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# COLLAPSE AND FRAGMENTATION MODELS OF CLOUD CORES WITH MAGNETIC FIELD SUPPORT

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## RESUMEN

En este trabajo presentamos modelos numéricos del colapso y fragmentación de núcleos de nubes moleculares con baja rotación ($\beta \approx 0.037$) y con energía térmica moderada ($\alpha \approx 0.36$), incluyendo los efectos de soporte magnético, difusión ambipolar y una interacción de marea debida a un encuentro gravitacional con otra protoestrella. Las fuerzas magnéticas retrasan el inicio del colapso dinámico y por consiguiente de la fragmentación por un lapso de tiempo que depende de la razón entre la masa y el flujo magnético en el centro de la protoestrella. Los resultados muestran que los modelos son susceptibles a fragmentarse en sistemas binarios y en algunos casos en sistemas triples o cuadruples dependiendo de la intensidad del soporte magnético y de la interacción de marea.

## ABSTRACT

In this work we present numerical models of the collapse and fragmentation of slowly rotating ($\beta \approx 0.037$), thermally supercritical ($\alpha \approx 0.36$), molecular cloud cores, including the effects of magnetic support, ambipolar diffusion and a tidal interaction due to a gravitational encounter with another protostar. The magnetic forces delay the onset of dynamic collapse and hence of fragmentation by an amount that depends on the initial central mass-to-flux ratio. The results show that the models are susceptible to fragment into binary systems and in some cases into triple and quadruple systems depending on the intensity of the magnetic support and the tidal interaction.

*Key Words:* **METHODS: NUMERICAL — STARS: FORMATION**

Fragmentation has long been advocated as the primary mechanism for explaining the observed binary frequency among pre-main-sequence stars, and more recently for explaining the emerging evidence for binary and multiple protostellar systems. The role of magnetic fields and ambipolar diffusion is essential for understanding how dense cloud cores begin dynamic collapse and eventually fragment into protostars. In this work we present numerical models of the collapse and fragmentation of slowly rotating, thermally supercritical, molecular cloud cores, including the effects of magnetic support, ambipolar diffusion and a tidal interaction due to a gravitational encounter with another protostar.

The effects of magnetic fields and ambipolar diffusion were included using a formulation similar to that employed by Boss (1997). The evolution of the models is obtained by solving the mass and momentum conservation equations for the neutral component of the gas along with the Poisson equation for the gravitational forces. The momentum equation takes the form (see Galli & Shu 1993)

$$\rho\left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right] = -\rho\nabla\Phi - \nabla\left(p + \frac{B^2}{8\pi}\right) + \frac{1}{4\pi}(\mathbf{B}\cdot\nabla)\mathbf{B}\ , \tag{1}$$

where $\rho$, $\mathbf{v}$, $\Phi$, $p$, and $\mathbf{B}$ (with $B^2 = \mathbf{B}\cdot\mathbf{B}$) are, respectively, the mass density, the fluid velocity, the gravitational potential, the gas pressure, and the magnetic field strength. The nonlinear induction equation for the time variation of the magnetic field is not solved and knowledge of the state of the field is obtained by means of the

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scaling relation (Mouschovias 1976, 1991)

$$\frac{B}{B_0} = \left(\frac{\rho}{\rho_0}\right)^{1/2} , \tag{2}$$

where $B_0$ and $\rho_0$ refer to initial central values.

The magnetic force terms on the right-hand side of equation (1) consist of a magnetic pressure plus the term $(\mathbf{B}\cdot\nabla)\mathbf{B}$, which represents an additional tension along the field lines. Our formulation is slightly different from that employed by Boss (1997), who assumed that $(\mathbf{B}\cdot\nabla)\mathbf{B} = 0$ even for curved field lines. The effects of ambipolar diffusion are approximated by replacing relation (2) with (Boss 1997)

$$B = B_0 \left(1 - \frac{t}{\tau_{\rm AD}}\right)\left(\frac{\rho}{\rho_0}\right)^{1/2} , \tag{3}$$

where $t$ is the evolution time and $\tau_{\rm AD}$ is the ambipolar diffusion timescale. For a fractional ionization of $\approx 1.5 \times 10^{-8}$, we estimate $\tau_{\rm AD} \approx 9\ t_{\rm ff}$ in the cores of magnetically supported clouds. For the calculations, we set $\tau_{\rm AD} = 10\ t_{\rm ff}$ in equation (3).

In large and massive cloud cores where cluster formation is well underway, gravitational interactions and encounters between star-forming clumps, and between clumps and stars, may occur frequently. In order to include the effects of a gravitational encounter, we calculate the tidal distortion induced on the protostellar core by an approaching object moving in a parabolic orbit. To do so we consider a point mass $M^\star$ in relative coplanar orbit around the collapsing protostar of mass $M$. The position of $M^\star$ is obtained by solving the equation of the orbit and the tidal potential $\Phi_{\rm T}^\star$ due to a moving point source of mass $M^\star$ is calculated as in Sigalotti & Klapp (1992).

The calculations were made using an isothermal version of the three-dimensional radiative hydrodynamic code described by Sigalotti (1998). The initial radial grid resolution was set by defining $1 + n_r = 51$ equally spaced cells and improved central resolution during collapse was obtained by allowing all interior radial points to contract while keeping the outer radius fixed in space and time. The angular grid resolution was given by $2 + n_\theta = 67$ fairly equidistant points for $0 \leq \theta \leq \pi$ and $n_\phi = 64$ uniformly spaced points for $0 \leq \phi < 2\pi$. Only the top hemisphere of the computational volume was represented by the calculations because of the assumption of reflection symmetry about the equatorial plane.

We followed the onset of protostellar collapse in a slowly rotating, magnetically subcritical cloud core contracting by ambipolar diffusion and undergoing a gravitational encounter with another protostar. We first considered a sequence of magnetic collapse calculations with varying strength of the frozen-in field, all with the same initial conditions of model A2 of Sigalotti & Klapp (1997). Thus, the starting point of collapse is a spheroid of prolate shape with a central condensation defined by a Gaussian density variation in radius. With these initial conditions, the models resemble both the elongated molecular cloud cores observed by Myers et al. (1991) and the centrally condensed precollapse cores studied by Ward-Thompson et al. (1994), André, Ward-Thompson, & Motte (1996), and more recently by Motte, André, & Neri (1998). The initial ratios of the thermal and rotational energy to the absolute value of the gravitational energy are, respectively, $\alpha \approx 0.36$ and $\beta \approx 0.037$, and the prolate shapes correspond to spheroids with axial ratios of 2:1.

In a first sequence of calculations, the models were allowed to collapse under the influence of a frozen-in magnetic field of varied strength (i.e., $25\ \mu{\rm G} \leq B_0 \leq 250\ \mu{\rm G}$, or equivalently $0.005 \lesssim \eta \lesssim 0.469$, in terms of the amount of magnetic energy). The results indicate that as long as the initial central ratio of the magnetic to the thermal pressure, $(p_{\rm mag}/p_{\rm therm})_0 < 1$, or equivalently when $\eta \lesssim 0.230$, the models undergo sustained collapse before fragmenting into well-defined binary systems. Only when $B_0 \gtrsim 180\ \mu{\rm G}$, is the ratio $(p_{\rm mag}/p_{\rm therm})_0 \gtrsim 1$ and so the models no longer collapse but rather contract slowly toward a magnetically stable condensation implying a range of magnetic stability of $0.30 \lesssim \eta \lesssim 0469$.

The magnetically stable clouds define a sequence of subcritical states with central mass-to-flux ratios $s_0 < 1$, and so they were used as initial conditions for a second set of calculations, now including the effects of ambipolar diffusion. In addition, the effects of the tidal interaction due to a gravitational encounter with another protostar were also included. Thus, the models are appropriate for describing the formation of binary systems during the magnetically controlled collapse of low-mass clumps within a cluster-forming environment. Two separate sequences of models with increasing size of the tidal perturbation ($0 \leq \tau < 0.45$) were calculated, which differed only in the central mass-to-flux ratio ($s_0 \approx 0.759$ and $0.607$), or equivalently in the amount of magnetic

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energy ($\eta \approx 0.285$ and 0.469). Initially the models evolved very slowly, with the central density increasing only gradually as matter condensed quasi-statically through the field lines due to ambipolar diffusion. The duration of this phase was seen to depend on the initial mass-to-flux ratio. The sequence of models that started with $s_0 \approx 0.607$ experienced a longer phase ($\gtrsim 4\ t_{\rm ff}$) than the higher $s_0(\approx 0.759)$ cases, which had delay periods $\gtrsim 3\ t_{\rm ff}$. This trend is consistent with the results of Fiedler & Mouschovias (1993). When the central density exceeded $\sim 10^{-15}$ g cm$^{-3}$, the central mass-to-flux ratio became supercritical ($s_0 \gtrsim 1$) and rapid collapse ensued. Supercritical collapse occurred in about 0.1 $t_{\rm ff}$, during which the central density enhanced to $\sim 10^{-13}$ g cm$^{-3}$ before binary fragmentation set in.

The sequence that started with $\eta \approx 0.285$ formed quadruple systems for low $\tau(\lesssim 0.137)$, triple systems for intermediate $\tau(\approx 0.201)$, and binary systems for higher $\tau(\gtrsim 0.251)$. This result indicates that tidal forces of moderate size can determine the outcome of binary formation in cloud cores which will otherwise fragment into higher-order systems. The models that started with higher magnetic support ($\eta \approx 0.469$), all formed binary systems irrespective of the size of the tidal perturbation. In these cases, the role of tidal forces in determining the final outcome was less evident because the increasing magnetic pressure also worked in the direction of impeding higher-order fragmentation. Compared to the calculations of Boss (1997), the present models predict much tighter binaries, with separations of ≈ 200–350 AU. The binary separation is a function of both the central field strength ($B_c$) and the size of the tidal perturbation. If most PMS binaries are formed by fragmentation, the results suggest that the observed distribution of binary separations below 250 AU, may be explained by the collapse and fragmentation of magnetically supported, slowly rotating ($\beta \lesssim 0.04$) cloud cores. The results of this work point once more toward the formation of binary systems as a viable outcome, and extend the range of initial conditions for which we may expect binary fragmentation to occur in magnetically supported clouds.

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