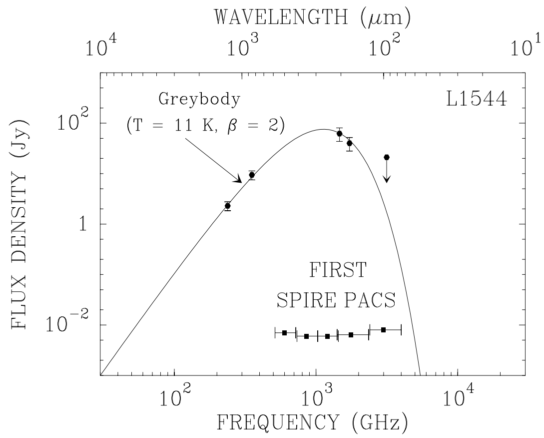

Figure 3. Spectral energy distribution of the starless core L1544 in Taurus (from Ward-Thompson & André 1999, 2000). The luminosity detected from this object ($L_{bol} \sim 0.6\, L_\odot$ in the ~ 3′-diameter ISOPHOT beam) is consistent with purely external heating from the local interstellar radiation field. The five photometric bands of the SPIRE and PACS instruments on FIRST are shown, along with their estimated (10σ, 1hr) sensitivities.

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). A number of candidate 'isothermal protostars' and 'Class −I' objects have been identified, in the form of very dense starless condensations only seen at submillimeter wavelengths (e.g. Mezger et al. 1992, Motte et al. 1998, Williams et al. 1999, Onishi et al. 1999, Wiesemeyer et al. 1999), but their true nature remains uncertain. In fact, the isothermal collapse phase is expected to be vanishingly short if the idealized scenario advocated by Shu et al. (1987), which uses singular isothermal spheres as initial conditions, is approximately correct. In practice, it is possible that two distinct collapse regimes occur in nature: dynamical protostellar core formation, with a significant runaway collapse phase, in the case of induced (multiple) star formation (e.g. Henriksen et al. 1997), and quasi-static core formation, with virtually no such phase, in the case of self-initiated, 'isolated' star formation (e.g. Shu et al. 1987).

Detailed knowledge of the pre-collapse phase and first collapse stages (including the isothermal stage and the Class 0 early accretion stage) is of key importance for a good understanding of phenomena occurring later on, during the PMS phase (corresponding to Class II and Class III objects – cf. Lada 1987 and AM94). For instance, it is during the early stages of collapse that close binary/multiple systems must form (e.g. Bonnell 1994), with consequences for the subsequent evolution of protoplanetary disks.

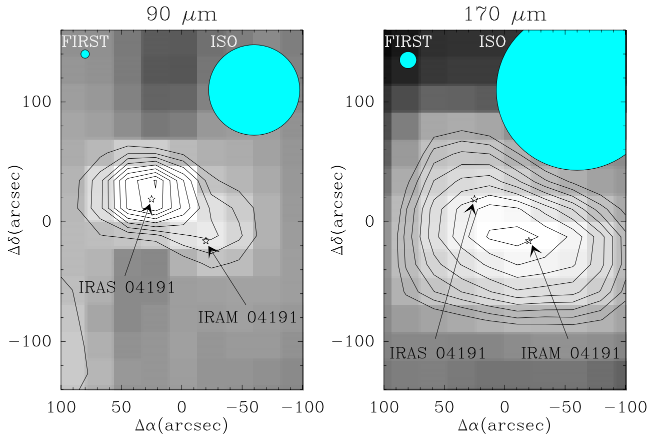

Figure 4. ISOPHOT maps at 90 μm and 170 μm of the cold Class 0 object IRAM 04191 recently discovered at 1.3 mm near the Class I source IRAS 04191 in Taurus (see Fig. 5 and AMB99). The FWHM beams of ISO and FIRST are indicated. Note that the angular resolution of ISOPHOT is barely sufficient to separate the two sources.

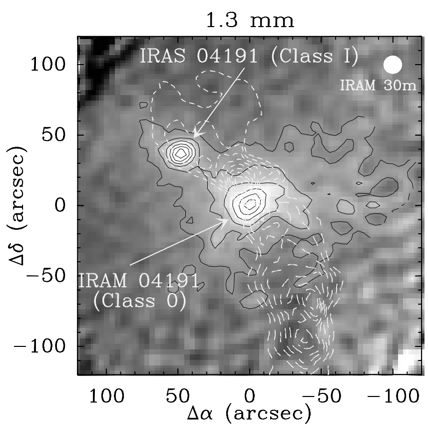

Figure 5. Dust continuum map of IRAM 04191 at 1.3 mm taken with the IRAM 30 m telescope and the MPIfR bolometer array in the on-the-fly dual-beam scanning mode (from AMB 1999). Effective angular resolution: 13″; base contour and contour step: 20 mJy/beam. The collimated CO(2–1) bipolar flow emanating from IRAM 04191 is superposed (dashed contours).

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 ($\lesssim 10^4$ yr) and the corresponding SEDs peak around $\lambda \sim 100$–300 μm (see Figs. 3 & 6), 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

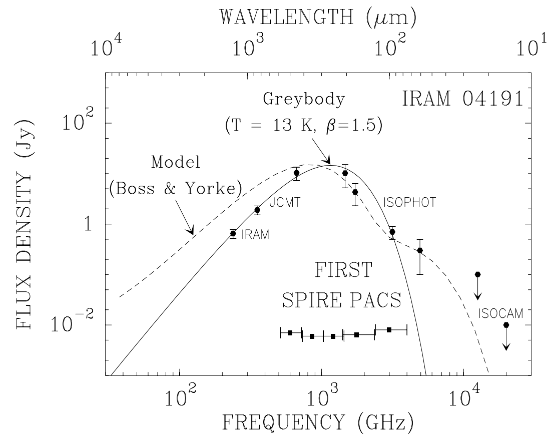

Figure 6. Spectral energy distribution of the Class 0 protostar IRAM 04191 (from AMB99). This object is at $d = 140$ pc and has $L_{bol} \approx 0.15\, L_\odot$, $T_{bol} \approx 18$ K, and $M_{env} \approx 0.5\, M_\odot$ (in a 1′-diameter aperture). The five photometric bands of SPIRE and PACS on FIRST are shown, along with their corresponding (10σ, 1hr) sensitivities. The solid curve is a greybody dust spectrum which fits the SED longward of 90 μm, while 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 $M_{proto} \gtrsim 0.03\ M_\odot$ and $d \sim 1$ kpc in the Galaxy.

(i.e., Class I, Class II, and Class III near-IR sources) in nearby clouds (e.g. Wilking et al. 1989, Bontemps, this volume), no such census exists yet for (Class 0) young accreting protostars, isothermal collapsing protostars, and cold pre-collapse condensations. Only about 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) 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 molecular cloud complex (e.g. Hartmann, this volume), 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 (see Fig. 1 and Fig. 4). Furthermore, the recent millimeter discoveries of the Class 0 object IRAM 04191+1522 in the vicinity of the Class I source IRAS 04191+1523 (André, Motte, & Bacmann 1999 – AMB99 – see Figs. 4 to 6) and of the cold protostellar 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 emphasize the need for deep, unbiased surveys of molecular clouds in the submillimeter band.

FIRST, the 3.5 m 'Far InfraRed and Submillimeter Telescope' to be launched by ESA in 2007 (see Pilbratt 2000), will cover the 80–700 μm wavelength range with good to moderate angular resolution and will be ideally suited to studying the earliest stages of star formation. It will be equipped with a Photoconductor Array Camera and Spectrometer (PACS – e.g. Poglitsch 1998) providing simultaneous broad-band photometry at 90 μm and 170 μm in instantaneous fields of view of $\sim 1' \times 1.5'$ and $\sim 2' \times 3'$, a Spectral and Photometric Imaging REceiver (SPIRE – e.g. Griffin et al. 1998) able to perform simultaneous broad-band photometry at 250 μm, 350 μm, and 500 μm in $4' \times 8'$, and a Heterodyne Instrument (HIFI – e.g. Whyborn 1997) providing high-resolution spectroscopy ($\Delta v \sim 0.03$–$300\,\mathrm{km\,s^{-1}}$) with complete wavelength coverage between $\sim 250\,\mu$m and $\sim 625\,\mu$m at least.

2. Wide-field Surveys of Molecular Clouds

One of the two top priorities of the PACS and SPIRE scientific programmes on FIRST is 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 five bands around $\lambda \sim 200\ \mu$m, i.e., around the peak of the SEDs (see, e.g., Figs. 3 and 6), will help solve one of the difficulties, namely distinguishing between the various types of objects. One indeed expects slight changes in the shape of the SED (close to its peak) and a progressive increase of the bolometric temperature, T_{bol}, as a source evolves from an isothermal condensation (either pre-collapse or already collapsing – see Fig. 3), to a 'Class −I' first protostellar core (see Boss & Yorke 1995 and dashed curve in Fig. 6), to an accreting Class 0 object (see Fig. 7 taken from Masunaga & Inutsuka 2000). Follow-up spectroscopic observations with FIRST (see § 4) and millimeter interferometers such as the planned Atacama Large Millimeter Array (ALMA – e.g. Wootten 2000) will identify those condensations that are collapsing.

Second, coordinated surveys with SPIRE and PACS on FIRST will yield *accurate bolometric luminosities* (down to low values $< 0.1\ L_\odot$) for cold protostellar sources, thanks to a good sampling of the SEDs with five photometric bands between $\sim 80\,\mu$m and $\sim 500\,\mu$m (see, e.g., Figs. 3 and 6). The much better angular resolution of FIRST ($\lesssim$ 7" at 90 μm with PACS) compared to IRAS or ISO 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. 3 and 6). This is of crucial importance as the bolometric luminosity is a fundamental variable of (proto)stellar astrophysics used in all evolutionary diagrams proposed to date for embedded YSOs, such as the M_{env}–L_{bol} diagram (e.g. AM94, Saraceno et al. 1996) and the L_{bol}-T_{bol} diagram (Myers et al. 1998).

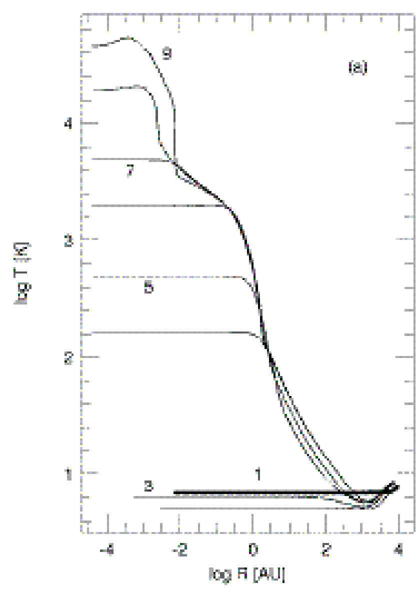

Figure 7. Predicted evolution (from 1 to 9) of the radial temperature profile of a collapsing protostellar envelope/condensation according to the numerical hydrodynamic model of Masunaga & Inutsuka (2000). Note that the temperature rises outward at early times.

Third, using combined SPIRE and PACS images to construct 80–500 μm SED maps for at least the nearest (spatially resolved) sources, it will be possible to derive the *thermal structure* of both protostellar envelopes and prestellar condensations/cores (see also § 4 below). This will allow us to determine the extent to which the envelopes of the youngest accreting (Class 0) protostars are already internally heated, and whether pre-collapse cloud cores –

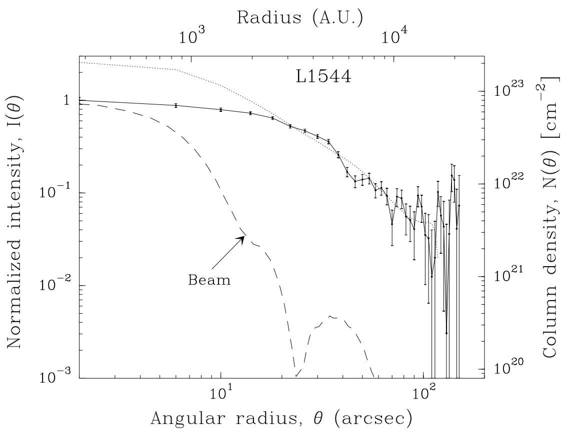

Figure 8. Radial intensity profile of the starless core L1544 at 1.3 mm (from Ward-Thompson, Motte, & André 1999). For comparison, the dotted curve shows a simulated profile for a model singular isothermal sphere with $\rho \propto r^{-2}$, normalized so as to match the observed profile at $r > 2500$ AU; the beam profile is shown as a dashed curve. Such a 1.3 mm profile, typical of pre-stellar cores, implies that these have flat inner density gradients if their dust (temperature and emissivity) properties are spatially uniform. With FIRST, it will be possible to check this assumption and to derive accurate radial temperature profiles across nearby pre-stellar cores.

presumably externally heated – are isothermal or colder in their inner regions (see, e.g., Falgarone & Puget 1985 and Fig. 7). Coupled with complementary ground-based observations in the submillimeter continuum, 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. 8). 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 2000). Indeed, 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* (cf. Motte, André, & Neri 1998). Thus, they make it possible to study the *genetic link between clouds, pre-stellar condensations, and young stars.* In particular, the large-scale surveys envisaged with SPIRE (see § 3 below) will allow us to derive the mass spectrum for the complete population of pre-stellar condensations in each mapped cloud. At the same time, combining the FIRST images with existing near-IR and mid-IR data (see E. Lada, this volume, Nordh et al. 1996, and Olofsson, this volume) will give us access to the YSO bolometric luminosity functions in the same clouds (e.g. Wilking et al. 1989, Bontemps et al. 1999, 2000). This will constrain the mass spectrum of protostars and YSOs. It will therefore be possible to *relate the mass spectrum of pre-collapse condensations to the mass spectrum of young stars* on a cloud to cloud basis, which will provide insight into the origin of the IMF and its possible regional variations.

The above approach has already been used successfully with recent ground-based dust continuum surveys of nearby clouds around 1 mm. In particular, Motte, André, & Neri (1998) 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. A total of 100 compact 'condensations' with characteristic angular scales of $\sim 15'' - 30''$ (i.e., $\sim$ 2500–5000 AU) can be identified in their mosaic. These small-scale condensations consist of 59 starless fragments (undetected by ISOCAM in the mid-IR – cf. Bontemps et al. 1999, 2000) and 41 circumstellar envelopes/disks around embedded YSOs (detected at IR and/or radio continuum wavelengths – cf. Leous et al. 1991). Comparison of the masses derived from the 1.3 mm continuum with Jeans or virial masses from molecular-line data suggests that most of the starless fragments are gravitationally bound (with $M_{1.3}/M_{vir} \gtrsim$ 0.3–0.5) 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. 9). It follows approximately $\Delta N/\Delta M \propto M^{-1.5}$ below $\sim 0.5 M_\odot$, but steepens to a Salpeter-like power law, $\Delta N/\Delta M \propto M^{-2.4}$, above $\sim 0.5 M_\odot$. In particular, it is very similar in shape to the YSO mass spectrum recently determined down to $\lesssim 0.1\,M_\odot$ for the Class II sources of the ρ Oph cluster from ISOCAM 7 μm and 15 μm observations (see Bontemps 2000, this volume).

By contrast, recall that the typical $\Delta N/\Delta M \propto M^{-1.5}$ clump mass spectra found by large-scale molecular line studies (e.g. Kramer et al. 1998) are much shallower than both the stellar IMF and the pre-stellar mass spectrum of

Fig. 9 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. On the other hand, *submillimeter dust surveys can detect the direct progenitors of individual stars.*

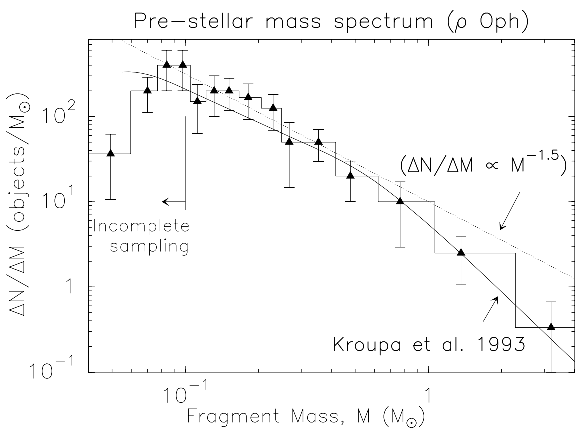

Figure 9. Mass spectrum of the 59 pre-stellar fragments extracted from the ρ Oph 1.3 mm continuum mosaic of Motte et al. (1998). The shape of this pre-stellar mass spectrum is remarkably similar to the piecewise power-law field star IMF (solid curve) advocated by Kroupa et al. (1993). Note the break at $\sim$ *0.3–0.5* $M_{\odot}$*, i.e., a mass comparable to the typical Jeans mass in the dense* DCO^{+} *cores of Loren et al. (1990).*

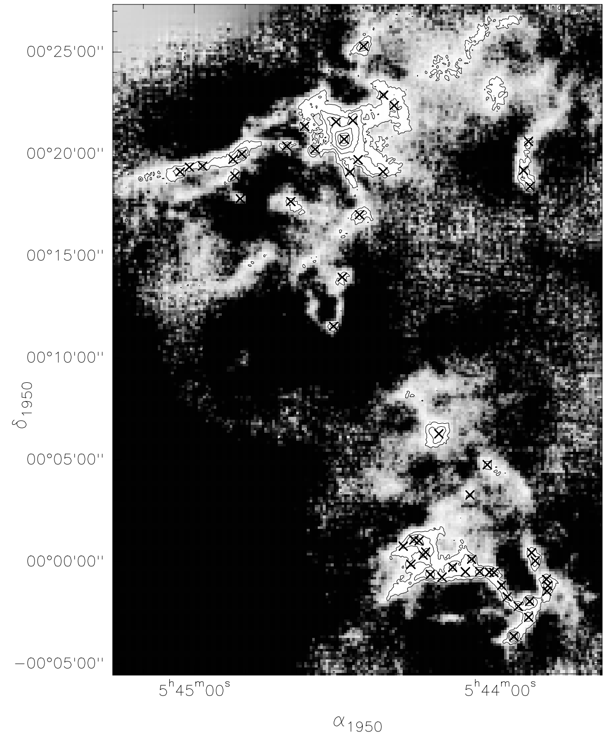

Figure 10. SCUBA 850 μm dust continuum mosaic of the NGC2068/2071 protoclusters in Orion B. A total of $\sim$ *55 compact starless condensations (cf. crosses) are detected above* $\sim 0.5\,M_{\odot}$ *(Motte, André, Ward-Thompson, & Kirk, in prep.).*

Two 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 32 starless condensations above $\sim 0.5\,M_{\odot}$ and measured their mass spectrum to be $\Delta N/\Delta M \propto M^{-2.1}$, i.e., close to the Salpeter IMF.
Very recently, Motte et al. (2000, in prep.) used SCUBA in the scan-map mode on JCMT to image a $30' \times 17'$ field at 850 μm around the NGC 2068 and NGC 2071 embedded clusters in Orion B (see Fig. 10). Their image reveals a total of $\sim$ 55 compact starless condensations whose mass spectrum is again reminiscent of the IMF between $\sim 0.5\,M_{\odot}$ and $\sim 10\,M_{\odot}$, although the dust continuum analysis is complicated by line contamination from outflow features in the vicinity of the luminous protostar NGC 2071–IR.

These recent ground-based (sub)millimeter continuum results on the mass spectrum of pre-stellar condensations in protoclusters are very encouraging because they support the view 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 also Larson 2000 and Elmegreen, this volume). It is nevertheless clear that present studies are limited by small-number statistics and restricted to nearby ($d \lesssim 450$ pc) star-forming clouds 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, 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, Dame 1999, Fukui 2000). 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, homo-

geneous samples of YSOs and protostars, and thus provide ideal laboratories for star formation studies (e.g. Zinnecker, McCaughrean, & Wilking 1993). Since the details of the star formation process appear to vary from cloud to cloud and to depend on environmental factors, it is crucial to study a large number of these regions in order to build a complete observational and theoretical picture. In particular, the typical Jeans mass is likely to differ from region to region, which may lead to a break in the mass spectrum of pre-stellar condensations at different characteristic masses (see Fig. 9). It would also be highly desirable to map both active clusters and *quiescent* regions, in order to shed light on the processes that initiate or inhibit star formation in molecular clouds.
Based on current estimates of the local star formation rate ($\sim 7.5\, M_\odot$ pc^{-2} Gyr^{-1} per unit area of the Galactic disk, implying a value ~ 0.02 M$_\odot$yr^{-1} in an area of $d \leq 1$ kpc around the Sun – e.g. McKee & Williams 1997, Mezger 1994), the above-mentioned regions should harbor $\gtrsim 500$ young low-mass protostars (cf. Mezger 1994), i.e., an order of magnitude more at least than those already identified from the ground (see § 1.2 above).

It would probably be too time-consuming to deeply survey all the Giant Molecular Clouds (GMCs) of the Galaxy with FIRST, but imaging only embedded clusters at $d < 1$ kpc with PACS (i.e., a total field area of less than ~ 3 deg^2 – cf. Zinnecker et al. 1993), as well as most known active regions plus a comparable area of quiescent fields within nearby GMCs with SPIRE (i.e., a total area of ~ 50 deg^2 at $d < 1$ kpc), seems perfectly feasible.
Assuming conservative detector-array performances, one should need only ~ 14 days to survey 1 deg^2 with PACS down to the $5\sigma_{180\mu}$ sensitivity of ~ 15 mJy required to detect proto-brown dwarfs of temperature $T_{proto} = 10K$ and mass $M_{proto} = 0.03\, M_\odot$ at the distance $d = 450$ pc of Orion, the nearest GMC. With SPIRE and its wider field of view ($4' \times 8'$), the same surface area can be covered in ~ 2 days down to the $10\sigma_{250\mu}$ sensitivity of ~ 30 mJy adequate to detect the same proto-brown dwarfs. Thus, about 1 month of FIRST time should be sufficient to image ~ 50 deg^2 to an appropriate sensitivity at 250 μm with SPIRE. Simultaneous operation of both instruments, if possible, would reduce the total time required by coordinated SPIRE and PACS surveys by a factor 1.5–2.

For this type of molecular cloud surveys FIRST should be ~ 2 orders of magnitude faster than SCUBA at 850 μm or SOFIA at 100–200 μm, and somewhat faster than ALMA at 1.3 mm. Furthermore, it is important to stress that ALMA and FIRST 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

The various spectrometers on board FIRST will provide very useful tools to better characterize the physics of the most interesting protostars and pre-stellar condensations found in the photometric surveys.
The SPIRE Fourier Transform Spectrometer (FTS), with its large field of view ($2.5' \times 2.5'$) and low spectral resolution ($20 \lesssim R \equiv \lambda/\Delta\lambda \lesssim 1000$), will permit imaging of the complete shape of the dust continuum spectrum from ~ 200 to $\sim 670\,\mu$m within and around most condensations. Variations of the SED over this wavelength range will give fundamental information on likely changes of dust grain emissivity and/or temperature across pre- and proto-stellar sources. It will also be possible to explore the line content of the brightest condensations and to measure the intensities of the various atomic (e.g. CI) or molecular (H_2O, CO) lines expected to dominate the cooling of the gas in collapsing protostellar envelopes and outflow shocks (e.g. Ceccarelli, Hollenbach, & Tielens 1996, Saraceno et al. 1999).
Follow-up HIFI measurements at high spectral resolution ($R \sim 10^6$–10^7) will constrain the associated velocity fields (e.g., inflow, rotation, and outflow) and chemical evolutionary states (cf. van Dishoeck 1997). The high spectral resolution of HIFI coupled with the good angular resolution of FIRST will help disentangle the contributions from the different velocity components. 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). Observations with the ISO-LWS have confirmed that water is abundant ($[H_2O]/[H_2] \sim 2 \times 10^{-5}$) in the inner parts of protostellar envelopes (e.g. Ceccarelli et al. 1999). The water lines will be easily resolved with the $\lesssim 0.1$ km s^{-1} velocity resolution of HIFI, providing valuable diagnostics of the mass accretion rate, $\dot{M}_{acc}$, *close the central object* (Ceccarelli et al. 1996, 1997). This is in contrast to millimeter lines (of e.g., H_2CO, CS, HCO^+) which are mainly sensitive to the outer parts ($r \sim 0.01$ pc) of dense cores and envelopes (e.g. Myers 1999). Combining FIRST and ALMA, it will thus be possible to study the kinematics of gravitational collapse in a *quantitative* way and on a *routine* basis.

5. CONCLUSIONS

The far-IR/submm is probably the most appropriate wavelength range for studying the earliest stages of star formation. Large-scale, multi-color surveys of nearby molecular clouds at $\lambda \sim 85$–300 μm with the PACS and SPIRE imaging instruments on FIRST will revolutionize our understanding of both the pre-collapse and collapse phases of star formation (see § 2 and § 3). In particular, they should allow us:

• to obtain a complete census of pre-stellar condensations, isothermal collapsing protostars, and young accreting protostars in active star-forming regions, 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 the mass spectrum of young stars, thereby giving insight into the fragmentation process and the origin of the IMF.

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