Rev. Mexicana Astron. Astrof., **18**, 11-20 (1989)

MAGNETIC FIELDS AND STAR FORMATION IN MOLECULAR CLOUDS

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RESUMEN. Revisamos brevemente la importancia del campo magnético para el soporte de las nubes moleculares contra su auto gravedad. Revisamos también el proceso bimodal de formación de estrellas. Para las nubes subcríticas que evolucionan por difusión ambipolar del campo magnético y forman pequeños núcleos densos, discutimos los 2 posibles tipos de evolución de los núcleos dependiendo de su masa. Para una masa mayor que una masa *umbral*, la difusión ambipolar produce núcleos centralmente condensados que eventualmente se colapsarán para formar estrellas. Estos núcleos son como los núcleos de amoniaco que se observan en la nube de Taurus, donde se forman estrellas de baja masa. Por otro lado, una región subumbral evoluciona hacia una configuración final estable donde el campo magnético se vuelve asimptóticamente uniforme, y la presión térmica y turbulenta soportan a la nube contra la gravedad. Esta región no será suficientemente densa o grande para producir emisión de amoniaco observable. Solamente si la turbulencia decae, este tipo de regiones podrá formar estrellas.

ABSTRACT. We review the importance of magnetic fields for the support of molecular clouds against self-gravity and the process of bimodal star formation. For the case of subcritical clouds that evolve through the process of ambipolar diffusion forming small dense cores, we discuss the two regimes for the evolution of the cores according to their mass. For a mass greater than an *umbral* mass, the process of ambipolar diffusion produces a centrally condensed core, that ultimately collapses, from inside out, to form a star. This core looks like the ammonia cores, sites of low mass star formation, observed in the Taurus dark clouds. On the other side, a subumbral region evolves towards a stable final configuration where the mean magnetic field asymptotically become uniform and straight with thermal and turbulent pressure providing support against gravity. This region, will not be either dense enough or big enough to excite measurable ammonia emission. Only if turbulence decays, these type of regions will be able to form stars.

Key words: **INTERSTELLAR-CLOUDS — MAGNETIC FIELDS — STARS-FORMATION**

I. INTRODUCTION

It has been argued that magnetic fields could be the main agents of support against self-gravity in molecular clouds (for reviews see Mouschovias 1978; Mestel 1985). Some agent of support other than thermal pressure is required since, for the temperatures and densities in molecular clouds, the latter is insufficient, and molecular clouds are not collapsing at a free-fall rate, otherwise the star formation rate would be too high (Zuckerman and Palmer 1974). Magnetic fields in dense clouds have been measured by Zeeman splitting of thermal OH. The magnitudes of these fields range between 20 to 120 μG (see review of Heiles 1987). These field strengths are enough to support the clouds against gravitational collapse and are not easily dissipated.

If magnetic fields do provide the main support against gravity in molecular clouds, MHD waves could produce the turbulent motions observed in the clouds (Arons and Max 1975; Zweibel and Jossafatson 1982) and the observed levels of turbulence in molecular clouds can be qualitatively explained (Shu 1987). Also, the mechanism of magnetic braking can operate and allow the contracting cloud to loose angular momentum (for a review see Mestel and Paris 1984). This process could explain the small values of angular velocity commonly observed in molecular clouds (Goldsmith and Arquilla 1985).

The magnetic critical mass M_B that can be supported by magnetic fields alone against gravity can be obtained by virial theorem arguments (Strittmatter 1966), or more accurately by detailed model calculations (Mouschovias and Spitzer 1976). The results can be expressed generically by the simple formula,

$$M_B = cG^{-1/2}\phi, \tag{1}$$

where G is the universal gravitational constant, ϕ is the magnetic flux threading the cloud, and c is a dimensionless coefficient having a value $\sim$ 0.1 to 0.2, depending on the adopted mass-to-flux distribution and boundary conditions. An extensive survey of models calculated by Tomisaka, Ikeuchi, and Nakamura (1988) gives $c = 0.17$. Given that turbulence and thermal pressure may also play a role in the cloud support, Lizano and Shu (1989; hereafter LS), proposed a critical mass that includes this extra means of support. This critical mass is given by

$$M_{cr} = M_a + (M_a^2 + M_K^2 + M_B^2)^{1/2}. \tag{2}$$

In this equation M_B is given by equation (1); M_a is the thermal mass

$$M_a \equiv (a^2/G)L \tag{3}$$

and is one half of the mass inside a radius L of a singular isothermal sphere with sound speed a; M_K is the turbulent mass

$$M_K \equiv (\pi K/2G)^{1/2}L^2 \tag{4}$$

and equals half of the mass inside the radius L of a singular logatropic sphere (which corresponds to an equation of state $P = K\ln(\rho/\rho_0)$ and a density distribution $\rho = [K/2\pi G]^{1/2}r^{-1}$). Given the observed levels of turbulence in the clouds, M_K is comparable to M_B at the parsec scale, but is small at the scale of the small dense cores (see below) where, instead, M_a becomes comparable to M_B. Finally, rotational support can also be included in M_{cr} (Tomisaka, Ikeuchi and Nakamura 1989); that term could be important for the support of the envelope.

II. BIMODAL STAR FORMATION

In a recent review (Shu, Adams, and Lizano 1987; hereafter SAL) argued that in self-gravitating molecular clouds, supported primarily by magnetic fields, star formation proceeds bimodally (see also Mestel 1985):

(1) Clouds (or clumps) with a mass M_{cl} less than a critical value M_{cr} are *subcritical* and will evolve by ambipolar diffusion, wherein the neutral components gradually slip past the charged particles and magnetic fields that provide the basic support (Mestel and Spitzer 1956). With a large initial ratio of magnetic to thermal pressure (such that the Jeans mass $M_J \ll M_{cl}$), many small dense cores would slowly condense from the common envelope of an extended region, an outcome descriptive of the situation in the Taurus molecular cloud (e.g., Myers and Benson 1983). This mode constitutes an ongoing background process for the formation of individual or binary stars in nearly every self-gravitating molecular cloud. Empirically, by the time the cores acquire high enough densities ($> 3 \times 10^4$ cm^{-3} within a radius of $\sim$ 0.05 pc) to excite measurable ammonia emission, about half of them have collapsed to form low-mass stars (Beichman *et al.* 1986). Since the ages of deeply embedded infrared sources of modest luminosities (low-mass protostars) are estimated to lie between 10^5 and 10^6 yr (Stahler, Shu and Taam 1980; Adams, Lada, and Shu 1987), this observation suggests that the lifetimes of molecular cloud cores, once they have reached central concentrations characteristic of the NH_3 observations, cannot much exceed 10^6 yr (Myers 1987). This number provides an important constraint on proposed mechanisms for the origin of the small dense cores.

(2) Clouds with a mass M_{cl} greater than a critical mass M_{cr} are *supercritical* and can collapse dynamically as a whole, overwhelming the internal magnetic support, even if the fields remain frozen in the fluid (e.g., Scott and Black 1980). Shu (1987) suggested that the production of supercritical regions from an ensemble of subcritical clouds could naturally arise by the agglomeration of clumps of gas and dust that have been gathered together in a large complex. Such a picture may provide a basis for understanding the triggering of OB stars behind galactic shocks and within the nuclear regions of starburst galaxies. This mode of star formation requires a high surface density of molecular material. Upon the cloud's flattening along the direction of the mean field, fragments of a size comparable to the cloud's thickness can themselves collapse as supercritical regions (Mestel 1965), yielding either a compact group of OB stars (e.g., Keto, Ho, and Haschick 1987; Welch *et al.* 1987), or a bound cluster if the high efficiency of star formation is not disrupted by the formation of too many luminous stars (e.g., Lada and Wilking 1984). The signature of a supercritical region would be coherent dynamical collapse involving large amounts of molecular gas (say,$\sim 10^2$ to 10^5 $M_\odot$) and an increase of the temperature of the gas relative to the dust by the effects of ion-neutral frictional heating (e.g., Lizano and Shu 1987).

III. AMBIPOLAR DIFFUSION AND CORE FORMATION

In this section, we concentrate on the subcritical clouds and discuss the mechanism of core formation. In order to do this, we review the results of 3-D axisymmetric models of the quasistatic evolution of self-gravitating regions as ambipolar diffusion lowers the amount of magnetic and "turbulent"support in these regions (LS). For a fixed mass, we find that the level of turbulent support determines whether a dense core forms or not. There is a threshold mass (called *umbral* mass) above which the condensing region can overcome the remaining means of support after ambipolar diffusion has tried to straighten out the magnetic field lines in a subcritical cloud.

The evolution of the cores is followed only within their "tidal lobe"as defined by a periodic chain of cores strung along the z axis. This geometry was chosen to mimic the physical situation of the existence of many dense regions (cores) in a much larger molecular cloud.

The models are computed in nondimensional variables. The density ρ is measured in units of the fiducial value ρ_0 (used to scale total masses), the gravitational potential V, in units of the square of the sound speed a^2, and magnetic fields in units of a fiducial "background value"B_0. Lengths are measured in units of $l_0 = a/(4\pi G\rho_0)^{1/2}$, magnetic flux in units of $\phi n_0 = a^2 B_0/2G\rho_0$, mass in units of $m_0 = 4\pi\rho_0 l_0{}^3$, and time in units of $t_0 = \left[\gamma C/(4\pi G)^{1/2}\right]\left[1/(4\pi G\rho_0)^{1/2}\right]$. The value of t_0 depends also on the ionization coefficient $C = 3\times 10^{-16}\, cm^{-3/2}\, g^{1/2}$ (Elmegreen 1979) and on the collision rate between ions and neutrals $\gamma = 3.5\times 10^{13}\, cm^3\, g^{-1}\, s^{-1}$ (Draine *et al.* 1983). To discuss the models below we will choose a kinetic temperature $T = 10$ K and mean molecular mass $m = 2.3\, m_H$ (resulting in an isothermal sound speed $a = 0.19$ km s^{-1}); a reference density $\rho_0/m = 1\times 10^3$ cm^{+3}; and a background magnetic field $B_0 = 30\,\mu G$. This implies that $l_0 = 0.11\, pc$, $\phi_0 = 2.5\,\mu G\, pc^2$, $m_0 = 0.96 M_\odot$, and $t_0 = 6\times 10^6\, yr$. We refer the reader to LS for a discussion of other choices of physical parameters relevant to molecular clouds.

a) Turbulent Pressure

To account heuristically for the mechanical support provided by interstellar "turbulence"(cf. Larson 1981), we assumed a total gas pressure P,

$$P = P_{th} + P_{turb}, \tag{5}$$

given by the sum of the thermal pressure,

$$P_{th} = a^2\rho, \tag{6}$$

where a^2 is the square of the isothermal sound speed, and an isotropic "turbulent"contribution,

$$P_{turb} = \mathcal{K}\, ln(\rho/\rho_0), \tag{7}$$

where $\mathcal{K}$ has a constant value and ρ_0 is some reference density. Note that any arbitrary constant could be added to P_{turb} without affecting the details of the forces exerted in the interior. The effective transport speed associated with this turbulent pressure,

$$v_{turb} \equiv (dP_{turb}/d\rho)^{1/2} = (\mathcal{K}/\rho)^{1/2}, \tag{8}$$

behaves like the empirical power-law correlation $\Delta v \propto \rho^{-1/2}$ found by studies for the nonthermal part of molecular line widths (Solomon and Sanders 1985, Dame *et al.* 1986, Myers 1987, Scoville *et al.* 1987). The best fit for the data assembled by Myers and Goodman (1988) suggests that $\mathcal{K} = 1.2\times 10^{-11}$ dyne cm^{-2}; the "cold"and "hot"GMCs surveyed by Solomon *et al.* (1987) have values of $\mathcal{K}$ which are 1.5 and 6 times larger. Although equation (7) has an empirical basis, the ultimate reason for choosing this particular functional form is for the mathematical convenience of having a barotropic equation of state when a^2 and $\mathcal{K}$ are taken to be constants.

The models are characterized by different values of the turbulent parameter

$$K = \frac{\mathcal{K}}{a^2\rho_0}. \tag{9}$$

This dimensionless constant yields $(v_{turb}/a)^2$ at the reference density ρ_0. In particular, for our choice of dimensional parameters, the value $\mathcal{K} = 1.2\times 10^{-11}$ dyne cm^{-2} mentioned above gives $K = 8.7$. In the ammonia cores, Myers and Benson (1983) obtained a mean turbulent contribution to the line width that is typically only 60% of sonic, corresponding to $K = 11$. In the subsample of cores without stars, the turbulent contribution drops to only 45% of sonic, corresponding to $K = 6$ (Fuller and Myers 1987).

We discuss here only the evolution of two representative cases: $K = 6$ and $K = 12$.

b) Evolution with Turbulent Parameter $K = 6$

The case $K = 6$ corresponds to a turbulent speed that is 45% of the isothermal sound speed at the density $\rho = 30$, which, for the dimensional parameters mentioned above, is representative of the density in the NH_3 cores.

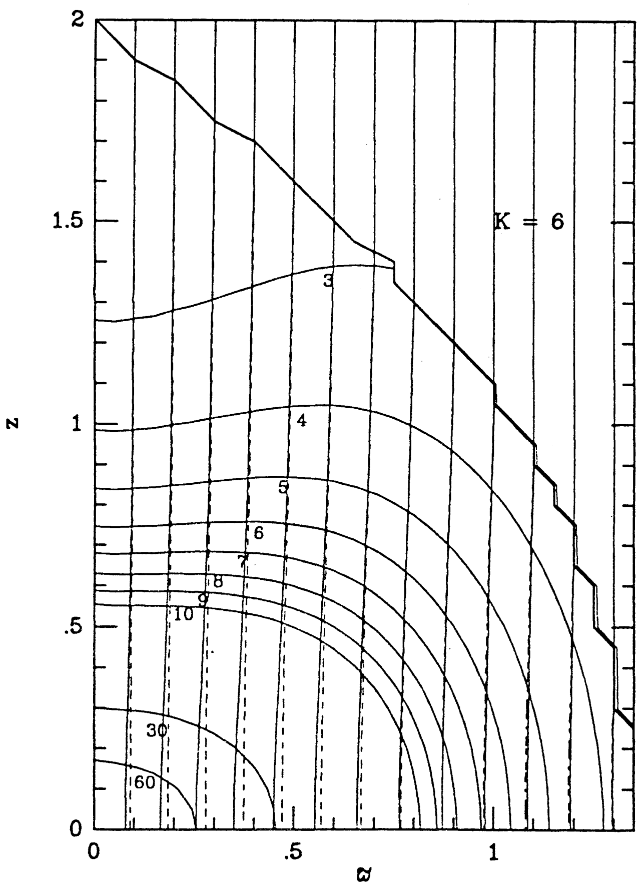

Fig.1 The superposition of isodensity contours and magnetic flux tubes for the case with $K = 6$ at the time $t = 0.21$ (solid lines). The dashed lines give the magnetic flux tubes at $t = 0$.

Figure 1 shows the isodensity contours and magnetic flux tubes for this case at the time $t = 0.21$ (solid lines). The dashed lines indicate the location of the flux tubes at time $t = 0$. Although the magnetic flux has diffused outward relative to the matter distribution by ambipolar diffusion, it has been dragged in, relative to an Eulerian grid, by the gravitational concentration of the neutrals. Therefore, the field strength B increases even though ambipolar diffusion is occurring (see below).

From $t = 0$ to $t = 0.21$, the central density ρ_c has increased from an initial value 23 to a value 97, well in excess of the critical density 30 needed to excite ammonia emission (for $\rho_0/m = 1 \times 10^3\ cm^{+3}$. At the time $t = 0.21$, the mass inside the density contour $\rho = 30$ is 1.0 (in units of m_0). For $m_0 = 0.96\ M_\odot$, this mass is comparable to typical values measured for Taurus ammonia cores. Note that nothing special exists about the isodensity contour $\rho = 30$ that would distinguish it *mechanically* from $\rho = 10$ (or 100, or 1). If the material (1.0 m_0) inside $\rho = 30$ were to fall into a star, without the interference of a protostellar outflow, nothing would prevent the entire mass M inside the tidal lobe (7.0 m_0 for these models) from following. Nor would the infall process stop there, because after this tidal lobe has emptied, material would be transferred over from neighboring tidal lobes (if gravitational collapse is not perfectly synchronized in all cells), as well as fall in from the common envelope. In other words, *no consideration of the mechanical properties of molecular clouds leads to a natural identification of stellar mass scales; stellar masses are likely to be determined by additional processes that occur inside the stars themselves* (see the review of SAL).

[1] To show the evolution of the magnetic flux tubes in time, we always plot the set of magnetic flux tubes that cross the tidal lobe, where $\phi = \varpi^2/2$, at the axial positions $\varpi = 0.1$ to 1.3 in steps of 0.1.

The radial extent of the $\rho = 30$ contour also agrees well (assuming $l_0 = 0.11$ pc) with the typical observed semidiameter of ammonia cores, ~ 0.05 pc. The statistics of the shapes of actual ammonia cores is not well known; this model has a modest axial ratio in $z{:}\varpi$ of about 2:3 at the density contour $\rho = 30$, although rotation might enhance this aspect ratio.

As was also found by Nakano (1982) for a different parameter regime, the evolution in the last stages proceeds very rapidly. Figure 2 shows the isodensity contours and magnetic flux tubes and the logarithmic density profiles in the ϖ and z directions. At $t = 0.23$, the mass inside the density contour $\rho = 30$ has increased to 1.6, and the central density has risen to 370, with a power-law exponent for the density distribution ($\rho \propto l^{-s}$) of $s \approx 2$. Along the z axis, the coefficient in the dimensional relation $\rho = Cr^{-2}$ is well represented by the value of the singular isothermal sphere $C = a^2/2\pi G$; on the ϖ axis, C is larger because of the contribution of the magnetic support.

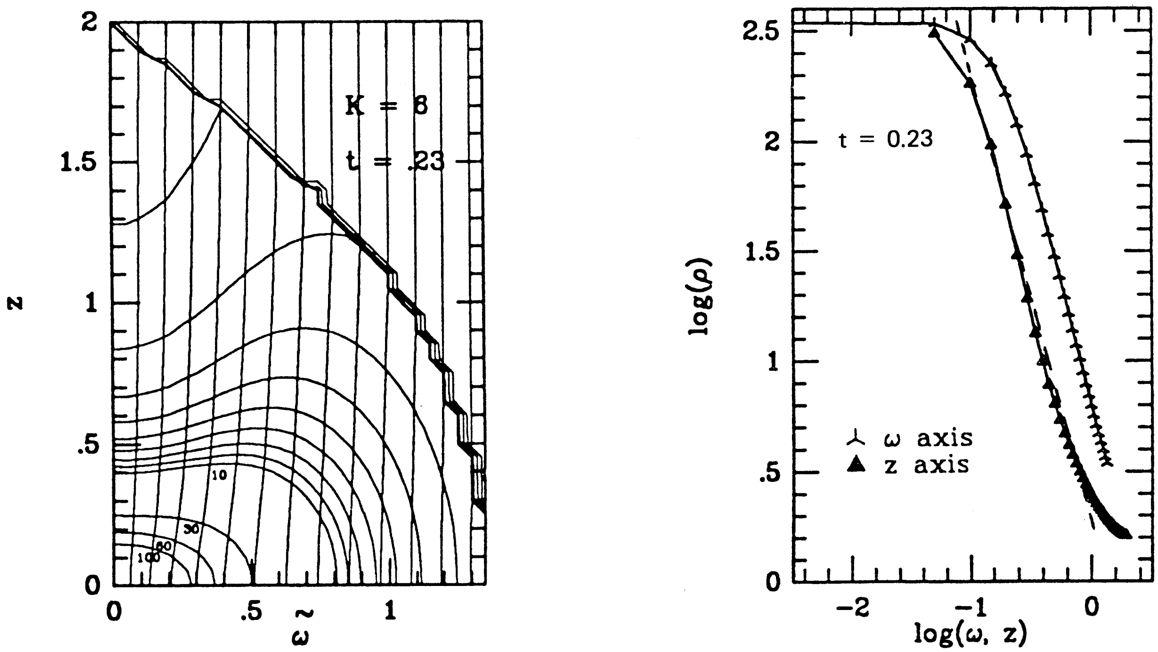

Fig. 2. Isodensity contours and magnetic flux lines at the time $t = 0.23$ are shown in the left diagram; logarithmic density profiles along the ϖ and z axes, in the right diagram. The density contours below $\rho = 10$ are 9, 8, 7, 6, 5, 4, 3, and 2. The dashed line gives the density profile for the singular isothermal sphere, $\rho = (a^2/2\pi G)r^{-2}$ expressed in nondimensional units.

Past $t = 0.23$, the available means of support (mostly thermal and magnetic in the densest parts of the cloud) are unable to prevent a runaway increase of the central density. We cannot follow the evolution during the stage when the core tries to develop a central cusp because the flow velocities along field lines (see LS for the estimate of neutral velocities) approach supersonic values, and the quasistatic assumption breaks down. But, since the contraction is very nonhomologous, with the center evolving quickly compared to the outer regions, one expects the developing core to eventually collapse from *inside-out* to form stars in the qualitative manner originally envisaged by Shu (1977).

This model evolves in $t \sim 1.3 \times 10^6$ yr (for $t_0 = 6 \times 10^6$ yr) from an "initial"state with no ammonia emission to a configuration that looks, in its innermost parts, like a classical ammonia core (Figure 1). After this point, the evolution in the center of the ammonia core proceeds very quickly, reaching a stage of dynamical collapse in another $\sim 10^5$ yr. Such short time scales imply that by the time ammonia cores are observed, an appreciable fraction of the cores should have formed stars. This is in qualitative agreement with the observation (see §II) that roughly half of the ammonia cores show embedded infrared sources (Beichman *et al.* 1986) and with the statistical arguments employed by Myers (1987).

c) Evolution with Turbulent Parameter K = 12

There is a trend with increasing K which leads to a threshold phenomenon beyond which ammonia cores will not form. To show this we will examine the case $K = 12$ which corresponds to a turbulent speed that is 63% of the isothermal sound speed at the density $\rho = 30$.

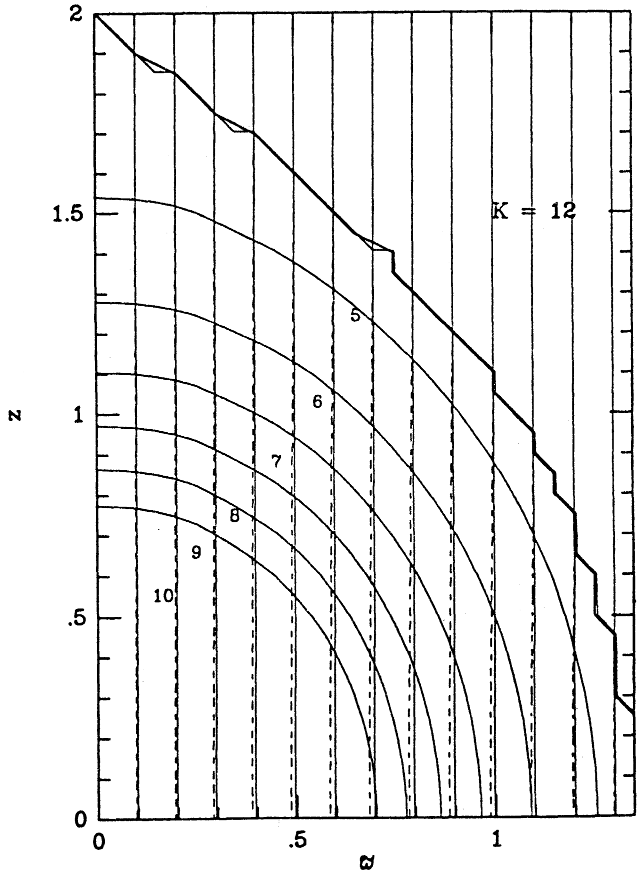

Fig. 3. The superposition of isodensity contours and magnetic flux tubes for the case $K = 12$ at the time $t = 1.2$ (solid lines). The dashed lines give the magnetic flux tubes at $t = 0$.

Figure 3 shows a superposition of isodensity contours and magnetic flux lines at the time $t = 1.2$ (solid lines). The dashed lines indicate the location of the flux tubes at $t = 0$. The core condensed from an initial central density $\rho_c = 14$ only to $\rho_c = 20$, not enough to excite ammonia emission (for the dimensional parameters adopted). We stopped the evolution at this time because the mass distribution has remained virtually unchanged since $t = 0.3$, when the magnetic field straightened almost completely by drifting outward relative to the Eulerian grid at all positions in the cloud.

The case $K = 12$ has failed to form an identifiable ammonia core because a stable *equilibrium* state is accessible to it where the magnetic field can evolve asymptotically to become straight and uniform, with the total support against self-gravitation taken up by turbulent and thermal pressure. The evolution from the "initial"state is very slow (characteristic of envelope values) because the drift velocity is proportional to the magnetic stress, and the latter is almost zero.

d) Magnetic Field Behavior

Finally we find that when the turbulent parameter K is less than a threshold value ($K \approx 11$), the magnetic field increases with time in the center even though ambipolar diffusion is occurring, demonstrating that, at these densities, the frictional coupling of the neutrals to the ions and magnetic field is still good (see discussion on magnetic decoupling in LS). Figure 4 shows that the magnetic field in the center tends to increase with density as a function of time roughly as ρ_c^{κ} where $\kappa \sim 0.5$, as found in the dynamical calculations by Scott and Black (1980), only in circumstances when the gravitational contraction along and across field lines more than makes up for the losses due to ambipolar diffusion (case $K = 6$; see also Nakano 1984).

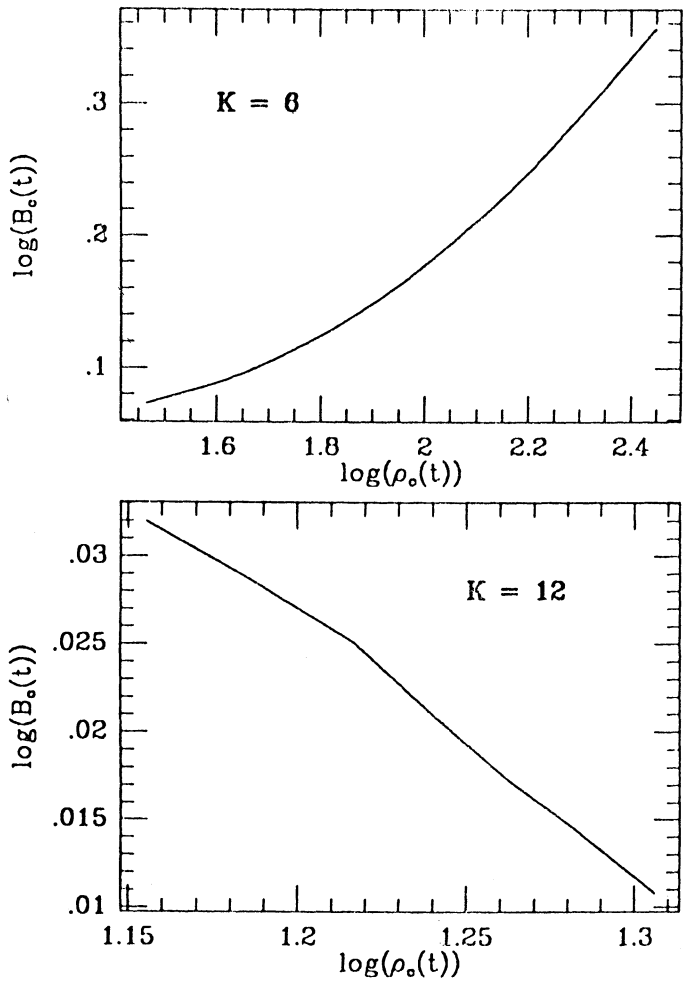

Fig. 4. Evolution of the central values of the magnetic field and gas density. The quantities $\log(B_c)$ and $\log(\rho_c)$ are plotted for both cases, demonstrating that the formation of an ammonia core ($K = 6$) is accompanied by an increase of B_c, while failure to produce a dense core ($K = 12$) results in the gradual straightening of the magnetic field lines.

e) Umbral Mass

The distinction between the 2 regimes of evolution described above is that in the case with turbulent parameter $K = 6$, the core mass is bigger than a threshold mass, sufficient to overcome the *non-magnetic* means of support as the magnetic field diffuses out by ambipolar diffusion. LS calculated an *umbral* mass above which the core would eventually collapse and form stars. This mass is given by

$$M_{umbral} = M_a + (M_a^2 + M_K^2)^{1/2}, \qquad (10)$$

with the same definitions as in equation (2).

As shown in Figure 5, there are then three regimes of interest for star formation. In the supercritical case $M_{cl} > M_{cr}$ given by equation (2), the cloud as a whole collapses and possibly fragments, providing the conditions for the formation of an OB association or an open cluster; in the subcritical-superumbral case, $M_{um} < M_{cl} < M_{cr}$, dense ammonia cores quasistatically form by ambipolar diffusion and collapse from inside-out to form low mass stars; in the subcritical-subumbral case, $M_{cl} < M_{um} < M_{cr}$, unless the turbulence decays, no core or star formation will occur.

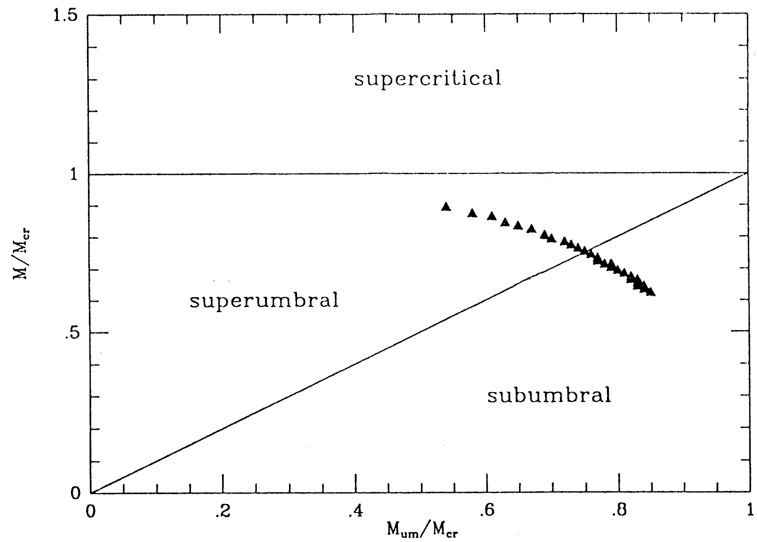

Fig. 5. The ratio of umbral mass to critical mass, M_{um}/M_{cr}, versus the ratio of the mass in the tidal lobe to the critical mass, M_{cl}/M_{cr}. The symbols refer to a set of models with the turbulent parameter varying from $K = 0$ (leftmost solid triangle) to $K = 11$ (umbral case) to $K = 30$ (rightmost open triangle).

IV. CONCLUSIONS

We have found that for superumbral regions with $M > M_{umbral}$, the process of ambipolar diffusion produces dense cores whose sizes and densities correspond well to those of the dense ammonia cores surveyed by Myers and Benson (1983) in the Taurus dark cloud. For quiescent regions (in terms of turbulent support), the time required to produce regions characterized by appreciable ammonia emission is 10^6 yr or less; for more active regions, it can exceed 10^7 yr. During the last stages of the evolution of these cores, a runaway develops on a characteristic time scale of a few times 10^5 yr, in which the density profile steepens into a power-law form, $\rho \propto r^{-s}$, with s approximately equal to 2. In the models, the magnetic field inside the ammonia core increases relatively little with respect to the background, not because there is a large amount ambipolar diffusion: a small amount, together with gas settling along field lines, goes a long way toward producing a central density cusp and the beginning of an inside-out core collapse. At this stage not much flux has been lost. In agreement with Nakano and Umebayashi (1986*a,b*), we found that the magnetic flux problem must be solved at much higher densities than those associated with ammonia cores.

On the other hand, unless the turbulence decays, ammonia cores will not form in very active regions, where the mass $M < M_{umbral}$. The existence of such a threshold implies that the molecular clouds may have many "failed"cores in regions where the turbulence has been increased, say, by the winds from neighboring low-mass protostars. Such a picture might even form a physical basis for current speculations concerning the role of "self-regulation"in star formation (e.g., Norman and Silk 1980, Franco 1984).

The magnetically supported cores look like the large flattened structures that surround newly formed stars, having a scale of $\sim$ 0.01-0.1 pc (e.g., Kaifu *et al.* 1984; Sargent *et al.* 1988; Rudolph 1988). The flattening of the modeled cores is typically not very severe for the regime of parameter space relevant to Taurus molecular cloud cores. Rotation parallel to the magnetic field would produce additional flattening in the cores, but, observationally, rotation is not dynamically important at the stage of the ammonia cores (Myers and Benson 1983).

Finally, the size and mass of a cloud core depend on the molecule observed, since different molecules trace different critical densities (e.g., Walmsley 1987). Here we have concentrated on the masses and sizes of the cores as observed in NH_3. Fuller (1989) has observed these cores in an optically thin transition of $C^{18}O$, which traces less dense material ($\sim 2 \times 10^3$ cm^{-3}). In a preliminary analysis, he obtains sizes that are a few times larger and masses that are several times larger than obtained by the ammonia measurements.

Then, the reservoir of material potentially available to form stars is much greater than the mass that actually ends up in the completed objects. Considerations of the physics of the interstellar medium, such as those given in the present paper, do not automatically produce, *by themselves*, mass scales characteristic of the stars.

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