Mem. S.A.It. Vol. 80, 54

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The impact of magnetic fields on star formation

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Abstract. We briefly review the role of magnetic fields during the phase of dynamical collapse of molecular cloud cores following the formation of strongly centrally concentrated density distributions. We discuss the importance of ohmic dissipation in the solution of the the magnetic flux problem of star formation illustrating the consequences of magnetic braking for the formation of disks around young stellar objects.

Key words. ISM: clouds, magnetic fields – Planetary systems: protoplanetary disks – Star: formation – magnetohydrodynamics

1. Introduction

The formation of stars occurs in dense cores inside giant molecular clouds (Evans 1999). The physical mechanisms that produce such cores are controversial: one possibility involves the leakage of magnetic support by a process called "ambipolar diffusion" (Mestel & Spitzer 1956), whereas a different explanation invokes transient compression by converging streams in a turbulent flow (Elmegreen 1993). Turbulent motions, observationally inferred from the the width of molecular lines, are expected to represent a fierce opposition to gravity in preventing molecular clouds from collapsing as a whole on a dynamical time scale of a few 10^5 yr as the Jeans criterion would imply.

However, both analytical studies and numerical simulations agree that hydro- or magnetohydrodynamical turbulence in the interstellar medium should decay in about one dynamical time (Gammie & Ostriker 1996; MacLow et al 1998), therefore requiring a continuous injection of turbulent energy to sustain the clouds over their lifetimes. Magnetic fields, on the other hand, are long lived: in a lightly ionized medium such as a the gas of a molecular cloud (ionization fraction $\sim 10^{-8}$–10^{-7}), ohmic losses are too weak to significantly reduce the magnetic field strength over the cloud's lifetime. For example, for an ionization fraction $\sim 10^{-8}$ and density $\sim 10^5$ cm^{-3}, the ohmic dissipation time of a magnetic field extending on a length scale of ~ 0.1 pc is of the order of 10^{15} yr (Pinto, Galli, & Bacciotti 2008; Pinto & Galli 2008). The relevant mechanism of field diffusion in molecular cores is *plasma drift*, or *ambipolar diffusion*, originally proposed by Mestel and Spitzer (1956), a process by which the fluid of charged particles with its frozen-in magnetic field can slowly drift with respect to the fluid of neutral particles, the two fluids being collisionally coupled. The ambipolar diffusion time scale is of the order of several times 10^6 yr, or about one–two orders of magnitude larger than the free-fall time scale.

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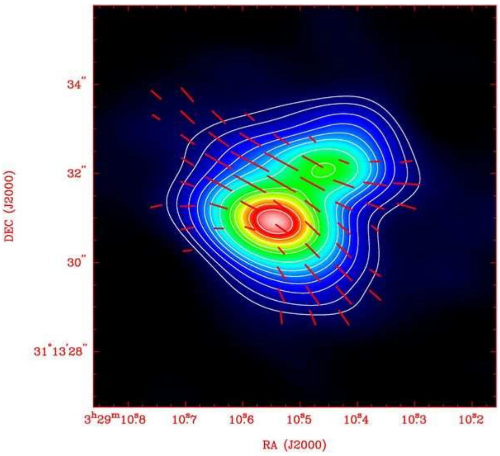

Fig. 1. Contour map of the 877 μm dust emission in the low-mass protostellar system NGC1333-IRAS4A. The direction of the vectors corresponds to the position angle of linear polarization (Girart, Rao, & Marrone 2006)

2. Observations of magnetic field in molecular clouds

The physical characteristics of magnetic fields in molecular clouds have been derived mainly by two methods: (*i*) measurements of the Zeeman splitting of hyperfine transitions of atoms and molecules, and (*ii*) measurements of polarization of the thermal radiation emitted at millimetre/submillimetre wavelengths by magnetically aligned aspherical dust grains. Here, it is sufficient to recall that the Zeeman effect in thermal (H, OH, and CN) and maser (OH and H_2O) lines is the most direct way of measuring the integrated line of sight component of the magnetic field: HI Zeeman observations sample gas densities from 10 cm^{-3} to 10^2 cm^{-3}, OH Zeeman observations cover the range from 10^3 cm^{-3} to 10^4 cm^{-3}, whereas OH and H_2O masers probe the field strength in very dense gas from 10^6 cm^{-3} up to 10^{11} cm^{-3}. However, in the cloud cores where star formation takes place, the gas is molecular and contains little HI, whereas the abundance of the highly reactive OH radical decreases rapidly with increasing density. Maser emission, on the other hand, originates from very small regions under special physical conditions, probably not representative of the bulk of molecular cloud material. In this respect, CN is probably the best candidate to measure field strengths in star forming cores with densities in the range 10^5–10^6 cm^{-3}.

Field strengths measured by Zeeman effect in HI and OH are of the order of a few times 10 μG up to $\sim$ 10^2 μG (Bourke et al. 2001; Crutcher et al. 2003), whereas CN observations indicate larger field intensities, up to 0.4–0.7 mG (Crutcher et al. 1999). In OH and H_2O masers the field is much stronger, about 10 mG and 10^2 mG, respectively (Fiebig & Güsten 1989; Güsten, Fiebig, & Uchida 1994). For comparison, the intensity of the local Galactic magnetic field is $\sim$ 5 μG (Troland & Heiles 1986).

Polarization of thermal dust emission, on the other hand, provides information about the direction of the component of the magnetic field in the plane of the sky. Thus, mapping the polarization at (sub)millimetre wavelengths is the most reliable mean of probing the magnetic field geometry in molecular clouds (Gonçalves, Galli, & Walmsley 2005). Polarization maps of molecular clouds and filaments associated with regions of star formation have revealed rather uniform patterns of magnetic field-lines (Ward-Thompson & Kirk 2000; Matthews, & Wilson 2002; Crutcher et al. 2003), indicating the presence of a dominating regular component of the field. High-resolution measurements of polarization recently obtained with sub-millimetre arrays (Girart, Rao, & Marrone 2006) indicate that the magnetic field on scales of $\sim$ 10^3 AU around young stellar objects has an evident "hourglass" morphology in agreement with the expectations of theoretical models of cloud collapse (see Fig.1).

Taken together, these observations imply that in the dense condensations within molecular clouds, the gravitational, thermal, and magnetic energy are roughly of the same order of magnitude (Myers & Goodman 1988). The magnetic field is therefore expected to play an important role in the evolution of local density enhancements.

3. Effects of magnetic fields on cloud collapse

The accumulation of matter into denser regions driven by gravity during the so-called ambipolar diffusion phase results in the formation of a flattened and centrally peaked core permeated by a hourglass-shaped magnetic field (Fiedler & Mouschovias 1992, 1993; Li & Shu 1996). An important effect of the field on the subsequent collapse dynamics is the strong non-radial Lorentz force resulting from the field configuration, that deflects infalling fluid elements toward the equatorial plane forming an inner non-equilibrium structure ("pseudo-disk") around the central protostar (Galli & Shu 1993a,b; Galli et al. 2006), see Fig. 2. In agreement with these results, Allen, Li, & Shu (2003) found that the infall on the central protostar proceeds at a constant rate, and magnetically supported, high density "pseudo-disks" form in the direction perpendicular to the initial magnetic field.

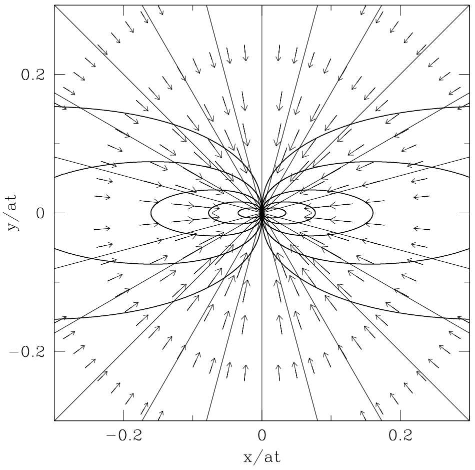

Fig. 2. Inner collapse solutions (valid asymptotically for small radii) showing the formation of the "pseudo-disk" and the accretion flow around the central protostar (Galli et al. 2006). The *heavy solid contours* in each panel are isodensity contours, the *thin solid lines* are the magnetic field lines (which coincide with the streamlines). The *arrows* show the velocity field at different radii.

3.1. Problems with field-freezing

Mass conservation (nr^3 = constant) and strict flux freezing (Br^2 = constant), valid if the collapse takes place on a time scale shorter than the ambipolar diffusion time scale, imply that the field strength increases as $B \propto n^{2/3}$ during the core collapse, but this scaling would lead to stellar magnetic field strength much in excess of those observed. This fact constitutes a fundamental problem for any theory of star formation: a $\sim 1\ M_\odot$ of interstellar material must reduce its magnetic flux by about 3–5 orders of magnitude to become a magnetic star, or by about 8 orders of magnitude to become an ordinary star like the Sun. This *magnetic flux problem* was already recognized by Mestel & Spitzer (1956).

There is little doubt that the the magnetic flux of a core cannot be totally incorporated into the newborn star, or the strength of the resulting stellar magnetic field would be of the order of $\sim 10^6$ G, in dramatic contrast with the measurements of ~ kG fields at the surface of T Tauri stars (Basri, Marcy, & Valenti 1992; Johns-Krull, Valenti, & Koresko 1999).[1] As already recognized by Mestel & Spitzer (1956), this is a fundamental problem for any theory of star formation.

3.2. Ohmic dissipation as a solution to the magnetic flux problem

Assuming quasi-steady state and a spatially uniform resisivity coefficient and quasi-steady state, Shu et al. (2006) showed that a solution of the magnetic flux problem of star formation outlined in the previous section was possible, and computed the resulting magnetic-field configuration when one adopts a kinematic approximation that ignores the back reaction of

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[1] Since the fields measured in T Tauri stars are probably generated by internal dynamo action, the discrepancy is even more severe than "merely" a factor of 10^4.

the changed magnetic topology on the flow to solve the induction equation.

The solution of the induction equation under this simplifying hypothesis can be obtained analytically. In this solution, the morphology of the magnetic field changes from almost radial at large distances to asymptotically straight and uniform in the innermost regions, where magnetic reconnection prevents the formation of a split monopole and its associated large electrical currents, a process first analyzed in this context by Mestel & Strittmatter (1967).

4. Rotation of molecular cloud cores

Besides magnetic fields, any realistic calculation of the collapse of a cloud should include the effects of rotation. In fact, small but detectable levels of rotation have been measured in the outer parts of molecular cloud cores (Goodman et al. 1993; Caselli et al. 2002), with typical values corresponding to a ratio of rotational to gravitational energy of $\sim$ 0.02. Although these velocity gradients are too small to contribute significantly to the support of cloud cores, the dynamical importance of rotation is expected to increase during the collapse of the core, leading ultimately to the formation of a centrifugally supported circumstellar disk around the accreting protostar (Terebey, Shu, & Cassen 1984). However, these observations show that the angular momentum of a typical cloud core is $\sim$ 1–2 orders of magnitude larger than that inferred for a typical protostellar disk, and about one order of magnitude larger than that of a wide binary of comparable mass with period $\sim 10^2$ yr (the *angular momentum problem*). Thus, about 90 to 99% of the angular momentum of a core of a given mass is lost when the same amount of material is transformed in a protostar surrounded by its circumstellar disk.

4.1. Magnetic braking as a solution to the angular momentum problem

An efficient mechanism for removing the angular momentum from a collapsing cloud is via transport along the magnetic field lines anchored in the ambient medium. If the direction of the magnetic field is parallel to the core's rotation axis, *magnetic braking* takes place on a time scale $t_{\rm braking}$ depending on the column density of the cloud and Alfvèn velocity in the ambient medium (Ebert, Hoerner, & Temesvary 1960; Mouschovias & Paleologou 1979, 1980). Physically, $t_{\rm braking}$ is the time taken by a torsional Alfvèn wave to cross a region with a momentum of inertia equal to that of the collapsing core.

This mechanism of magnetic braking, often invoked to explain the relatively low rotation rates of cloud cores, may also control the formation and radial extent of circumstellar disks if these are magnetically coupled to an external medium (Contopoulos, Ciolek, & Königl 1998; Krasnopolsky, & Königl 2002) or to the rest of the collapsing cloud (Allen, Shu, & Li 2003; Allen, Li, & Shu 2003). In this case, the magnetic torque associated with the field of the central protostar reduces the angular momentum of the accreting gas, constraining the azimuthal velocity to decrease as $r^{1/2}$ at small radii. Magnetic braking becomes dominant over angular momentum conservation when the infall velocity u_r becomes smaller than the local Alfvèn speed $v_{\rm A}$ inside the Alfvèn radius $r_{\rm A}$. Thus, magnetic braking during the collapse of an initially rotating and magnetized cloud, under field-freezing, is so strong as to make impossible the formation of centrifugally supported disks for realistic values of the initial magnetic field and rotation speed.

Clearly, the ubiquitous presence of circumstellar disks around young stars imply that the condition of field-freezing must be violated at some stage during the process of star formation. The same conclusion was reached in Sect. 3 on the basis of considerations of magnetic flux in cores and young stars.

5. Conclusions

The results summarized in this paper confirm and explain the trend emerging from several numerical simulations addressing the phase of collapse of molecular cloud cores with realistic values of rotation and magnetization: with field-freezing, magnetic braking prevents the formation of centrifugally supported disks and cloud fragmentation. Non-ideal MHD effects leading to field dissipation must occur prior or simultaneously to the formation of the disk, and need to be incorporated in realistic models. A spatially uniform resistivity (although higher in magnitude than the standard collisional value) can dissipate enough magnetic field so as to solve the magnetic flux problem satisfying the available observational constraints. However a complete understanding of the problem must await the solution of the full dynamic problem of magnetic field dissipation and formation of a centrifugally supported protoplanetary disk in a self-consistent way. The mean-field MHD model of a viscous-resistive accretion disks of Shu et al. (2007) represents a first important step in this direction.

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