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THE EVOLUTION OF MOLECULAR CLOUDS

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Abstract. We review the problem of the structure and evolution of molecular clouds, with particular emphasis given to the relationship with star formation. Our basic hypothesis is that magnetic fields are the primary agents for supporting molecular clouds, although damped Alfven waves may play an important role in the direction parallel to the field lines. This picture naturally leads to a conception of "bimodal star formation." We propose that high-mass stars form from the overall gravitational collapse of a supercitical cloud, whereas low-mass stars form from small individual cores that slowly condense by ambipolar diffusion from a more extended envelope until they pass the brink of gravitational instability and begin to collapse dynamically from "inside-out." We also review the evidence that the infall stage of protostellar evolution is terminated by the development of a powerful stellar wind. Recent observations indicate that the wind in low-mass protostars is largely neutral and atomic. We outline a possible origin for such winds as the result of a centrifugally-driven magnetized flow from the equator of a protostar rotating at break-up because it is accreting matter of high specific angular momentum from a surrounding nebular disk.

I. MECHANISMS OF CLOUD SUPPORT

Molecular clouds constitute the principal sites of the births of stars (Zuckerman and Palmer 1974; Burton 1976, Evans 1978; Solomon, Scoville, and Sanders 1979; Blitz and Thaddeus 1980), but they cannot all be collapsing at free fall or star formation would proceed at far too great a rate (Zuckerman and Evans 1974). Although the exact lifetimes of molecular clouds have excited some controversy (see the review of Elmegreen 1985), there exists little disagreement on the issue that they need to be supported against their considerable self-gravity for timescales that exceed at least $\sim 10^7$ yr. Since the Jeans mass M_J of a large cloud, computed at the mean temperature and density, is typically much smaller than the mass of the cloud $M_{\rm cl}$, large clouds cannot be supported as a whole by thermal pressure. Thermal pressure could be important for the cores (see below), but not for their envelopes.

Without reviewing the history of this subject (see, however, Shu, Adams, and Lizano 1987), we merely note that most proposals suppose either turbulence (e.g., Larson 1981) or magnetic fields (e.g., Mouschovias 1976) to play the dominant role (for a recent review of magnetic field measurements, see Heiles 1987). The large line-widths generally observed in molecular clouds have posed a problem for theoretical understanding ever since Alan Barrett and his collaborators taught us how to decompose the thermal and "turbulent" contributions (Barrett, Meeks, and Weinreb 1964). It has recently been pointed out by Shu (1987) and by Myers (1987) that the observed levels of "turbulence" in molecular clouds may be explicable in terms of nonlinear Alfven waves that permeate molecular clouds supported by magnetic fields.

As Bruce Elmegreen has also noted in his lecture, the energy for the turbulence may originate with many sources: stellar winds, cloud collisions, field entanglements, expanding H II regions, supernovae, etc., but ultimately the disturbances will excite a spectrum of MHD waves. Waves with superalfvenic fluid motions will generate compressive shocks that dissipate them rapidly. Thus, the fluid velocities will generally become subalfvenic (but still supersonic): $v_f \leq v_A$.

In the ^{12}CO line, there is an observational selection toward seeing the highest velocities, $v_f \sim v_A$, because photon trapping tends to shield regions of common (low) velocities (Peter Goldreich, private communication). However, it is easy to show that for magnetically supported clouds, the mean Alfven speed is automatically of the magnitude needed for virial equilibrium, *i.e.*,

$$v_A^2 \equiv \frac{B^2}{4\pi\rho} \sim \frac{GM_{cl}}{R}. \tag{1}$$

Thus, $v_f \sim v_A$ implies that $v_f \sim (GM_{cl}/R)^{1/2}$, i.e., cloud "turbulence" automatically has a tendency to look sufficient for virial equilibrium. Moreover, if B does not vary strongly from region to region (where CO is observed), equation (1) with $\rho \propto M_{cl}R^{-3}$ implies that the regions being supported magnetically should have nearly the same mean column densities, $M_{cl}/\pi R^2 \propto \rho R \propto B \approx$ constant. This yields $v_A \propto \rho^{-1/2} \propto R^{1/2}$. This line of argument then provides a mechanistic basis for understanding the observed correlation (Dame et al. 1985, Solomon and Sanders 1985): $v_f \propto R^\alpha$ with $\alpha \approx 0.5$.

II. BIMODAL STAR FORMATION

The importance of magnetic fields for molecular cloud support can be gauged by a comparison of its actual mass M_{cl} against the critical mass

$$M_{cr} = 0.13G^{-1/2}\Phi, \tag{2}$$

where Φ is the total magnetic flux that threads M_{cl} (see, e.g., Mouschovias and Spitzer 1976). Logically, two regimes of interest exist in the problem of star formation (see, e.g., the discussion of Mestel 1985):

(a) In the *supercritical* regime, $M_{cl} > M_{cr}$, the cloud's self-gravity can overwhelm the magnetic support *even if the fields were to remain frozen in the fluid.* Cloud evolution in this state would be characterized by magnetically diluted collapse (e.g., Scott and Black 1980).

(b) In the *subcritical* regime, $M_{cl} < M_{cr}$, one cannot induce indefinite gravitational collapse (star formation) by *any* amount of increased external load (external pressure) if Φ is conserved (field freezing) because the mass-to-flux ratio M_{cl}/Φ would remain fixed and subcritical. Cloud evolution in this state would likely be driven by ambipolar diffusion (e.g., Nakano 1979, 1981, 1982).

Shu, Lizano, and Adams (1987) have argued that these two cases provide a natural basis for the phenomenon of bimodal star formation, the notion that somehow the formation of low and high mass stars involve distinctly separate mechanisms (Herbig 1962, Mezger and Smith 1977). In our view, OB stars form from portions of molecular clouds that are supercritical and also contain insufficient "turbulence" to provide the necessary support against the self-gravitation of the region. The formation of supercritical regions probably occurs by agglomeration of smaller clouds in the spiral arms of a galaxy (or in any other circumstance under which molecular clouds become closely packed; see the discussion of Shu 1987). In any case, a relatively large supercritical region (a massive molecular cloud core) would tend to collapse as a whole, yielding the well-known tendency of OB stars to form in groups. The molecular gas surrounding the compact H II regions in G10.6−0.4 apparently exhibits such an overall collapse (Ho and Haschick 1986; Keto, Ho, and Haschick 1987). An even more spectacular case is the discovery by Welch et al. (1987) that $\sim 10^5\ M_\odot$ is collapsing dynamically toward the center of the most luminous cluster of OB stars in our Galaxy – the W49A region containing a spectacular "ring" of compact H II regions. A similar phenomenon may also be occurring in W51 (W. J. Welch, private communication).

When a cloud has less mass than $M_{\rm cr}$, the cloud could theoretically attain a stable equilibrium state even if the nonmagnetic sources of internal support were reduced to zero (see Fig. 1 of Mouschovias and Spitzer 1976). Realistically, however, such a cloud, even if left perfectly alone, would evolve toward a condition of gravitational instability by the process of ambipolar diffusion (Mestel and Spitzer 1956). The dominant constituent of molecular clouds is electrically neutral and is, therefore, not directly affected by magnetic forces. Its tendency to contract gravitationally can be balanced (temporarily) by the frictional force set up when neutrals try to slip past ions and the magnetic fields to which the latter are tied. Nevertheless, with the passage of time, the magnetic flux is gradually expelled from every local dense pocket of gas and dust, and such small molecular cloud cores (Myers and Benson 1983) become the sites for the formation of low-mass stars (Shu 1983, Lizano and Shu 1987a, Myers 1987).

Figure 1 shows an example of the process. Assuming symmetry with respect to rotations about the z axis, we consider an infinite periodic chain of mutually gravitating, identical, regions, spaced a uniform distance apart along z. The calculation for ambipolar diffusion and force balance is carried out for the points interior to the "Roche lobe" of each region, with the magnetic field assumed to have a uniform value B_0 on the boundary. Because no attempt is made to follow the evolution of the material or field outside the Roche lobe (the common envelope), matter is not allowed to cross the Roche surface. The ionization fraction is approximated by an analytic fit to the equilibrium calculations of Elmegreen (1979). We compute the gas kinetic pressure

$$P = a^2\rho, \tag{3a}$$

where ρ is the mass density and $a \equiv (kT/m)^{1/2}$ is the isothermal sound speed, by assuming a constant temperature T. We simulate Alfvenic "turbulence" by the heuristic inclusion of an additional pressure $P_{\rm turb}$ with an associated dispersion velocity squared that satisfies:

$$dP_{\rm turb}/d\rho = K/\rho, \tag{3b}$$

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where K is taken to be a constant in accordance with the empirical relationship noted earlier. (See Lizano and Shu 1987b for further details.)

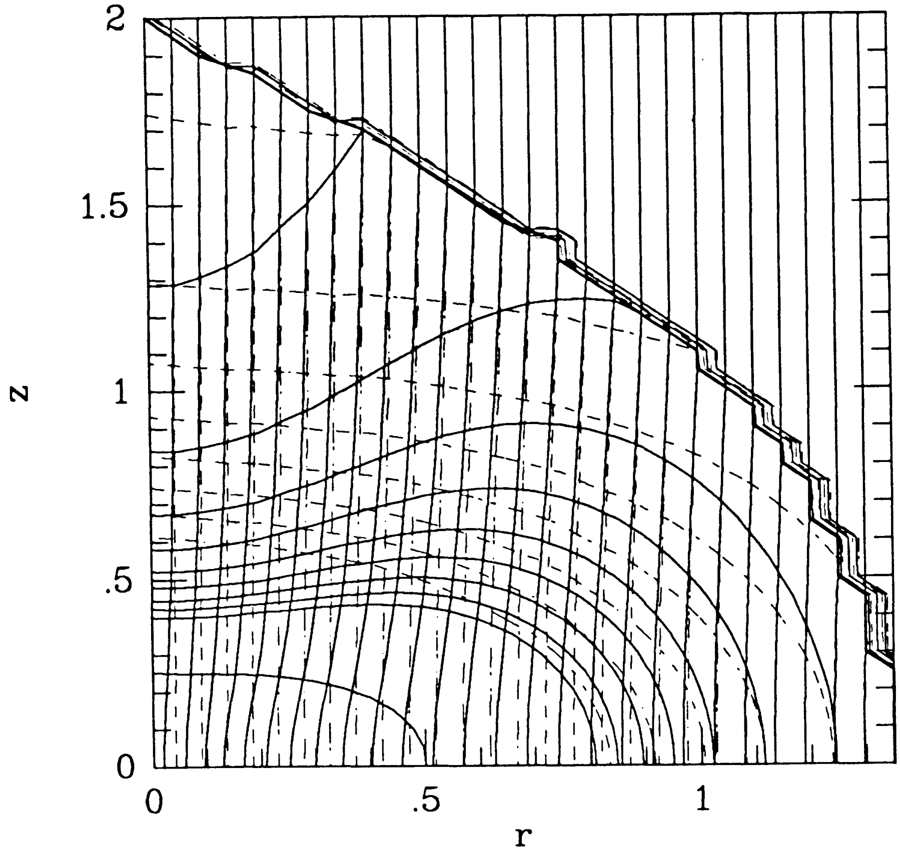

Figure 1. The evolution of a molecular cloud core by ambipolar diffusion. The growing central concentration drags in field lines slightly as indicated by the displacement of the solid vertical curves from the dashed ones. The isodensity contours for the dashed initial state correspond, from top to bottom, to 3, 4, 5, 6, 7, 8, 9, and 10 in units of ρ_0, and the central density is 23. The isodensity contours for the solid curves correspond, from top to bottom to 2, 3, 4, 5, 6, 7, 8, 9, 10, 30 in units of ρ_0, and the central density is 370. The piling up of the contours outside the Roche lobe is an artifact of the plotting routine.

The dimensionless parameters in the specific calculation illustrated in Figure 1 have been chosen so that if $B_0 = 30\ \mu\text{G}$, $T = 10$ K ($a = 0.2$ km s^{-1}), and the unit of density ρ_0 corresponds to 10^3 hydrogen molecules per cm^3, then the unit of length approximately equals 0.1 pc (i.e., the spacing 4 between adjacent Roche lobes equals 0.4 pc), and the mass interior to each Roche lobe is approximately 7 $M_\odot$. The constant K has been chosen so that $dP_{\text{turb}}/d\rho$ is 6 times larger than a^2 at a density ρ_0. The dashed curves display a somewhat arbitrarily chosen "initial" state; and the solid curves illustrate the situation a time 1.5×10^6 yr later, when the central density has increased by a factor of 16 over its original value. The magnetic field has diffused outward relative to the neutrals in a Lagrangian sense, but the increasing central concentration of the matter due to its growing self-gravitation has pulled the field lines inward in an Eulerian sense. The central portions of the configuration given by the solid curves have sizes, densities, and velocity widths that resemble the NH_3 cores of Myers and Benson (1983). The evolution of the inner regions at this stage proceeds very quickly, with the central density trying to develop a singular cusp on a time scale $\sim 10^5$ yr. The ensuing dynamical collapse cannot be followed with a quasistatic code.

III. OUTFLOWS AND THE DISRUPTION OF REMNANT MOLECULAR CLOUD CORES

The above description gives an outline of the processes that lead up to the gravitational collapse of molecular cloud cores and the formation of accreting protostars. Although considerable progress has been made in recent years on the problem of protostellar structure and evolution (see the review of Shu, Adams, and Lizano 1987), we shall not discuss it here inasmuch as the topic lies beyond our charge at this symposium. Instead, we wish to jump to the last stage of star formation – the process by which infall is terminated and the newborn star becomes optically revealed. Growing evidence has accumulated that this process is mediated by the onset of powerful stellar winds (see the reviews of Lada 1985, Welch et al. 1985, and Bally 1987). The disruption of the remnant molecular cloud core by the stellar outflow has been captured especially convincingly in the case of L43 (Mathieu et al. 1987).

Until recently, however, the underlying properties of the hypothesized stellar wind have remained largely conjectural. Attempts to find the wind from its signature as an ionized gas have generally set upper limits that lie one to two orders of magnitude below the momentum requirement of the observed bipolar outflow of swept-up molecular gas (Rodriguez and Canto 1983, Levreault 1985, Strom et al. 1986). Nevertheless, recent investigations of extended far-infrared emission associated with the CO lobes of L1551 (Clark and Laureijs 1986; Edwards et al. 1986) leave little doubt that there must exist a powerful source of missing mechanical luminosity coming from the central source IRS 5 (a rotating protostar according to the models of Adams, Lada, and Shu 1987). The stellar photons from L1551 are insufficient to heat the very extended distribution of warm dust; the latter must somehow be heated by a mechanical outward transport of energy, presumably in the form of a *neutral* stellar wind.

Recent observations validate this expectation in the case of the bipolar flow source, HH7-11. Emerging from the central star, SVS 13, is a stellar wind composed of *atomic* hydrogen (Lizano et al. 1987). (A similar situation may also hold for L1551 IRS 5, but the viewing geometry is less favorable – nearly equator-on – so that galactic hydrogen at moderately high velocities supplies more opportunities for confusion.) The H I detected in HH7-11 by the Arecibo telescope reaches speeds as high as ± 170 km s^{-1}, with $\sim 0.015\ M_\odot$ being contained in the fast moving gas represented by the line wings in Figure 2. Since the profile is roughly triangular, the average line-of-sight velocity is 170 km $s^{-1}/3 \approx 60$ km s^{-1}, yielding a travel time across the (projected) radius represented by the Arecibo beam of ~ 0.3 pc/60 km s^{-1} ~ 5000 yr. Thus, the rate of mass loss $\dot{M}_w$ being suffered by SVS 13 is ~ 0.015 $M_\odot$/5000 yr ≈ 3×10^{-6} $M_\odot$ yr^{-1}. The accumulated atomic hydrogen represented by the line core in Figure 2 amounts (after various corrections) to ~ 0.2 $M_\odot$, implying a total outflow time of 0.2 $M_\odot/3 \times 10^{-6}$ $M_\odot$ yr^{-1} ~ 7×10^4 yr. Such a stellar wind would more than suffice as the underlying power that drives the extended CO lobes (see, e.g., Edwards and Snell 1984).

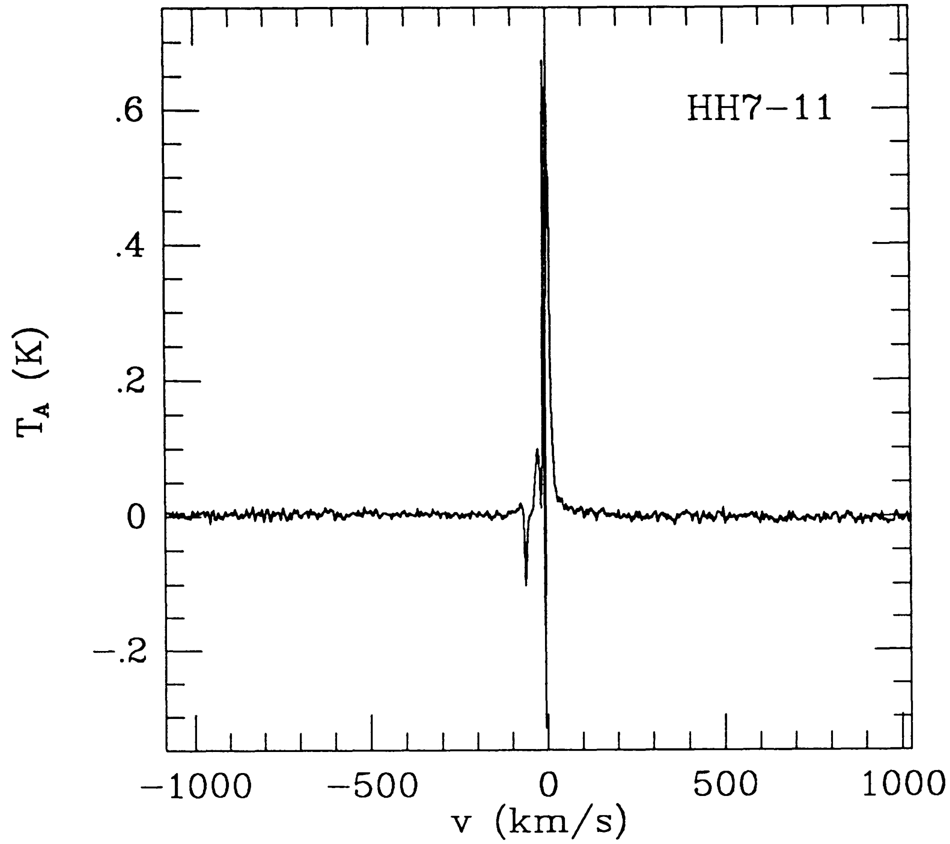

Figure 2. H I profile of HH7-11 taken at Arecibo.

IV. A POSSIBLE MASS-LOSS MECHANISM

An important property of the stellar wind in HH7-11 is the finding (on the Kitt Peak 12-m dish) that the high-velocity gas (up to ± 150 km s^{-1}) bears CO in a proportion consistent with all of the elemental carbon being contained in the form of that molecule. The combination CO plus *atomic* hydrogen characterizes matter in cool stellar atmospheres (rather than, say, molecular clouds or molecular disks), and places strong contraints on the possible physical mechanisms that can be responsible for accelerating the stellar wind. We have proposed that the mass loss originates from the interface of a magnetized protostar rotating break-up on its equator and an adjoining accretion disk (Shu, Lizano, and Najita 1987). The basic mechanism is that of a centrifugally-driven magnetic wind (Hartmann and MacGregor 1982).

The physical reasoning leading to our conclusion is as follows. Heavy mass loss $\dot{M}_w$ of the magnitude seen in HH7-11 must originate from near the photosphere of a star (to have sufficient density at the sonic transition). However, the sound speed in the photosphere forms a very small ratio compared to the escape speed; therefore, thermal pressure is able to overcome gravity only where the local gravity is relatively weak (cf. an analogous problem in the case of mass-transfer binaries considered by Lubow and Shu 1975). A narrow band where the gravity is locally weak will naturally occur on the equator of a protostar rotating at break-up because the central star is being formed by accretion from a surrounding nebular disk (that is itself supplied by infall from a rotating molecular cloud core). Nevertheless, the centrifugal effects can bring about a reversal in sign of the effective gravity only if the gas can be kept (nearly) corotating with the star. If the gas pushed outward by the thermal pressure preserves its original angular momentum, it will rotate too slowly to remain in orbit at the larger radius, and inertial effects would force it back on the star. Strong magnetic fields (generated, say, by dynamo action after the low-mass protostar has developed an extensive outer convective zone), tied to the deep interior of the star, will try to enforce the requisite corotation of the surface layers. (The coupling between the the neutrals and the small fraction of ions is assumed good enough to treat the gas as a single conducting medium.) The gas pushed out by the thermal pressure in an equatorial band now acquires more than enough angular momentum to maintain itself at the enlarged distance, so it continues to move outward as it is torqued up by the stellar rotation. The process drives the gas eventually to superalfvenic speeds, at which point the motions become essentially ballistic. If the gas speed at the Alfven point exceeds the local escape speed, the flow will develop into a wind that blows to infinity. Detailed model calculations are underway at Berkeley to assess the quantitative merits of the model, as well as to investigate the degree to which the stellar outflow may eventually be channeled magnetically toward the rotational poles.

To complete the overall evolutionary picture, we consider what regulates the numerical value of the mass-loss rate $\dot{M}_w$. In our view, because a protostar is likely to be rotating at break-up during the epoch when it is accompanied by a surrounding nebular disk, incorporation of the material from the disk, which contains a high specific angular momentum, cannot take place on the star *without* a mechanism for magnetically braking the latter in the first place. In a quasi-steady state, the wind must blow at a rate $\dot{M}_w$ that is a significant fraction f of the disk accretion rate $\dot{M}_d$ (which is itself approximately given by the mass infall rate from the surrounding molecular cloud core). A detailed analysis for low-mass protostars on the deuterium-burning birthline shows the fraction f to be approximately given by the formula (Shu et al. 1987):

$$f \approx 1.5/(2.5 + v_{\rm term}^2), \tag{4}$$

where $v_{\rm term}^2$ is the (streamline-averaged value of the) square of the terminal speed of the stellar wind measured in units of the square of the break-up speed $(\Omega_* R_*)^2$ on the equator of the star. For HH7-11, equation (4) yields the prediction $f \approx 0.4$, which is in good agreement with an atomic mass-loss rate $\dot{M}_w = 3 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ and a mass-infall rate (deduced from modeling of the infrared spectral energy distribution, F. C. Adams, private communication) of $\sim 1 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$.

It has been a privilege to be able to contribute to a symposium volume that honors the career of Alan H. Barrett. His pioneering studies of molecules in space, and the careful follow-up work of his many students, have made possible much of the modern advance in our knowledge concerning dark cloud evolution and its connection with star formation. This work is funded in part by grants from the National Science Foundation and from the NASA astrophysics program which supports a joint Center for Star Formation Studies at UC Berkeley, UC Santa Cruz, and NASA Ames Research Center. S. L. gratefully acknowledges the support of fellowships from the National University of Mexico and the Amelia Earhart Foundation.

REFERENCES

Adams, F. C., Lada, C. J. and Shu, F. H. 1987, *Ap. J.*, **312**, 788.

Barrett, A. H., Meeks, M. L., and Weinreb, S. 1964, *Nature*, **202**, 475.

Blitz, L., and Thaddeus, P. 1980, *Ap. J.*, **241**, 676.

Burton, W. B. 1976, *Ann. Rev. Astr. Ap.*, **14**, 275.

Clark, F. O., and Laureijs, R. J. 1986, *Astr. Ap.*, **154**, L26.

Dame, T.M., Elmegreen, B. G., Cohen, R. S., and Thaddeus, P. 1985, in IAU Symposium No. 106, The Milky Way, ed. H.van Woerden, R. J. Allen and W.B. Burton, (Dordrecht: Reidel), p. 303.

Edwards, S., and Snell, R. L. 1984, *Ap. J.*, **281**, 237

Edwards, S., Strom, S. E., Snell, R. L., Jarrett, T. H., Beichman, C. A., and Strom, K. M. 1986, *Ap. J. (Letters)*, **307**, L65.

Elmegreen, B. G. 1979, *Ap. J.*, **232**, 729.

Elmegreen, B.G. 1985, in *Protostars and Planets II*, ed. D. C. Black and M. S. Matthews (Tucson: University of Arizona Press), 33.

Evans, N. J. 1978, in *Protostars and Planets*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), pp. 152-164.

Hartmann, L., and MacGregor, K. B. 1982, *Ap. J.*, **259**, 180.

Heiles, C. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach and H. A. Thronson (Dordrecht: Reidel), p. 171.

Herbig, G. 1962, *Adv. Astr. Ap.*, **1**, 47.

Ho, P. T. P., and Haschick, A. D. 1986, *Ap. J.*, **304**, 541.

Keto, E. R., Ho. P. T. P., and Haschick, A. D. 1987, *Ap. J.*, **318**, 712.

Lada, C. J. 1985, *Ann. Rev. Astr. Ap.*, **23**, 267.

Larson, R. B. 1981, *M. N. R. A. S.*, **194**, 809.

Levreault, R. M. 1985, Ph.D. Thesis, University of Texas.

Lizano, S., Heiles, C., Rodriguez, L., Koo, B. C., Shu, F. H., Hasegawa, T., Hayashi, S., and Mirabel, I. F. 1987, *Ap. J.*, submitted.

Lizano, S., and Shu, F. H. 1987a, in *NATO/ASI, The Interstellar Medium*, ed. G. Morfill, in press.

Lizano, S., and Shu, F. H. 1987b, in preparation.

Lubow, S. H., and Shu, F. H. 1975, *Ap. J.*, **198**, 383.

Mathieu, R. D., Benson, P. J., Fuller, G. A., Myers, P. C., and Schild, R. E. 1987, preprint.

Mestel, L., and Spitzer, L. 1956, *M. N. R. A. S.*, **116**, 503.

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

Mezger, P. G. and Smith L. F. 1977, in *IAU Symposium No. 75, Star Formation*, ed. T. de Jong and A. Maeder, (Dordrecht: Reidel), p. 133.

Mouschovias, T. Ch. 1976, *Ap. J.*, **207**, 141.

Mouschovias, T. Ch., and Spitzer, L. 1976, *Ap. J.*, **210**, 326.

Myers, P. C. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach and H. A. Thronson (Dordrecht: Reidel), p. 71.

Myers, P. C., and Benson, P. J. 1983, *Ap. J.*, **266**, 309.

Nakano, T. 1979, *Pub. Astr. Soc. Japan*, **31**, 697.

Nakano, T. 1981, *Prog. Theor. Phys. Suppl. No. 70*, 54.

Nakano, T. 1982, *Pub. Astr. Soc. Japan*, **34**, 337.

Rodriguez, L. F. and Canto, J. 1983, *Rev. Mex. Astr. Astrof.*, **8**, 163.

Scott, E. H., and Black, D. C. 1980, *Ap. J.*, **239**, 166.

Shu, F. H. 1983, *Ap. J.*, **273**, 202.

Shu, F. H. 1987, in *Star Formation in Galaxies*, ed. C. J. Lonsdale Persson (NASA Conference Publ. 2466), p. 743.

Shu, F. H., Adams, F. C., and Lizano, S. 1987 *Ann. Rev. Astr. Ap.*, **25**, 23.

Shu, F. H., Lizano, S., and Adams, F. C. 1987, in *Star Forming Regions*, ed. M. Peimbert and J. Jugaku (Dordrecht: Reidel), 417.

Shu, F. H., Lizano, S., Ruden, S., and Najita, J. 1987, in preparation.

Solomon, P. M. and Sanders, D. B. 1985, in *Protostars and Planets II*, ed. D. C. Black and M. S. Matthews (Tucson: University of Arizona Press), p. 59.

Solomon, P. M., Scoville, N. Z., and Sanders, D. B. 1979, *Ap. J. (Letters)*, **232**, L89.

Strom, K. M., Strom, S. E., Wolf, S. C., Morgan, J., and Wenz, M. 1986, *Ap. J. Suppl.*, **62**, 39.

Welch, W. J., Vogel., S. N., Plambeck, R. L., Wright, M. C. H., and Bieging, J. H. 1985, *Science*, **228**, 1329.

Welch, W. J., Dreher, J. W., Jackson, J. M., Terebey, S., and Vogel, S. N. 1987, *Science*, submitted.

Zuckerman, B., and Evans, N. J. 1974, *Ap. J. (Letters)*, **192**, L149.

Zuckerman, B., and Palmer, P. 1974, *Ann. Rev. Astr. Ap.*, **12**, 279.