PROBING THE EARLIEST PHASES OF STAR FORMATION: AN HERSCHEL PHOTOMETRIC SURVEY OF NEARBY MOLECULAR CLOUDS

Philippe André[1] and Paolo Saraceno[2]
[1]Service d'Astrophysique, CEA/DSM/DAPNIA, C.E. Saclay, F-91191 Gif-sur-Yvette, France
[2]IFSI, CNR, Via Fosso del Cavaliere, I-00133 Roma, Italy

Abstract

The study of the earliest stages of star formation in molecular clouds is one of the fields that should benefit most from *Herschel* and ALMA. Improving our understanding of these deeply embedded stages is crucial to gain insight into the origin of stellar masses, multiple systems, and protoplanetary disks. As prestellar cores and young protostars emit the bulk of their luminosity between ~ 80 and $\sim 500\,\mu$m, the two imaging instruments of *Herschel* (SPIRE and PACS) are uniquely suited finding and characterizing such objects in the nearby cloud complexes of the Gould Belt ($d < 0.5$ kpc). Here, we summarize the case for an *Herschel* guaranteed-time key project aimed at a wide-field SPIRE/PACS survey of the densest part of the Gould Belt. This *Herschel* photometric survey will provide, for the first time, the mass and luminosity functions for complete samples of thousands of cold condensations down to the proto-brown dwarf regime. Thanks to its large spatial dynamic range, it will probe the link between diffuse ISM structures and compact self-gravitating condensations, thereby setting strong constraints on possible core formation mechanism(s). The *Herschel* survey discussed in this paper will also provide a unique database, including in the Southern hemisphere, for follow-up high-resolution molecular line/dust continuum studies with ALMA.

Key words: Molecular clouds – Stars: formation – Stars: mass distribution – Missions: *Herschel*.

1. Introduction

Understanding star formation on both small and large scales is a major unsolved problem of modern astrophysics, which is fundamental in its own right and also has a profound bearing on both planet formation and the physics of galaxies.

1.1. Background

A reasonably robust evolutionary sequence has now been established for the formation and early evolution of individual low- to intermediate-mass ($M_\star \lesssim 8\,M_\odot$) stars within molecular clouds (e.g. Shu, Adams, Lizano 1987; Lada 1987; André, Ward-Thompson, Barsony 1993, 2000; Shu, Li, Allen 2004). Five stages are distinguished, corresponding to prestellar cores (e.g. Ward-Thompson et al. 1994), two classes of protostars (Class 0 and Class I – Lada 1987; André et al. 1993), and two classes of pre-main sequence stars (Class II and Class III – Lada 1987; André & Montmerle 1994). Prestellar cores are gravitationally-bound starless ($M_\star = 0$) condensations, which are so cold that they emit only at far-IR/submm wavelengths. Class 0 sources are very young protostars for which the envelope mass still greatly exceeds that of the central stellar object ($M_{env} >> M_\star$). Class 0 objects retain detailed memory of their initial conditions. Observationally, they are characterized by high submillimeter to bolometric luminosity ratios ($L_{smm}^{\lambda>350\mu}/L_{bol} \gtrsim 1\%$) and overall spectral energy distributions (SEDs) resembling 15–30 K blackbodies. While *IRAS*, *ISO*, and ground-based near-IR studies have provided a fairly complete census of Class I–III sources in nearby clouds (e.g. Bontemps et al. 2001), no such census exists yet for cold prestellar condensations and Class 0 protostars.

Improving our knowledge of prestellar cores and Class 0 protostars is of prime importance to distinguish between collapse models and shed light on the origin of stellar masses. Recent ground-based (sub)-millimeter continuum surveys of nearby, compact cluster-forming clouds such as ρ Ophiuchi, Serpens, and Orion B have uncovered 'complete' (but small) samples of prestellar condensations whose associated mass distributions resemble the stellar initial mass function (IMF) (Motte, André, Neri 1998 – MAN98; Testi & Sargent 1998; Johnstone et al. 2000; Motte et al. 2001 – see Fig. 1a).

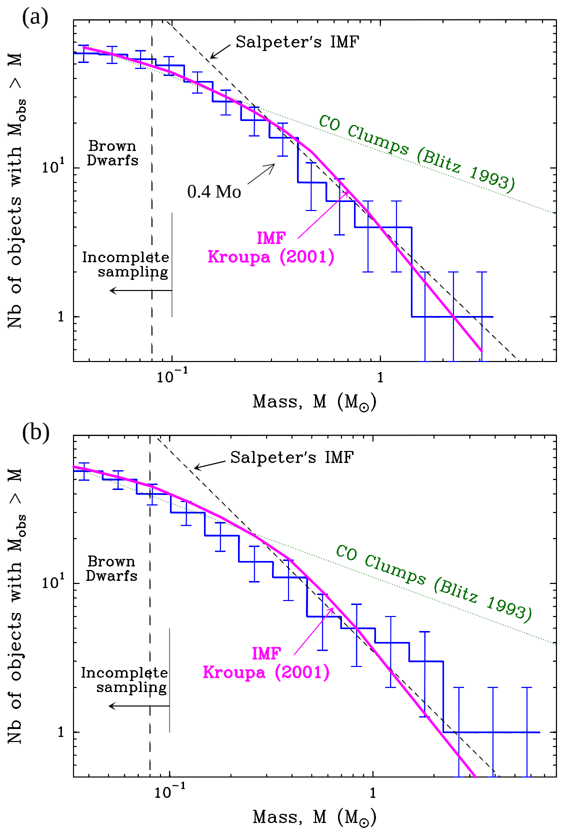

Figure 1. **(a)** *Cumulative mass distribution of a sample of 57 prestellar condensations, complete down to* $\sim 0.1\,M_\odot$, *in the* ρ *Oph protocluster (histogram with error bars – from MAN98). (Here, the condensation masses were derived from a 1.3mm dust continuum map assuming the same dust properties for all condensations:* $T_d = 15$ *K,* $\kappa_d(1.3\mathrm{mm}) = 0.005\,cm^2\,g^{-1}$*.) For comparison, the dotted and dashed lines show power-laws of the form* $N(>M) \propto M^{-0.6}$ *(typical mass distribution of CO clumps – see Blitz 1993) and* $N(>M) \propto M^{-1.35}$ *(Salpeter's IMF), respectively. The solid curve shows the shape of the field star IMF (e.g. Kroupa 2001). Note the flattening of these distributions below* $\sim 0.4\,M_\odot$. **(b)** *Same as (a) but assuming a distribution of dust temperatures for the* ρ *Oph condensations, in agreement with radiative transfer calculations which suggest that more massive, higher column-density condensations may be colder (e.g. Bouwman et al. 2004). The flattening of the prestellar mass distribution near* $\sim 0.4\,M_\odot$ *goes away. Direct temperature measurements, possible only with Herschel (§ 2.3), are thus crucial to derive reliable core mass distributions.*

Albeit limited by small-number statistics, these recent findings are encouraging because they support scenarios according to which the bulk of *the IMF is at least partly determined by pre-collapse cloud fragmentation* (cf. Padoan & Nordlund 2002). The problem of the origin of the IMF may thus largely reduce to a good understanding of the processes responsible for the formation of prestellar cores/condensations within molecular clouds.

1.2. Open Problems

Despite significant progress in the past two decades (e.g. § 1.1 above), several fundamental aspects of the star formation process remain poorly understood, including:

- What determines the distribution of stellar masses at birth, i.e., the IMF ?
- What generates prestellar cores in molecular clouds and what governs their evolution to protostars ?
- What controls the efficiency of star formation within a giant molecular cloud (GMC) ?
- On the scale of a GMC, is star formation generally a slow process (taking several dynamical times) or a fast, dynamic process ?
- What are the detailed physical conditions at the onset of protostellar collapse and how is protostellar collapse initiated ? How does this affect protostellar evolution ?
- Are the initial cloud conditions required for the "clustered mode" of star formation fundamentally different from the conditions for the "isolated mode" ?
- Is the formation process of brown dwarfs ($M_\star < 0.08\,M_\odot$) on the one hand and massive ($M_\star \gtrsim 8\,M_\odot$) stars on the other hand similar to the formation process of low- to intermediate-mass ($0.1 \lesssim M_\star \lesssim 8\,M_\odot$) stars (i.e., direct cloud core collapse and subsequent accretion/ejection) or qualitatively different ?
- Why and how does protostellar collapse typically produce binary/multiple systems of young stars ?

Herschel and ALMA will provide unique tools to address all of these fundamental issues.

2. Need for a Wide-Field Far-IR/Submm Survey with *Herschel*

We here summarize the unique potential of *Herschel* for studying the earliest stages of star formation.

2.1. Unmatched Mapping Speed for a Complete Census of Cold Condensations

With present ground-based mm/submm telescopes, systematic surveys for prestellar condensations and cold protostars are possible only down to $\sim 0.1\,M_\odot$ in nearby ($d \sim 150$ pc), compact regions such as the ρ Oph cloud (MAN98; Johnstone et al. 2000). Recent discoveries of new Class 0–like objects in well-documented regions such as Taurus and Lynds dark clouds through limited mm/submm mapping (e.g. André et al. 1999; Visser et al. 2002) show that the current census of protostars in the nearby ISM is incomplete. Complete, unbiased surveys of molecular clouds in the submm band are also needed to address the issue of whether or not there is a threshold for core formation. It has recently been suggested that cores cannot form below a minimum background column density $N_{\rm H2} \sim 10^{22}\,{\rm cm}^{-2}$ or $A_V \sim 10$ (Onishi et al. 1998, Johnstone et al. 2004). However, present claims are unconvincing because (i) they are based on surveys whose detection thresholds are themselves close to $A_V \sim 10$, and (ii) the ISM is known to be highly structured down to much lower column densities (e.g. Elmegreen & Falgarone 1996). Much deeper surveys, sensitive to $A_V \sim 1$, are required to settle this issue.

With a mapping speed $\sim$ 2–3 orders of magnitude faster than SCUBA at 850 μm or SOFIA at 100–200 μm (cf. Erickson, this volume) and nearly $\sim$ 1 order of magnitude faster than SCUBA2, SPIRE will make possible deep searches for low-mass, cold condensations over the entire extent of nearby cloud complexes in a reasonable time. Carrying out such surveys with the high angular resolution of PACS ($8''$ at 110 μm) and SPIRE ($17''$ at 250 μm) will be essential (i) to limit cirrus confusion, (ii) to probe individual ($\sim 0.01 - 0.1$ pc) condensations in nearby regions (up to $\sim$ 0.5 kpc), and (iii) to resolve the structure of the nearest (< 0.2 kpc) objects (§ 2.3).

2.2. Deriving Accurate Luminosities

Prestellar cores, Class 0 protostars, and Class I objects emit typically $\sim$ 100%, $>$ 80%, and $>$ 40% of their bolometric luminosity L_{bol}, respectively, in the 75–500 μm wavelength range sampled by *Herschel* photometers. Because of typical source clustering in star-forming regions, high-resolution *Herschel* mapping at these wavelengths is essential to derive accurate L_{bol} values for these objects. It is important to stress here that L_{bol} is a fundamental variable of (proto)stellar astrophysics used in all evolutionary diagrams proposed to date for embedded YSOs (e.g. Adams et al. 1987; André & Montmerle 1994; Saraceno et al. 1996; Myers et al. 1998).

2.3. Temperature/Density Structure Reconstructions

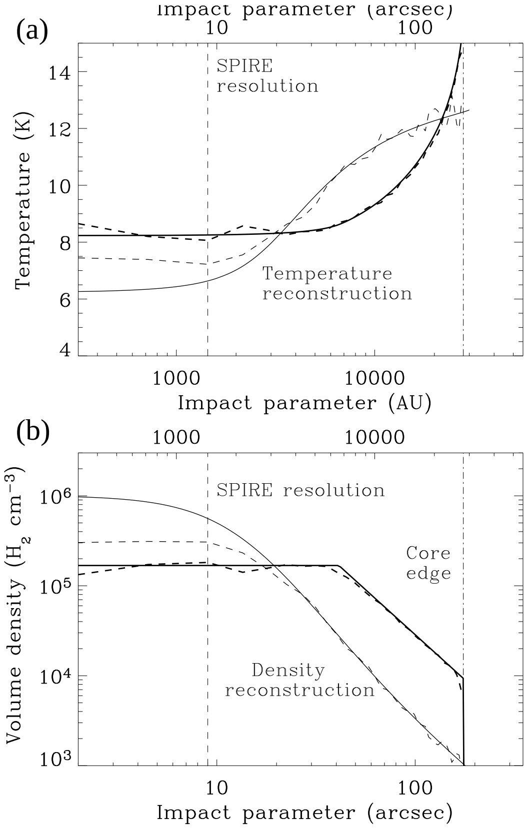

Figure 2. Reconstruction of the temperature **(a)** *and density* **(b)** *structure of a prestellar core such as L1689B in Ophiuchus based on simulated PACS and SPIRE images of this core between 110 μm and 500 μm. The solid curves show two model temperature and density profiles consistent with present observations of L1689B (e.g. Bacmann et al. 2000). The dashed curves correspond to temperature and density profiles reconstructed from the simulated Herschel images assuming that the 3D geometry of the core is known. Note that the two models can be distinguished with Herschel and that the reconstruction becomes uncertain near core center, i.e., below the angular resolution of SPIRE.*

Combining SPIRE and PACS images to construct 75–500 μm SED maps for the nearest, spatially resolved sources, it will be possible to derive the temperature distribution within both prestellar cores and protostellar envelopes. Recent radiative transfer modelling of the thermal energy balance suggests that starless cores are significantly colder in their central regions (with T as low as $\sim$ 5–7 K) than in their outer parts (e.g. Evans et al. 2001; Zucconi et al. 2001; Stamatellos et al. 2004). *Herschel* will allow us to directly measure the magnitude of this effect for the first time. Coupled with complementary ground-based dust continuum observations at longer submillimeter wavelengths, the column density structure of the same sources will also be derived with unprecedented accuracy, setting detailed constraints on the initial conditions for individual protostellar collapse. We stress that the only way to reach unambiguous conclusions on core structure is to reconstruct the temperature and column-density profiles simultaneously through multi-band imaging from the Rayleigh-Jeans part of the emission spectrum up to and beyond the peak of the SED (see § 3.3 of André et al. 2003 and Fig. 2 here).

2.4. Determining the Core Mass Distribution down to the Substellar Regime

In order to confirm the possible cloud fragmentation origin of the IMF (cf. end of § 1), it is crucial to improve on the current estimates of the core mass distribution in nearby star-forming clouds, which are limited by small-number statistics, especially at the low- and high-mass ends (see Fig. 1). Furthermore, the core mass distribution in the ρ Oph main cloud shows a tentative break at $\sim 0.4\,M_\odot$ (see Fig. 1a) which is reminiscent of the flattening observed in the stellar IMF below $0.5\,M_\odot$ (e.g. Kroupa 2001). The break in the IMF defines a characteristic stellar mass $\sim 0.5-1\,M_\odot$ which is possibly related to the typical Jeans mass in the parent cloud (e.g. Larson 2005; Padoan & Nordlund 2002). In this case, one may expect the location of this break to vary from region to region according to the local Jeans mass (which depends on the background density and temperature). To establish or rule out such an effect requires observations of a wide range of nearby star-forming clouds with much better statistics than presently available.

In the nearest ($d \lesssim 0.2$ kpc) clouds, the sensitivity SPIRE and PACS on *Herschel* will allow us to see whether the prestellar mass distribution remains consistent with the IMF in the brown dwarf mass regime or not, which will provide important clues to the much debated brown dwarf formation mechanism(s) (e.g. Reipurth & Clarke 2001; Padoan & Nordlund 2004).

Current mm/submm continuum determinations of the core mass distribution have to rely on rather strong assumptions about the *dust (temperature and emissivity) properties*. Both T_{dust} and κ_{dust} are uncertain (by a factor $\gtrsim 2$) and may possibly vary from object to object. Radiative transfer calculations show that the dust temperature at the center of a starless condensation depends primarily on the degree of shielding from the external interstellar radiation field (e.g. Bouwman et al. 2004). Since more massive condensations tend to have higher column densities (cf. MAN98) and to be more shielded, one may expect them to be colder on average than low-mass condensations, which may lead to a differential distortion of the derived mass distribution if uniform dust properties are assumed (see Fig. 1b). Using SPIRE and PACS observations, it will be possible to substantially reduce the mass uncertainties via direct constraints on the dust temperature (§ 2.3).

2.5. Sensitivity to Low Surface Brightness Structures and Spatial Dynamic Range

A *global view* of molecular cloud complexes is required if we are to explain the process(es) by which prestellar cores form out of the diffuse ISM at specific locations inside star-forming regions. In particular, there is ample evidence that dense cores are not distributed randomly within molecular clouds but are often organized along large-scale filamentary structures. The formation of prestellar cores thus appears to be intimately related to the formation of large-scale filaments within cloud complexes, and it has been proposed that both prestellar cores and molecular clouds form by collision of large-scale supersonic flows in the interstellar medium (e.g. Hartmann et al. 2001). Wide-field imaging surveys with SPIRE and PACS, coupled with follow-up molecular line observations with ground-based mm/submm telescopes, will provide powerful tests of such a scenario by probing a wide range of spatial scales from ~ 0.01 pc (corresponding to the $\sim 17''$ resolution of SPIRE in the nearest regions) to several pc.

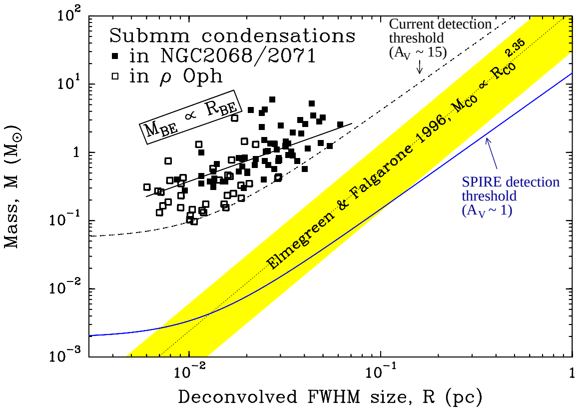

Figure 3. Mass vs. size diagram comparing the locations of the (sub)mm continuum prestellar condensations of ρ Oph and NGC2068/2071 (MAN98, Motte et al. 2001) with the correlation observed for diffuse CO clumps (shaded band – cf. Elmegreen & Falgarone 1996). The (5σ) detection threshold of current (sub)mm (e.g. SCUBA) surveys as a function of size is shown by the dashed curve. (The shape of this curve reflects a constant sensitivity to column density until source size approaches the beam size.) The detection threshold of the planned Herschel survey (§3) will be more than an order of magnitude lower (solid curve), allowing us to probe the genetic link between diffuse cloud structures (with $A_V \sim 1$) and dense, self-gravitating cores ($A_V > 10$).

Besides a high spatial dynamic range, one needs a high surface brightness dynamic range to be simultaneously sensitive to compact condensations *and* diffuse cloud structure. This point is illustrated in the mass vs. size diagram of Fig. 3 adapted from Motte et al. (2001). Known prestellar condensations are more than an order of magnitude more massive than typical CO structures for a given radius and follow a different mass–size relation (close to $M \propto R$, as opposed to $M \propto R^2$ for CO clumps). Fig. 3 reflects the fact that prestellar condensations are centrally-condensed, self-gravitating structures, while most CO clumps are transient unbound structures primarily shaped by turbulence (e.g. Elmegreen & Falgarone 1996). The typical sensitivity of present ground-based mm/submm continuum surveys is insufficient to detect low-density CO clumps. With its improved surface brightness sensitivity (see solid curve in Fig. 3), *Herschel* will probe deep into the regime of diffuse CO clumps, *making possible direct comparisons between CO clumps and prestellar condensations with a single tracer.*

3. An *Herschel* Photometric Survey of the Gould Belt

Owing to their proximity ($d \lesssim 0.5$ kpc), the molecular cloud complexes of the Gould Belt (e.g. Pöppel 1997, Guillout 2001) offer the best opportunity to investigate the formation process of low- to intermediate-mass stars in detail.

An *Herschel* guaranteed-time key project has thus been designed by the SPIRE and PACS consortia to address the open issues outlined in § 1.2 based on an extensive photometric mapping survey of nearby molecular clouds, mostly belonging to the Gould Belt. The current plan is to use SPIRE to take an homogeneous 250–500 μm survey of the $A_V \gtrsim 3$ portions of the Gould Belt complexes, corresponding to a total surface area $\sim 140\,\mathrm{deg}^2$. In a concerted effort, PACS will be used at 110–170 μm to map the densest ($A_V \gtrsim 6$) part of the Gould Belt, covering a total of $\sim 15\,\mathrm{deg}^2$ and including most cluster-forming regions and isolated dense cores within $d < 0.5$ kpc of the Sun, as well as representative, selected areas at lower ($A_V \sim 1-3$) extinction levels.

Assuming nominal sensitivities for the SPIRE and PACS instruments, the 5σ column-density detection level of this *Herschel* survey would be $N_{\mathrm{H2}} \sim 10^{21}\,\mathrm{cm}^{-2}$ or $A_V \sim 1$, which is well matched to the expected cirrus confusion limit.

The target regions span a wide range of physical conditions, from 'active', cluster-forming complexes (Ophiuchus, Corona Australis, Serpens, Perseus, Orion) to more 'quiescent' clouds with no or only distributed, low-mass star formation activity (Coalsack, Lupus, Polaris flare, Taurus). They include the nearest examples of massive GMCs forming a significant number of intermediate-mass and high-mass stars (e.g. Orion). Some of them (e.g. Ophiuchus, Corona Australis, Serpens, Perseus, Orion) harbor compact embedded clusters ontaining large, homogeneous samples of YSOs and protostars, which have been the subject of detailed investigations at near-IR wavelengths. These embedded clusters are believed to be representative of the basic building blocks where most ($\sim 70-90\%$) stars form in the Galaxy (e.g. Lada & Lada 2003).

Based on current estimates of the local star formation rate in the Galaxy (e.g. McKee & Williams 1997), the planned *Herschel* survey will provide a complete sample of a few hundred Class 0 protostars and several thousand prestellar condensations, i.e., an order of magnitude more cold protostellar objects than presently identified from the ground. These objects will have well-characterized dust temperatures, luminosities, and masses, as well as radial (temperature and density) profiles in many cases. The relative numbers of objects in the various evolutionary phases will set strong constraints on the associated lifetimes as a function of mass, central density, and environment, hence on models of slow *vs.* fast core/star formation (e.g. Shu et al. 1987, 2004 *vs.* Klessen et al. 2000 and Hartmann et al. 2001). With ~ 20 prestellar condensations expected per 0.15 dex mass bin around $0.01\,M_\odot$ and $5\,M_\odot$, the number of prestellar condensations detected in the survey will be adequate to derive an accurate core mass function from the substellar to the intermediate-mass regime.

4. Conclusions and Prospects with ALMA

With an angular resolution $\sim 7''$–$25''$ at 80–350 μm comparable to, or better than, the largest ground-based single-dish radiotelescopes at ~ 1 mm, *Herschel* will make possible a deep census and detailed characterization of the population of prestellar condensations and young (Class 0) protostars in the nearby ($d \leq 0.5$ kpc) molecular cloud complexes of our Galaxy. On small scales, the temperature and density structure of the nearest (≤ 0.2 kpc) objects will be resolved, setting detailed constraints on the initial conditions for individual protostellar collapse. On a more global level, the large spatial dynamic range of the planned SPIRE/PACS survey will provide a unique view of the formation of dense cores within molecular cloud complexes, by probing the link between the diffuse interstellar medium and compact self-gravitating condensations. The main scientific goal is to elucidate the physical mechanisms responsible for the formation of prestellar condensations out of the diffuse ISM, which appears to be the key to understanding the origin of stellar masses.

The *Herschel* guaranteed time key project described in this paper will also provide a unique database, including in the Southern hemisphere, for follow-up high-resolution molecular line/dust continuum studies with ALMA. In particular, ALMA will allow the detailed properties of complete, statistically representative samples of multiple protostars to be determined (e.g. frequency as a function of separation, orbital motions), which will set strong constraints on viable mechanisms for the formation of binary systems (cf. Looney et al. 2000, Zinnecker & Mathieu 2001, Tohline 2002). Detailed kinematical studies of both prestellar condensations and protostellar envelopes in a large number of molecular line tracers will also be possible on a routine basis, which will yield *direct estimates of the associated infall, outflow, and rotation rates* and help discriminate between collapse models (cf. Belloche et al. 2002).

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References

Adams, F., Lada, C.J., & Shu, F. 1987, ApJ, 312, 788

André, P., Bouwman, J., Belloche, A., & Hennebelle, P. 2003, in Chemistry as a Diagnostic of Star Formation, Eds. C.L. Curry & M. Fich, NRC Press, p. 127

André, P., & Montmerle, T. 1994, ApJ, 420, 837

André, P., Motte, F., & Bacmann, A. 1999, ApJ, 513, L57

André, P., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122

André, P., Ward-Thompson, D., & Barsony, M. 2000, in Protostars & Planets IV, Eds. V. Mannings et al., The University of Arizona Press, p. 59

Bacmann, A., André, P., Puget, J.-L. et al. 2000, A&A, 361, 555

Belloche, A., André, P., Despois, D. & Blinder, S. 2002, A&A, 393, 927

Blitz, L. 1993, in Protostars and Planets III, Eds. E.H. Levy & J.I. Lunine, The University of Arizona Press, p. 125

Bontemps, S., André, P., Kass, A.A., Nordh, L., Olofsson, G. et al. 2001, A&A, 372, 173

Bouwman, J., André, P., Galli, D. 2004, in preparation

Elmegreen, B.G., & Falgarone, E. 1996, ApJ, 471, 816

Evans, N.J. II, Rawlings, J.M.C., Shirley, Y.L., & Mundy, L.G. 2001, ApJ, 557, 193

Guillout, P. 2001 in From Darkness to Light, Eds. T. Montmerle & P. André, ASP Conf. Ser., 243, p. 677

Hartmann, L., Ballesteros-Paredes, J., & Bergin, E. 2001, ApJ, 562, 852

Johnstone, D., Wilson, C. D., Moriarty-Schieven, G., et al. 2000, ApJ, 545, 327

Johnstone, D., Di Francesco, J., & Kirk, H. 2004, ApJ, 611, L45

Klessen, R.S., Heitsch, F., & Mac Low, M.-M. 2000, ApJ, 535, 887

Kroupa, P. 2001, MNRAS, 322, 231

Lada, C.J. 1987, in Star Forming Regions, IAU Symp. 115, p. 1

Lada, C.J., & Lada, E.A. 2003, ARA&A, 41, 57

Larson, R.B. 2005, in IMF50, Eds. E. Corbelli, F. Palla, & H. Zinnecker, Kluwer Academic Publishers, in press (astro-ph/0406624)

Looney, L.W., Mundy, L.G., & Welch, W.J. 2000, ApJ, 529, 477

McKee, C.F., & Williams, J.P. 1997, ApJ, 476, 144

Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150 - MAN98

Motte, F., André, P., Ward-Thompson, D., & Bontemps, S. 2001, A&A, 372, L41

Myers, P.C., Adams, F.C., Chen, H., & Schaff, E. 1998, ApJ, 492, 703

Onishi, T., Mizuno, A., Kawamura, A., Ogawa, H., & Fukui, Y. 1998, ApJ, 502, 296

Padoan, P., & Nordlund, A. 2002, ApJ, 576, 870

Padoan, P., & Nordlund, A. 2004, ApJ, 617

Pöppel, W. 1997, Fund. Cos. Phys., 18, 1

Reipurth, B., & Clarke, C. 2001, AJ, 122, 432

Saraceno P., André P., Ceccarelli C., Griffin M., Molinari S. 1996, A&A, 309, 827

Shu, F.H., Adams, F.C., & Lizano, S. 1987, ARA&A, 25, 23

Shu, F.H., Li, Z.-Y., Allen, A. 2004, ApJ, 601, 930

Stamatellos, D., Whitworth, A.P., André, P., & Ward-Thompson, D. 2004, A&A, 420, 1009

Testi, L., Sargent, A.I 1998, ApJL, 508, L91

Tohline, J. E. 2002, ARA&A, 40, 349

Visser, A.E., Richer, J.S., & Chandler, C.J. 2002, AJ, 124, 2756

Ward-Thompson, D., André, P., & Kirk, J.M. 2002, MNRAS, 329, 257

Ward-Thompson, D., Motte, F., & André, P. 1999, MNRAS, 305, 143

Ward-Thompson, D., Scott, P.F., Hills, R.E., & André, P. 1994, MNRAS, 268, 276

Zinnecker, H., & Mathieu, R.D. 2001, The Formation of Binary Stars, IAU Symposium, Vol. 200, Astronomical Society of the Pacific

Zucconi, A., Walmsley, C.M., & Galli, D., 2001, A&A, 376, 650