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HEATING OF MOLECULAR CLOUD CORES

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RESUMEN. Examinamos el papel que la difusión ambipolar del campo magnético tiene en el calentamiento de las regiones densas en nubes moleculares. Siguiendo a Shu (1983) hemos calculado la evolución quasiestática de una nube plano-paralela autogravitante de gas ligeramente ionizado debido a la difusión del campo magnético.La temperatura en cada punto de la nube es calculada, tomando en cuenta los procesos mas importantes de calentamiento y enfriamiento. Los resultados (Lizano y Shu 1987) pueden explicar parcialmente las diferencias térmicas entre las regiones densas donde se forman estrellas de alta masa y aquellas donde se forman estrellas de baja masa.

ABSTRACT. We examine the role of ambipolar diffusion in heating molecular cloud cores. Following Shu (1983) we calculate the quasistatic evolution of a plane-parallel self-gravitating slab of slightly ionized gas due to the ambipolar diffusion of the field.The temperature in each point of the cloud is computed, taking into account the most important heating and cooling processes. The results (Lizano and Shu 1987) can partially explain the thermal differences between the cores which form low and high mass stars.

Key Words: INTERSTELLAR-CLOUDS

INTRODUCTION

By now, it is well established that molecular clouds are the principal sites of active star formation (Zuckerman and Palmer 1974; Burton 1976). A typical giant molecular cloud (GMC) have might have a mass $M_{\rm GMC} \sim 10^5\ M_\odot$, a radius $R \sim 20$ pc, and a mean molecular density $n_{\rm H_2} \sim 50\ {\rm cm}^{-3}$ (Blitz and Thadeus 1980), although the exact numbers are slightly controversial (see, *e.g.*, Solomon, Scoville, and Sanders 1979). Observed in CO emission with moderately high spatial resolution, GMCs are seen to be cloud complexes, breaking up into clumps with masses $M_{\rm cl} \sim 10^3$-$10^4\ M_\odot$, sizes $R \sim 2$-5 pc, densities $n_{\rm H_2} \sim 10^{2.5}\ {\rm cm}^{-3}$, and temperatures $T \sim 10$ K (Sargent 1977; Evans 1978; Stark and Blitz 1978; Rowan-Robinson 1979). It is unclear to what extent the observed clump sizes, masses, and densities are the results of observational selection since the excitation of ^{12}CO, even with radiative trapping, requires H_2 densities of a few hundred per cm^3 (Kutner and Leung 1985).

The clumps resemble the nearby dark clouds surveyed by Lynds (1962). A well-known complex of such dark clouds exists in Taurus, containing about $6 \times 10^3\ M_\odot$ of material (Kleiner and Dickman 1984) actively forming an unbound association of low-mass stars (Herbig 1962; Cohen and Kuhi 1979). The clumps of molecular gas in Taurus have regions of higher density – small cloud cores – which have been mapped in ammonia emission by Myers and Benson (1983). The masses enclosed within the density contours to which ammonia is sensitive, roughly, $n_{\rm H_2} > 10^4$ cm^{-3}, are $M_{\rm core} \sim 10^0\ M_\odot$. The cores defined this way have sizes $R \sim 10^{-1}$ pc, temperatures $T \sim 10$ K, and NH_3 linewidths that are almost thermal. The contention by Myers and Benson that these quiet dense cores are the sites of formation of low mass stars is supported by their close association with known T Tauri stars, and by the fact that *IRAS* detected infrared sources in approximately half of the cores (Beichman *et al.* 1986). The deeply embedded sources can be identified as protostars by the characteristics of their infrared spectral energy distribution (Adams and Shu 1986; Adams, Lada, and Shu 1986; Myers *et al.* 1986).

There are also denser clumps like the R Coronae Australis and ρ Ophiuchi regions which seem to be forming bound clusters because the efficiency of star formation is locally high (between 25-50%, Wilking 1983; Lada and Wilking 1984; Wilking *et al.* 1986). These clumps have radii $\sim$ 0.3-0.6 pc, masses $\sim$ 19-110 $M_\odot$, average densities $\sim 10^3$ cm^{-3} (Loren, Sandqvist, and Wooten 1983), and may be complexes of cores with internal densities greater than 10^6 cm^{-3} (Snell *et al.* 1984).

Even though the Jeans mass M_J associated with the average conditions of a clump is only a few $M_\odot$, molecular clouds cannot be collapsing in bulk on a free-fall time scale or the rate of star formation in the galaxy would be far too high (Zuckerman and Palmer 1974). In addition, there have been no unambiguous observational detections of large-scale collapse motions, indicating that the initial process of star formation is quasistatic, at least to the stage of core formation (however, see Ho and Haschick 1986; Reid, Myers and Bieging 1986; and Walker *et al.* 1986 for examples of infall on scales of the order of 10^{-2} pc). A quasistatic origin of small molecular cloud cores is also suggested by their narrow ammonia linewidths. The linewidths in the Taurus cores are consistent with turbulent or systematic velocities being generally only half as large as the sound speed in the overall gas mix when averaged over sizes $\sim 10^{-1}$ pc. Moreover, there is a tendency for the linewidths to be narrower in cores without embedded infrared sources than cores with sources (Myers 1986).

Since $M_J \ll M_{cl}$, a molecular cloud clump cannot be supported as a whole by thermal pressure. Thermal pressure could be important for the cores, but not for their envelopes. Various mechanisms of molecular cloud support have been invoked at one time or another: turbulence (Norman and Silk 1980; Larson 1981), rotation (Field 1978), and magnetic field (Chandrasekhar and Fermi 1953; Mestel 1965; Spitzer 1968; Mouschovias 1976).

Here we will consider that the magnetic fields provide the dominant means of mechanical support of molecular clouds. Unlike turbulence, magnetic fields have the virtue that they not easy to get rid of. Their longevity makes them a natural candidate as a resiliant obstacle to rapid star formation. The strength of the magnetic fields needed to provide appreciable mechanical support of molecular clouds against their self- gravity can be ascertained by virial theorem arguments (Strittmatter 1966) or more accurately, by detailed model calculations (Mouschovias and Spitzer 1976). A magnetic flux Φ can support a cloud provided its mass does not exceed a critical value given by

$$M_{cr} = 0.15\frac{\Phi}{G^{1/2}} = 10^3 M_\odot \left(\frac{B}{30\mu\mathrm{G}}\right)\left(\frac{R}{2\,\mathrm{pc}}\right)^2, \tag{1}$$

where B is the strength of the magnetic field. Although magnetic field strengths in molecular clouds are generally not well known, it is interesting to note that a field strength of $\sim 38\mu$G has been detected in Orion B by the Zeeman splitting of thermal OH (Crutcher and Kazes 1983; Heiles and Stevens 1986).

For a canonical gas to dust ratio, equation (1) is equivalent to the existence of a critical mean visual extinction:

$$A_V > 4\,\mathrm{mag}\left(\frac{B}{30\,\mu\mathrm{G}}\right). \tag{2}$$

The figure 30μG may typify the average conditions only in the envelopes of small dark clouds; dense cores after gravitational contraction may have considerably larger values. Thus, it is interesting to note the following observed progression:

(a) The visual extinction through the envelope of the Taurus molecular cloud is ~ 2 mag (*e.g.*, Dickman 1978); its cores have $A_V \sim 10^1$ mag (Myers and Benson 1983), which probably formed from an initial state that was subcritical ($M < M_{cr}$). The gas temperatures in these cores are generally 10-11 K. Taurus is, of course, a region of low star-formation efficiency and seems to forming an unbound association of low-mass stars (Herbig 1962; Elias 1978b; Cohen and Kuhi 1979).

(b) The visual extinction through the envelope of the ρ Ophiuchi molecular cloud is ~ 6 mag (*e.g.*, Encrenaz, Falgerone and Lucas 1975; Frerking, Langer, and Wilson 1982); the cores in its densest portion have $A_V \sim 10^2$ mag (Wilking and Lada 1983). The gas temperatures in the cores of the general region are higher than in Taurus, perhaps ~ 18 K, (Martin-Pintado *et al.* 1983; Zeng, Batrla, and Wilson 1984; Wadiak *et al.* 1985), and ^{12}CO and ^{13}CO measurements indicate temperatures of 30-35 K (Loren, Sandqvist, and Wooten 1983; Wilking and Lada 1983). The densest portion of the cloud has a high star-formation efficiency and may be forming a bound cluster containing mostly low-mass stars but also a B star or two (Grasdalen, Strom, and Strom 1973; Elias 1978a; Lada and Wilking 1984). Wilking and Lada (1983) observed CO line profiles that were asymmetrically self-reversed over the whole face of the ρ Ophiuchi core (Lada, private communication). The sense of the asymmetry corresponds to overall contraction, consistent with the entire dense region being supercritical ($M > M_{cr}$).

(c) The average visual extinction through GMCs is controversial; estimates range from 4 mag (Blitz and Shu 1980) to 12 mag (Sanders, Solomon, and Scoville 1984; Solomon 1986). In any case, GMCs are very inhomogeneous, and portions of them are very likely to be supercritical; hence, it is informative that massive GMCs often have large dense cores with $A_V \sim 10^3$ mag (*e.g.*, Turner and Welch 1984). The gas temperatures in the parts of the cores traditionally measured by molecular radio line workers are about 50-100 K. These hot-core sites contain an abundance of OB stars.

HEATING BY FRICTION BETWEEN IONS AND NEUTRALS

When a cloud has less mass than M_{cr}, the cloud can attain a stable equilibrium state as long as it is surrounded by a medium of finite pressure and/or finite magnetic field. However, such a cloud cannot remain forever in the same equilibrium state. The neutral particles, the main constituent of the cloud, are not affected directly by the magnetic force and tend to contract by self gravity. Therefore, a drift motion and frictional force between neutral and charged particles will appear – the process of ambipolar diffusion investigated first by Mestel and Spitzer (1956) and followed by many other authors (*e.g.*, Spitzer 1968; Mouschovias and Paleologou 1981; Mouschovias, Paleologou and Fiedler 1985; Nakano 1979, 1981, 1982, 1983, 1984; Scott and Black 1982; Shu 1983). In this way the magnetic force acts indirectly on the neutral particles through the intermediary of friction, and the cloud is kept from collapsing dynamically. However, relative to the distribution of the neutral matter, the magnetic flux is gradually expelled by the drift, resulting in the quasistatic condensation of a dense pocket of gas and dust. If $M_{cl} > M_{cr}$, ambipolar diffusion will also take place, but against the backdrop of a dynamically shrinking envelope.

The friction between ions and neutrals due to the ambipolar diffusion of the field is a source of heating for the cloud (Scalo 1977; Mouschovias 1978). To analyze in a quantitative and detailed manner how important this effect may be, Lizano and Shu (1987) calculated the expected temperature of a cloud core, taking into account the most important heating and cooling processes.

Because the cooling and heating times are short compared to the ambipolar diffusion time t_{AD}, the energy equation for the neutrals becomes a condition for thermal balance:

$$\Lambda = \Gamma, \tag{3}$$

where Λ is the rate of heat loss per unit volume and Γ is the heat gain. We consider heating by ambipolar diffusion

$$\Gamma_{AD} = \rho_n \rho_i \gamma |\mathbf{v}_d|^2, \tag{4}$$

where $\mathbf{v}_d$ is the drift velocity of the ions relative to the neutrals given by

$$\mathbf{v}_d \equiv \mathbf{u}_i - \mathbf{u}_n = \frac{1}{4\pi\gamma\rho_i\rho_n}(\nabla \times \mathbf{B}) \times \mathbf{B},$$

and γ is the drag coefficient associated with momentum exchange in ion-neutral collisions, and heating by cosmic rays,

$$\Gamma_{CR} = \varsigma \rho_n \epsilon_0, \tag{5}$$

where ϵ_0 is the energy (per unit mass) deposited per primary ionization by cosmic rays and ς is the cosmic ray ionization such that the total heat gained per unit volume is

$$\Gamma = \Gamma_{AD} + \Gamma_{CR}. \tag{6}$$

The main cooling processes are line radiation by the ^{12}CO molecule, and collisional transfer of kinetic energy by neutrals of a temperature T to dust grains at a different temperature T_{dust} (heating occurs if $T_{dust} > T$). The total cooling rate is the sum:

$$\Lambda = \Lambda_{CO} + \Lambda_{dust}. \tag{7}$$

Cooling by ^{12}CO was calculated using 20 coupled rotational levels of the CO molecule and an escape probability formalism for the line photons, with the optical depth in a line $\propto N_{CO}/\Delta v$, where N_{CO} is the carbon monoxide column density to the nearest boundary and Δv is a postulated linewidth (see de Jong, Dalgarno, and Boland 1980). In our numerical calculations, we assumed that the grains have a fixed temperature T_{dust} which is determined by radiative equilibrium with an unspecified ambient radiation field. The thermal coupling of gas to dust can then be taken from the formula given by Draine (1980):

$$\Lambda_{dust} \propto n_{H_2} n_{dust} (T - T_{dust}). \tag{8}$$

Following Shu (1983), we calculated the quasistatic contraction of a plane-parallel self-gravitating slab of isothermal gas which is lightly ionized due to the ambipolar diffusion of the field, but instead of assuming $T =$ constant, equation (3) was solved for the gas temperature at each point in the quasistatically contracting cloud (slab).

Figures 1a, 1b, and 1c show three cases with different values of the parameter σ_∞ which is the integrated surface density to the midplane ($\sigma = \int_0^\infty \rho_n(z', t)\, dz'$). The choices $\sigma_\infty = 0.02$, 0.2, and 0.5 g cm^{-2} give two-sided column densities $2\sigma_\infty$ which correspond to 10, 100, and 250 magnitudes of visual extinction for a canonical dust opacity. Thus, one might be tempted to identify these cases with models of the molecular cloud cores in Taurus, Ophiuchus, and a moderate GMC; however, the computed size scales will be too small by a factor of ~ 2 because the surface gravitational field of a slab, $2\pi G(2\sigma_\infty)$, overestimates the value, $GM_{\rm core}/R^2_{\rm core}$, if we identify $2\sigma_\infty$ with the mean surface density $M_{\rm core}/\pi R^2_{\rm core}$. When this is taken into account, the sizes and densities of the models for Taurus and ρ Ophiuchi correspond well to the observed values (*e.g.*, Myers and Benson 1983; Wadiak *et al.* 1985).

The initial states in the three displayed cases have been chosen to have a ratio of magnetic to gas pressure α in the midplane equal to ~ 10; the dust temperature is 10 K; the Gaussian line widths ($\propto \Delta$v) are computed from the sum of the squares of the local thermal speed (of CO) and a turbulent speed $= \eta$ times the Alfven speed in the combined medium, with $\eta = 0.5$. The graphs show the evolution of the temperature profile as the magnetic field drifts out of the cloud. They also show the evolution of the ratio of magnetic to gas pressure α, density and magnetic field profiles.

Increasing central condensation results as time advances from 0, 1, 3, 5, 10, and 20 Δt where $\Delta t = 6 \times 10^5$, 6×10^4, and 2.5×10^4 yrs, for $\sigma_\infty = 0.02, 0.2$, and $0.5\ {\rm g\,cm^{-2}}$, respectively. At later times, the amount of magnetic support, and therefore the amount of plasma slip, has become relatively small, and the heating of the neutrals is almost entirely by cosmic-rays. In all cases, there is no slip, and therefore no heating by ambipolar diffusion, at the midplane $\sigma = 0$ because of the symmetry boundary condition imposed at $z = 0$. The increase in temperature there for increasing σ_∞ is solely due to the increase of radiative trapping.[1]

Figure 1a shows that ambipolar diffusion yields little extra heating above that provided by cosmic-rays for the case that is supposed to simulate the ammonia cores of Taurus, $\sigma_\infty = 0.02\ {\rm g\,cm^{-2}}$. In contrast, the high surface density cases can achieve significantly higher temperatures during the part of their evolution where the ratio of magnetic to gas pressure remains of order unity or larger. As shown in Figure 1b, when the magnetic and gas pressures have dropped to near equality, the gas temperatures in the envelope and central portions of our model of an Ophiuchus cloud core have values, respectively, of about 20-28 K and 12-20 K. These values are in rough agreement with the

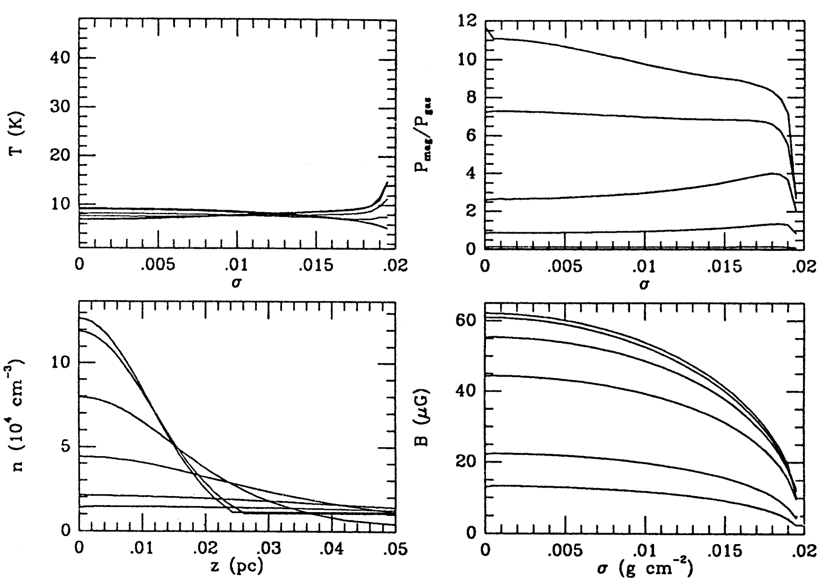

Fig. 1a. Time evolution of the temperature, magnetic to gas pressure, density and magnetic field profiles for the integrated surface density from the midplane to infinity $\sigma_\infty = 0.02\ {\rm g\ cm^{-2}}$. The profiles shown correspond to times 0, 1, 3, 5, 10, and 20 Δt where $\Delta t = 6 \times 10^5$ yrs. (Note that the density graph has the abcissa given in parsecs instead of column density).

[1] The geometric symmetry constraint is less important for a three dimensional cloud where the slip velocity must vanish at only one point, the gravitational potential minimum at the center, instead of over an entire plane.

observations, and nominally imply an "effective sound speed" of about 0.3-0.4 km/s (if we heuristically include the effects of the inferred magnetic field in the central portions). This occurs in part because the evolution is faster as σ_∞ increases and in part because the gravitational pull which drives the drift of the neutrals relative to the ions is larger as σ_∞ increases. Thus, the net heating rate by ambipolar diffusion is proportional to the square of the column density, while the net cooling rises less quickly than the square of the volume density when radiative trapping becomes important. Hence, cores of high visual extinction should be warmer than cores of low visual extinction, all other factors being equal.

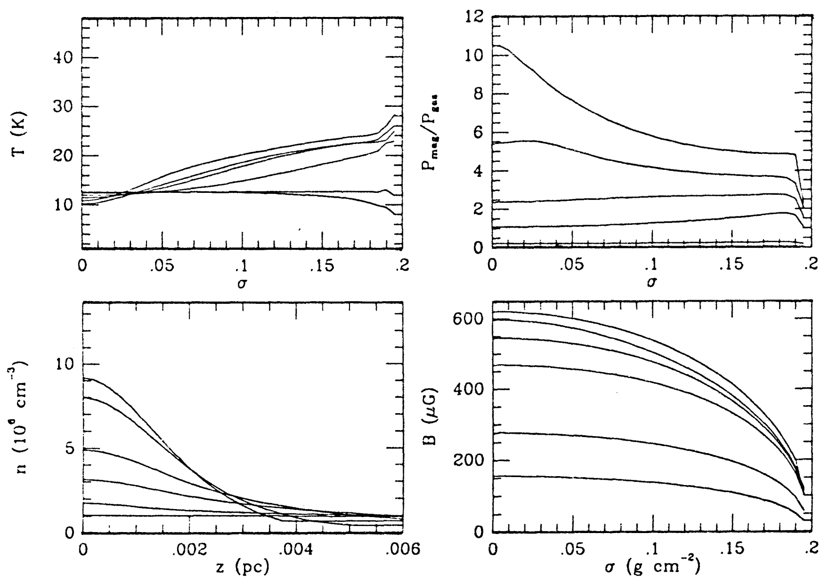

Fig. 1b. Time evolution of the temperature, magnetic to gas pressure, density and magnetic field profiles for the integrated surface density from the midplane to infinity σ_∞ = 0.2 g cm^{-2}. The profiles shown correspond to times 0, 1, 3, 5, 10 and 20 Δt where $\Delta t = 6 \times 10^4$yrs. (Note that the density graph has the abcissa given in parsecs instead of column density).

This effect may well explain the relatively high CO temperatures in ρ Ophiuchi (30-35 K – Loren, Sandqvist, and Wooten 1983; Wilking and Lada 1983) in comparison with that in Taurus (10-11 K – Myers and Benson 1983). The higher gas temperature in Ophiuchus is unlikely to be due to heating of gas by warm dust grains (which are in turn heated by luminous stars) because the entire Ophiuchus region only has two embedded B stars (Elias 1978a). Moreover, because the core suffers limited compression even in a $\sigma_\infty = 0.2$ g cm^{-2} model, the thermal coupling of gas to the dust is sufficient only to give gas temperatures T which are about 60-70 % of the dust temperature $T_{\rm dust}$, even for number densities approaching 10^7 cm^{-3}. To obtain $T \sim$ 30-35 K by this mechanism would therefore require $T_{\rm dust}$ of $\sim$ 50 K, which can be ruled out on the basis of the *IRAS* observations of this region.

However, there is some uncertainty in the interpretation of the high column density models. Low column-density cores like those in Taurus are probably subcritical, at least for much of their evolutionary lifetimes, and a quasistatic contraction driven solely through the gradual loss of magnetic support by ambipolar diffusion may be a realistic description. However, high column density cores are probably supercritical from the beginning, and their simulation by a slab geometry where the gravity saturates (at a finite value $\propto \sigma_\infty$) can, at best, only be illustrative. The enhanced heating by ambipolar diffusion in such cases (which basically releases gravitational energy and converts it into frictional heating rather than into kinetic energy of ordered bulk motions) must represent a lower limit to what can actually be achieved in a more realistic geometry.

As illustrative examples, figures 1a-1c do show that heating by ambipolar diffusion may provide a promising explanation for the observed correlation of gas temperature and core column density. The accompanying increase of the "effective sound speed" will then result in greater accretion rates $\dot{M} \sim a^3/G$ (Shu 1977; Stahler, Shu, and Taam

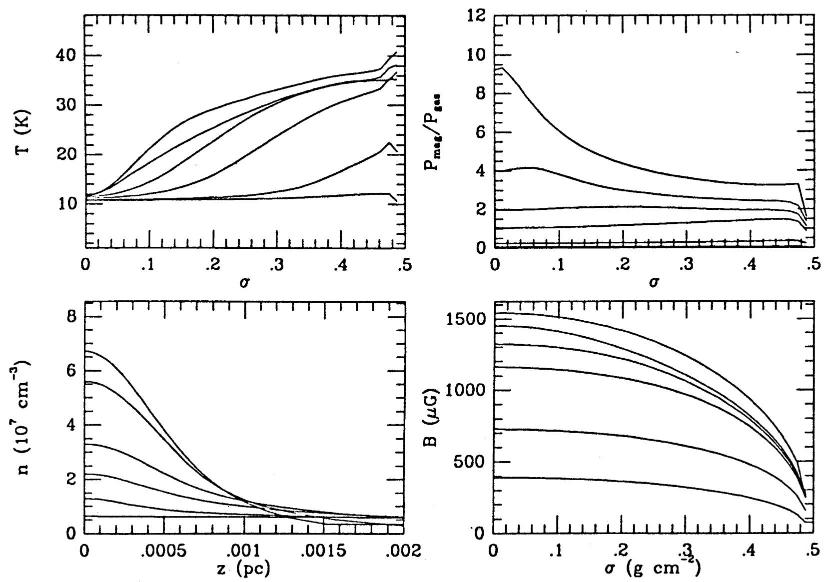

Fig. 1c. Time evolution of the temperature, magnetic to gas pressure, density and magnetic field profiles for the integrated surface density from the midplane to infinity σ_∞ = 0.5 g cm^{-2}. The profiles shown correspond to times 0, 1, 3, 5, 10, and 20 Δt where $\Delta t = 2.5 \times 10^4$yrs.(Note that the density graph has the abcissa given in parsecs instead of column density).

1980; Terebey, Shu, and Cassen 1984) when the cores collapse gravitationally, and will then eventually give rise to higher mass stars, everything else being equal (Shu, Lizano, and Adams 1986). From this viewpoint, high mass stars form (in part) because their predecessor cores were hot; in the older picture, cores became hot because high mass stars formed inside them (Goldreich and Kwan 1974). The two possibilities may be related by feedback, but we note that the latter relies on the prior existence of high mass stars, whereas the former provides an *a priori* mechanism for forming such objects.

REFERENCES

Adams, F.C. and Shu, F.H. 1986, *Ap. J.*, in press.
Adams, F.C., Lada, C.J., and Shu, F.H. 1987, *Ap. J.*, in press.
Beichman, C.A., Myers, P.C., Emerson, J.P., Harris, S., Mathieu, R., Benson, P.J., and Jennings, R.E. 1986, *Ap. J.*, July 15, in press.
Blitz, L. and Shu, F.H. 1980, *Ap. J.*, 238, 148.
Blitz, L. and Thaddeus, P. 1980, *Ap. J.*, 241, 676.
Burton, W.B. 1976, *Ann. Rev. Astr. Ap.*, 14, 275.
Chandrasekhar, S. and Fermi, E. 1953, *Ap. J.*, 118, 116.
Cohen, M. and Kuhi, L.V. 1979, *Ap. J. Suppl.*, 41, 743.
Crutcher, R.M. and Kazes, I. 1983, *Astr. Ap.*, 125, L23.
de Jong, T., Dalgarno, A., and Boland, W. 1980, *Astr. Ap.*, 91, 68.
Dickman, R.L. 1978, *Ap.J. Suppl.*, 37, 407.
Draine, B.T. 1980, *Ap. J.*, 241, 1021.
Elias, J.A. 1978a, *Ap. J.*, 224, 453.
Elias, J.A. 1978b, *Ap. J.*, 224, 857.

Encrenaz, P.J., Falgerone, E., and Lucas, R. 1975, *Astr. Ap.*, 44, 73.
Evans, N.J. 1978, in *Protostars and Planets*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), pp. 152-164.
Field, G.B. 1978, in *Protostars and Planets*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), pp. 243-264.
Frerking, M.A., Langer, W.D., and Wilson, R.W. 1982, *Ap. J.*, 262, 590.
Goldreich, P. and Kwan, J. 1974, *Ap. J.*, 189, 441.
Grasdalen, G.L., Strom, K.M., and Strom, S.E. 1973, *Ap. J. (Letters)*, 184, L53.
Heiles, C. and Stevens, M. 1986, *Ap. J.*, 301, 331.
Herbig, G. 1962, *Adv. Astr. Ap.*, 1, 47.
Ho, P. and Haschick, A.D. 1986, *Ap. J.*, 304, 541.
Kleiner, S.C. and Dickman, R.L. 1984, *Ap. J.*, 286, 255.
Kutner, M.L. and Leung, C.M. 1985, *Ap. J.*, 291, 188.
Lada, C.J. and Wilking, B.A. 1984, *Ap. J.*, 287, 610.
Larson, R.B. 1981, *M.N.R.A.S.*, 194, 809.
Lizano, S. and Shu, F.H. 1987, in preparation.
Loren, R.B., Sandqvist, A., and Wootten, A. 1983, *Ap. J.*, 270, 620.
Lynds, B.T. 1962, Catalog of Dark Nebulae, *Astrophys. J. Suppl.*, 7, 1.
Martin-Pintado, J., Wilson, T.L., Gardner, F.F., and Henkel, C. 1983, *Astr. Ap.*, 117, 145.
Mestel, L. 1965, *Quart. J.R.A.S.*, 6, 161.
Mestel, L. and Spitzer, L. 1956, *M.N.R.A.S.*, 116, 503.
Mouschovias, T. Ch. 1976, *Ap. J.*, 207, 141.
Mouschovias, T. Ch. 1978, in *Protostars and Planets*, ed. T. Gehrels (Tucson: University of Arizona Press), p. 209.
Mouschovias, T. Ch. and Paleologou, E.V. 1979, *Ap. J.*, 230, 204.
Mouschovias, T. Ch. and Paleologou, E.V. 1980, *Ap. J.*, 237, 877.
Mouschovias, T. Ch. and Paleologou, E.V. 1981, *Ap. J.*, 246, 48.
Mouschovias, T. Ch. Paleologou, E.V., and Fiedler, R.A. 1985, *Ap. J.*, 291, 772.
Mouschovias, T. Ch. and Spitzer, L. 1976, *Ap. J.*, 210, 326.
Myers, P.C. 1986, in *Star Forming Regions*, ed. M. Peimbert and J. Jugaku (Dordrecht: D. Reidel), in press.
Myers, P.C. and Benson, P.J. 1983, *Ap. J.*, 266, 309.
Myers, P.C., Fuller, G.A., Mathieu, R.D., Beichman, C.A., Benson, P.J., and Schild, R.E. 1986b, *Ap. J.*, submitted.
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.
Nakano, T. 1983, *Pub. Astr. Soc. Japan*, 35, 209.
Nakano, T. 1984, *Fundam. Cosmic Phys.*, 9, 139.
Norman, C., and Silk, J. 1980, *Ap. J.*, 238, 158.
Reid, M., Myers, P.C., and Bieging, J. 1986, preprint.
Rowan-Robinson, M. 1979, *Ap. J.*, 234, 111.
Sanders, D.B., Solomon, P.M., and Scoville, N.Z. 1984, *Ap. J.*, 276, 182.
Sargent, A.I. 1977, *Ap. J.*, 218, 736.
Scalo, J.M. 1977, *Ap. J.*, 213, 705.
Scott, E.H. and Black, D.C. 1980, *Ap. J.*, 239, 166.
Shu, F.H. 1977, *Ap. J.*, 214, 488.
Shu, F.H. 1983, *Ap. J.*, 273, 202.
Shu, F.H., Lizano, S., and Adams, F.C. 1986, in *Star Forming Regions*, ed. M. Peimbert and J. Jugaku (Dordrecht: D. Reidel), in press.
Snell, R.L., Mundy, L.G., Goldsmith, P.F., Evans, N.J. II, and Erickson, N.R. 1984, *Ap. J.*, 276, 625.
Solomon, P.M. 1986, in *Star Formation in Galaxies*, ed. G. Neugebauer and N.Z. Scoville, in press.
Solomon, P.M., Scoville, N.Z., and Sanders, D.B. 1979, *Ap. J. (Letters)*, 232, L89.
Spitzer, L., Jr. 1968, in *Stars and Stellar Systems, Vol. 7, Nebulae and Interstellar Matter*, ed. B. Middlehurst and L.H. Aller (Chicago: University of Chicago Press), p. 1.
Stahler, S.W., Shu, F.H., and Taam, R.E. 1980, *Ap. J.*, 241, 637.
Stark, A.A. and Blitz, L. 1978, *Ap. J. (Letters)*, 225, L15.
Strittmatter, P.A. 1966, *M.N.R.A.S.*, 132, 359.
Terebey, S., Shu, F.H., and Cassen, P. 1984, *Ap. J.*, 286, 529.
Turner, J.L. and Welch, W.J. 1984, *Ap. J. (Letters)*, 287, L81.
Wadiak, E.J., Wilson, T.L., Rood, R.T., and Johnston, K.J. 1985, *Ap.J. (Letters)*, 295, L43.

Walker, C.K., Lada, C.J., Young, E.T., Maloney, P.R., and Wilking, B.A. 1986, *Ap. J. (Letters)*, in press.
Wilking, B.A. and Lada, C.J. 1983, *Ap. J.*, 274, 698.
Wilking, B.A., Taylor, K.N.R., and Storey, J.W.V. 1986, *Astron. J.*, 92, 103.
Zeng, Q., Batrla, W., and Wilson, T.L. 1984, *Astr. Ap.*, 141, 127.
Zuckerman, B. and Palmer, P. 1974, *Ann. Rev. Astr. Ap.*, 12, 279.

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