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Testing the Paradigm of Low-Mass Star Formation

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Abstract. Protostellar core formation is probably much more dynamic, and magnetic fields are probably much less important, than has been previously assumed in the standard model of low-mass star formation. This revised picture has important consequences: it is easier to understand the observed rapidity of star formation in molecular clouds; cores are more likely to have structures favoring high infall rates at early times, helping to explain the differences between Class 0 and Class I protostars; and core structure and asymmetry will strongly favor post-collapse fragmentation into binary and multiple stellar systems.

1. Introduction

What do we mean when we speak of "testing the paradigm of low-mass star formation"? If it is simply questioning the sequence of events – a molecular cloud core collapses at near free-fall velocities to a protostar plus disk system, followed by accretion through a disk onto the star, and eventual planet formation (e.g., Shu, Adams, & Lizano 1987) – then there is little controversy. On the other hand, if one is testing details from older models – for example, that molecular cloud cores must lose substantial magnetic flux by ambipolar diffusion before collapse; that cores are essentially static before collapsing; and that core collapse occurs "inside-out'– then there is much less agreement. Indeed, developments over the last several years have cast significant doubt on many of these details.

More broadly, it is obvious that any theory of low-mass star formation must encompass the end points: specifically, the formation of protostellar cores, and the formation of binary and/or multiple systems (probably through post-collapse fragmentation in many if not most cases). The standard paradigm is essentially silent on these issues; it must be expanded if we are to understand aspects of star formation such as the initial mass function.

In this contribution I will focus on the origin of protostellar cores, which has implications for core structure and therefore for subsequent phases of collapse and fragmentation.

2. Molecular clouds and magnetic fields

Because cores are subunits of molecular clouds, some attention must be paid to the processes of cloud formation and dispersal. For some time it was thought that giant molecular clouds are relatively long-lived (e.g., Solomon et al. 1979).

This view implies that molecular clouds must be supported by supersonic turbulence (Norman & Silk 1980; Larson 1981); that this turbulence is responsible for preventing wide-spread gravitational collapse, which would result in far too large a galactic star formation rate (Zuckerman & Evans 1974); and that cloud turbulence must be strongly Alfvenic in character, to avoid dissipating too rapidly (Arons & Max 1975; see discussion in Shu, Adams, & Lizano 1987).

A preliminary step toward changing this long-life view was taken by Blitz & Shu (1980). They used several arguments to argue that typical cloud lifetimes are $\lesssim$ 30 Myr, including the concentration of OB associations to spiral arms (implying that molecular gas does not drift for a long time past the arms) and the rapidity with which massive stars can disperse molecular gas.

Table 1
Star forming regions

Region	$< t >$ (Myr)	Molecular gas?
Coalsack	–	yes
Cha III	?	yes
Orion Nebula	1	yes
Taurus	2	yes
Oph	1	yes
Cha I,II	2	yes
Lupus	2	yes
MBM 12A	2	yes
IC 348	1-3	yes
NGC 2264	3	yes
Upper Sco	2-5	no
Sco OB2	5-15	no
TWA	$\sim$ 10	no
η Cha	$\sim$ 10	no

However, stellar population ages suggest that cloud lifetimes in the solar neighborhood are of order 3-5 Myr, i.e. an order of magnitude smaller than the Blitz-Shu estimate. As shown in Table 1, taken from Hartmann, Ballesteros-Paredes, & Bergin (2001; HBB), it is very rare to find substantial molecular clouds without at least some young stars forming within them. In almost all local clouds, the typical age of the stellar population is $\sim 1 - 3$ Myr. And older groups, whether OB associations or low-mass groups, of ages 5-10 Myr have no associated molecular gas. These data clearly demonstrate that star formation proceeds almost immediately upon cloud formation; that molecular clouds are transient structures; and that clouds are rapidly dispersed.

This picture has a number of important implications. Numerical simulations have indicated that, contrary to expectation, MHD turbulence decays rapidly (Stone, Ostriker, & Gammie 1998; Mac Low et al. 1998; Mac Low 1999). However, even with this rapid dissipation, short cloud lifetimes comparable to or less than crossing times (Elmegreen 2000; HBB) imply that turbulence need not be regenerated, but could simply be left over from cloud formation. This avoids difficulties using stellar energy sources to maintain turbulence for long periods of time, which in at least in the case of massive stars are much more likely to disrupt the cloud than stabilize it. Short cloud lifetimes also imply that the low rate of star formation is the result of reduced efficiency of conversion to gas to stars (Hartmann 1998; Elmegreen 2000) rather than slow cloud contraction as ambipolar diffusion proceeds.

The short lag time between cloud formation and the onset of star formation makes it unlikely that ambipolar diffusion can operate for a long time. In turn, this implies that large amounts of magnetic flux need not be removed from the cloud; i.e., that the cores cannot be highly magnetically subcritical. This seems to fly in the face of the so-called magnetic flux problem (Mestel & Spitzer 1956), which would seem to imply that formation of clouds from diffuse interstellar conditions would result in far too much magnetic flux for clouds of thousands of solar masses or less to contract without flux loss.

To avoid the magnetic flux problem, supercritical clouds can be formed by flows *along* the magnetic field (e.g., Mestel 1985). This requires large-scale flows, at least if molecular clouds are to be formed by accumulation out of the diffuse galactic interstellar medium. The accumulation length l needed to produce a critical cloud, measured along the magnetic field, adopting interstellar medium parameters typical of the solar neighborhood, is

$$l_c \ \sim \ 430\,(B/5\mu G)\,(n_H/1\mathrm{cm}^{-3})\,\mathrm{pc}\,, \tag{1}$$

While l_c appears to be rather large, Blitz & Shu (1980) considered formation of giant molecular clouds from accumulation over 500 pc along the field.

Observations of large GMCs suggest that cloud accumulation lengths often are very large. In a number of cases, the lateral crossing times of star-forming regions or young associations are substantially longer than the ages of the stellar population (HBB). It is difficult if not impossible to explain this coordination over large distance scales by propagating information along the cloud. The natural explanation is that the clouds are swept up by large scale flows driven by either stellar winds, supernovae, spiral density wave shocks, or a combination of all three. The flows must have substantial correlation lengths to explain some of the largest regions. For instance, the Sco OB2 association has a projected extent of order 150 pc (and an internal velocity dispersion in the plane of the sky of only $1.5\mathrm{km\,s}^{-1}$ or less; de Bruijne 1999). Flows of hundreds of pc in length are much more likely to exhibit such lateral coherence.

The numerical simulations of the interstellar medium by Enrique Vazquez and his collaborators (Passot, Vazquez-Semadeni & Pouquet 1995; see also Ballesteros-Paredes et al. 1999 and HBB) also suggest that accumulation lengths are large, and lead to supercritical clouds. These ideal MHD simulations have some limitations – they are two-dimensional, and do not reach high densities – but they are extremely important because they cover very large regions (1 kpc on a side) and can thus address cloud formation by flows on larger scales than any other simulation.

These simulations show that flows do extend for hundreds of pc, and that they do tend to accumulate mass along magnetic field lines, as required to make supercritical clouds out of the diffuse medium. The simulations also indicate that the flows can bend the magnetic field lines, if necessary, to accomodate mass accumulation. Finally, the simulations indicate that massive regions tend to be magnetically supercritical, as shown in Figure 1.

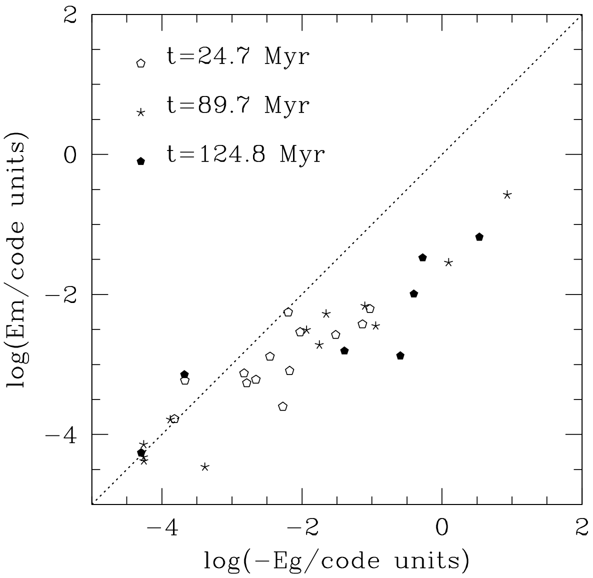

Figure 1. Cloud magnetic energies (vertical axis) vs. gravitational energies (horizontal axis) for clouds in the simulations discussed in HBB. The dotted line indicates magnetic criticality; the massive clouds are supercritical. From HBB.

There is a fairly straightforward argument to be made why molecular clouds formed in this way should be supercritical, as discussed in HBB. In essence, dense regions tend to be magnetically-supercritical because supercritical conditions are dynamically favorable for cloud formation. If the internal magnetic field in a cloud creates a pressure force stronger than the force of gravity (i.e., the cloud is subcritical), then the cloud will expand unless external pressures confine it. Therefore dense clouds tend to have magnetic pressure forces weaker than the external (ram) pressures. But star formation generally proceeds in clouds where gravitational forces are important in comparison with external pressure forces. Thus, self-gravitating clouds tend to have gravitational forces larger than both external pressure and internal magnetic forces, i.e. they are supercritical. In addition, molecular clouds only form in the solar neighborhood when the column density of material is sufficient (generally, visual extinctions of order unity or larger) to shield the molecules from the dissociating interstellar radiation field. At this point, the self-gravity of the cloud is comparable to or larger than that of typical interstellar medium pressures (Franco & Cox 1986). Thus when clouds accumulate enough material to become molecular, they also tend to be both self-gravitating and supercritical.

Independent arguments suggesting that giant molecular clouds are at least critical if not supercritical were given by McKee (1989). Nakano (1998) also made somewhat similar arguments that cores are generally supercritical. Finally, recent observational studies of dense regions indeed suggest that cores are roughly critical if not supercritical (Crutcher 1999; Bourke et al. 2001).

Note that, given the low efficiency of star formation on a global scale (i.e., the entire molecular cloud), gravitational collapse need only occur rapidly over limited scales. Thus, even if the cloud as whole is close to critical, some regions will be magnetically-strong and others magnetically-weak, and the B-weak regions will probably collapse first. Ambipolar diffusion is thus unlikely to slow protostellar collapse, and magnetic forces do not prevent local rapid star formation upon the formation of molecular gas, as required by observations.

3. Filaments and fragmentation

The rapidity of star formation in molecular clouds indicates the need for a dynamic theory of protostellar core formation. Indeed, it is difficult to see how it could be otherwise, as one must take diffuse molecular gas and concentrate it somehow, with some kind of motions. There are two extreme possibilities here. One is that the turbulent motions present in the cloud occasionally focus material into small enough volumes that become Jeans unstable and then collapse (e.g., Padoan & Nordlund 1999). The other extreme picture invokes gravitational focusing in a relatively quiescent medium (e.g., Larson 1985). It seems likely that the true solution lies somewhere in between these two extremes; clouds are supersonically turbulent, but gravity must obviously play an important role as well.

As an initial step towards addressing these problems, consider the situation in the Taurus star-forming region. Taurus may not be typical of such regions; it is of relatively low density, it is not making massive stars, and it appears to have a somewhat distinctive initial mass function in comparison with other regions (e.g., Briceño et al. 2002). However, it is close, easy to study, and relatively quiescent. If the paradigm of low-mass star formation applies anywhere, it should apply in Taurus.

While it has long been recognized that the distribution of dense gas in Taurus is filamentary, it has only recently been emphasized that the distribution of young stars is extremely filamentary (Hartmann 2002). In particular, as shown in Figure 2, on a large scale most of the stars (and the dense gas) are distributed in three extensive, roughly parallel bands. One of these bands extends the entire length of the association.

To see the implications of this structure, it is again useful to compare with the results of numerical simulations. Klessen (2001) and Klessen & Burkert (2001) have computed dynamical structures with forced driving of turbulence on a variety of scales. Driving with fluctuations on small scales unsurprisingly produces small-scale structures with no hint of large-scale filaments. In contrast, low-spatial-wavenumber (large-scale) driving of turbulence yielded long filaments in the Klessen et al. simulations. Therefore the Taurus structure suggests large-scale driving. It is tempting to identify this large-scale driving source with the large-scale flow that I suspect formed Taurus in the first place.

How are the filaments produced? One possibiity is that turbulence is entirely responsible, as in the Klessen et al. simulations. There is clearly smaller-scale structure in the dense gas filaments, as shown in the left panel of Figure 3,

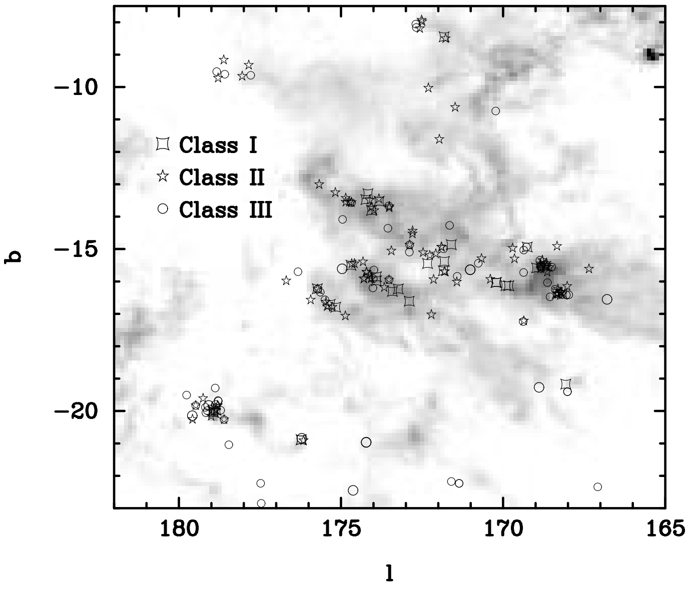

Figure 2. Young stellar objects in the Taurus region, labelled by their spectral energy distribution class, superimposed upon the ^{12}CO map of Megeath, Dame, & Thaddeus (2002, personal communication)

which almost certainly reflects small-scale motions of some kind. Alternatively, gravity could play an important role in focusing material into filaments, as for example in the simulations by Miyama et al. (1987a,b).

However the filaments are formed, it seems most likely to me that core production is the result of gravitational fragmentation in the filaments, as envisaged by Larson (1985). It seems unlikely to me that even if non-gravitational flows form the filaments, sub-flows would then arise to break up the filament; in contrast, gravitational fragmentation should naturally operate.

The gravitational fragmentation hypothesis predicts that the initial scale of fragmentation should be longer than the typical width of the filament. In support of this hypothesis, as shown in the right hand panel of Figure 3, cores are typically elongated along their host filaments. Note that this picture of gravitational fragmentation can only work if the filaments are supercritical; otherwise the magnetic field would prevent concentration.

Thus I suggest that core formation is essentially the initial stages of gravitational collapse, at least in Taurus. Supersonic flows, however induced, make filaments in this picture. In the post-shock gas within filaments, gravitational fragmentation and subsequent collapse occurs. This picture predicts that there should be large-scale infall motions, as seen for example by Tafalla (1998) and Lee, Myers, & Tafalla (2001). It also predicts that core collapse follows immediately upon core formation (because formation occurs by gravitational instability); this is also reasonably consistent with core statistics which suggest that starless cores do not live for many free-fall times (Jijina et al. 1999).

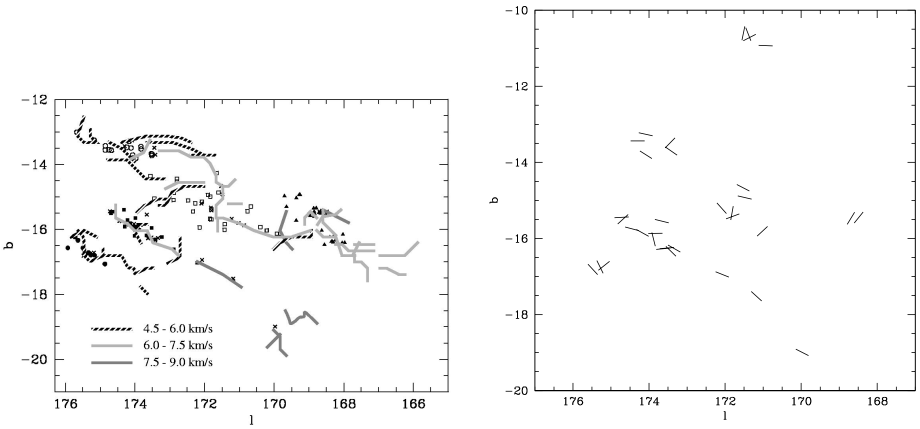

Figure 3. Left: Approximate position of ^{13}CO filaments in the central region of Taurus found by Mizuno et al. (1995), with young stars indicated. The CO filaments are sorted into the same LSR velocity ranges as Mizuno et al. . Right: Spatial distribution of optical cores from Lee & Myers (1999), with the orientation of the line indicating the position angle of the core major axis. Comparison of the two panels shows that cores in Taurus are generally elongated along filaments. From Hartmann (2002).

4. Core structure

Most protostellar cores are elongated in projection. Myers et al. (1991) argued that typical cores are more prolate than oblate, which if true would pose significant problems for simple magnetically-dominated models of core structure, which most naturally tend to be oblate (flattened along the magnetic field) than prolate. Prolate magnetic models have been constructed by Curry & Stahler (2001), but these are quasi-static; Fiege & Pudritz (2000) constructed static models, but the plausibility of the adopted boundary conditions is in doubt.

Several independent investigations of core structure have been carried out which exhibit some tendency to support the notion of prolate (like) cores (Jones & Basu 2002; Curry 2002). However, most studies assume a random distribution of core inclinations and then make statistical analyses. It is quite clear from Figure 3 (right) that the cores in Taurus are NOT randomly distributed in space; there is a definite overall orientation. Given the elongation of cores along large-scale filaments, it seems inescapable that the cores are more prolate-like than oblate.

In the picture of core formation and evolution advanced in the previous section, cores are not completely static but are dynamic. In principle, this makes it easier to understand prolate and other complex structure; all forces need not be balanced perfectly, as in true hydrostatic equilibrium. Even a relatively ordered, smooth-looking core like L1544 (Figure 4) is not only elongated, but asymmetric along the major axis; this structure would require some carefully arranged magnetic field distribution to explain in pure hydrostatic equilibrium.

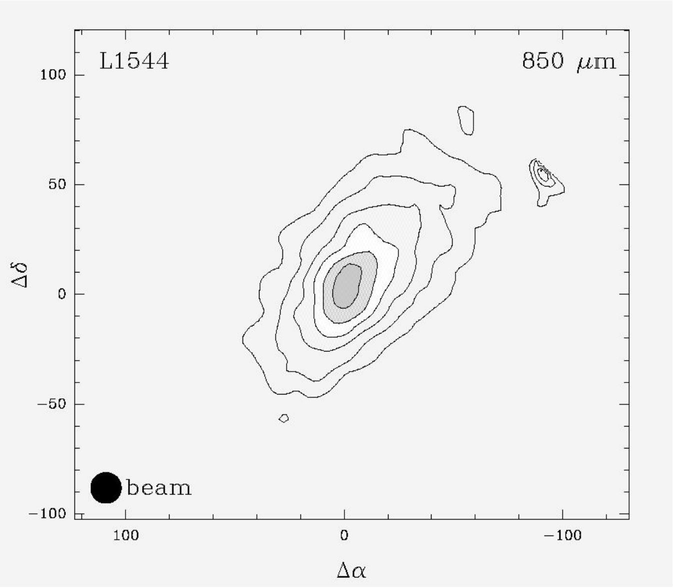

Figure 4. Submm image of the starless core L1544, showing flattened core structure, a flat inner density region, and an overall asymmetry. From Shirley et al. 2000).

Such careful arrangements are not necessary in the dynamic model. Increasingly realistic calculations of dynamic core formation are needed to test against the observations. The simulations discussed by Ballesteros-Paredes et al. (2003) are a start; these calculations "turn on" gravity late in the process, which seems unrealistic.

For purposes of initial analysis, and in the absence of dynamic models, static equilibrium models of cores can be useful. It has become increasingly popular to compare observations of cores with so-called Bonnor-Ebert spheres, isothermal, pressure-bounded models. The BE sphere models have a significant advantage over the earlier singular isothermal sphere models; they can be stable, while the singular sphere is not. In addition, it has become increasingly clear that starless cores tend to have flattened density distributions near their centers (as in L1544, Figure 4) rather than singular distributions (e.g., Bacmann et al. 2000). The BE sphere models can match these properties qualitatively. In the special case of B68, a rather spectacular fit can be made to the circularly-averaged data (Alves et al. 2001).

Caution should be employed that such analyses are not overinterpreted, especially if used to conclude that cores are generally in hydrostatic equilibrium, and deriving extremely precise properties. Averaging can make a very big difference to the interpretation. For example, consider the toy core model in Figure 5; it is a uniform rectangle (filament) projected on the sky. Now, circularly average; the resulting surface density has a flat inner region with an r^{-1} falloff, because the mass grows with r but the surface area increases as r^2. Next, interpret this

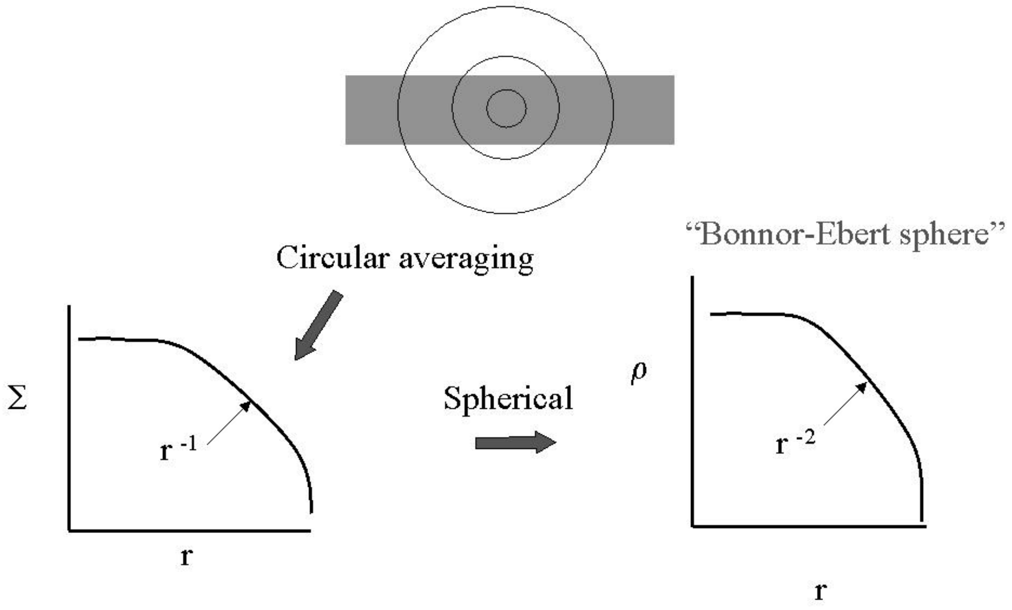

Figure 5. Toy model, showing how circular averaging of an intrinsically elongated surface density distribution, followed by spherical volume modelling of the density distribution, can yield misleading results (see text)

in terms of spherical structure; this introduces an extra power of r in the volume density outside the "core". In this way it is possible to produce something that looks like a BE sphere, with a flat inner core, and an r^{-2} volume density dependence outside this core, from a density distribution that is qualitatively different.

Real cores don't look like my toy core; they are more centrally-condensed. Nevertheless, it is clear that circular averaging smooths over a lot of real structure, and that interpretation in terms of a spherical structure can be misleading. I think this is true even in the case of B68, which is fairly, but not precisely, round; which has significant lumps in non-smoothed extinction maps; and which has significant, though subsonic, correlated velocity structure (Lada et al. 2003). In short, B68 is probably close to, but not quite in, hydrostatic equilibrium; and B68 is far from typical of most cores. We need dynamic models, plus some clever way of applying these models to non-smoothed data if we are really going to understand cores.

Why is core structure important? For one thing, the mass infall rate of cores with flattened inner structures vary substantially with time, with higher rates at earlier times (Foster & Chevalier 1993; Henriksen, André, & Bontemps 1997; Whitworth & Ward-Thompson 2001); this probably helps to explain the Class 0 phase of protostellar collapse as a high-infall phase compared with Class I objects (André, Ward-Thompson, & Barsony 1993). In contrast, the singular isothermal sphere models produce a constant infall rate with time. Perhaps more importantly, cores with flattened inner density distributions and with strong non-axisymmetric structure are more favorable for the production of binaries and multiple systems through post-core-collapse fragmentation (Bodenheimer et al. 2000, and references therein).

Clearly we are at a very early stage in understanding the consequences of a more dynamic picture of low-mass core collapse and star formation. Much more realistic time-dependent numerical simulations are needed to fully exploit the increased observational capabilities at nearly all wavelengths to understand star formation and the origin of the stellar initial mass function.

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References

Alves, J. F., Lada, C. J., & Lada, E. A. 2001, Nature, 409, 159

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

Arons, J. & Max, C. E. 1975, ApJ, 196, L77

Bacmann, A., André, P., Puget, J.-L., Abergel, A., Bontemps, S., & Ward-Thompson, D. 2000, A&A, 361, 555

Ballesteros-Paredes, J., Hartmann, L., & Vazquez-Semadeni, E. 1999, ApJ, 527, 285

Ballesteros-Paredes, J., Klessen, R. S., & Vázquez-Semadeni, E. 2003, ApJ, 592, 188

Blitz, L. & Shu, F. H. 1980, ApJ, 238, 148

Bodenheimer, P., Burkert, A., Klein, R. I., & Boss, A. P. 2000, in Protostars and Planets IV, eds. Mannings, V., Boss, A. P., & Russell, S. S., University of Arizona Press, Tucson, 675

Bourke, T.L., Myers, P.C., Robinson, G., & Hyland, A.R. 2001, ApJ, 554, 916

Crutcher, R.M. 1999, ApJ, 520, 706

Curry, C.L. 2002, ApJ, in press (astro-ph/0206311)

Curry, C. L. & Stahler, S. W. 2001, ApJ, 555, 160

de Bruijne, J.H.J. 1999, MNRAS, 310, 585

Elmegreen, B.G. 2000, ApJ, 530, 277

Fiege, J. D. & Pudritz, R. E. 2000, ApJ, 534, 291

Foster, P. N. & Chevalier, R. A. 1993, ApJ, 416, 303

Franco, J. & Cox, D. P. 1986, PASP, 98, 1076

Henriksen, R., Andre, P., & Bontemps, S. 1997, A&A, 323, 549

Hartmann, L. 1998, Accretion Processes in Star Formation (Cambridge University Press), 33

Hartmann, L. 2002, ApJ, 578, 914

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

Jijina, J., Myers, P. C., & Adams, F. C. 1999, ApJS, 125, 161

Jones, C. E. & Basu, S. 2002, ApJ, 569, 280

Klessen, R.S. 2001, ApJ, 556, 837

Klessen, R. S. & Burkert, A. 2001, ApJ, 549, 386

Lada, C. J., Bergin, E. A., Alves, J. F., & Huard, T. L. 2003, ApJ, 586, 286

Larson, R. B. 1981, MNRAS, 194, 809

Larson, R.B. 1985, MNRAS, 214, 379

Lee, C.W. & Myers, P.C. 1999, ApJS, 123, 233

Lee, C. W., Myers, P. C., & Tafalla, M. 2001, ApJS, 136, 703

Mac Low, M.-M. 1999, ApJ, 524, 169

Mac Low, M.-M., Klessen, R. S., Burkert, A., & Smith, M. D. 1998, Phys. Rev. Lett., 80, 275

McKee, C. F. 1989, ApJ, 345, 782

Mestel, L. 1985, in Protostars and Planets II, eds. D.C. Black & M.S. Matthews (Tucson: University of Arizona Press), 320

Mestel, L. & Spitzer, L. 1956, MNRAS, 116, 503

Miyama, S.M., Narita, S., & Hayashi, C. 1987a,b, Prog. Theoretical Physics, 78, 1051, 1273

Mizuno, A., Onishi, T., Yonekura, Y., Nagahama, T., Ogawa, H., & Fukui, Y. 1995, ApJ, 445, L161

Myers, P. C., Fuller, G. A., Goodman, A. A., & Benson, P. J. 1991, ApJ, 376, 561

Nakano, T. 1998, ApJ, 494, 587

Norman, C. & Silk, J. 1980, ApJ, 238, 158

Padoan, P. & Nordlund, Åke 1999, ApJ, 526, 279

Passot, T., Vazquez-Semadeni, E., & Pouquet, A. 1995, ApJ, 455, 536

Shirley, Y. L., Evans, N. J., Rawlings, J. M. C., & Gregersen, E. M. 2000, ApJS, 131, 249

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

Solomon, P. M., Sanders, D. B., & Scoville, N. Z. 1979, in The Large-Scale Characteristics of the Galaxy, IAU Symp. 84, ed. W.B. Burton (Dordrecht:Reidel), 35

Stone, J. M., Ostriker, E. C., & Gammie, C. F. 1998, ApJ, 508, L99

Tafalla, M., Mardones, D., Myers, P. C., Caselli, P., Bachiller, R., & Benson, P. J. 1998, ApJ, 504, 900

Whitworth, A. P. & Ward-Thompson, D. 2001, ApJ, 547, 317

Zuckerman, B. & Evans, N. J. 1974, ApJ, 192, L149