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From Magnetized Cores to Protoplanetary Disks

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Abstract. We highlight several recent theoretical results that show how magnetic fields, with the magnitudes currently observed in molecular clouds, affect the structure and evolution of dense cores and protoplanetary disks to form stars and planets.

Keywords. magnetic fields, stars: formation, accretion: accretion disks

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1. Introduction

Magnetic fields have been observed in molecular clouds with strengths large enough to give support against gravity. The relevant parameter is the mass-to-flux ratio, $\lambda = 2\pi G^{1/2} M/\Phi$, where G is the gravitational constant, M is the mass of the cloud, and Φ is the magnetic flux that permeates the cloud; $\lambda > 1$ is required for stability. Observations of magnetic fields at different gas densities show $-0.5 < \log(\lambda) < 0.5$ (e.g., Zeeman OH measurements, Troland & Crutcher 2008; CN measurements, Falgarone *et al.* 2008). Recently, beautiful high resolution submillimeter dust polarization maps obtained with the SMA show the hourglass shape predicted by models of magnetic fields dragged in during the gravitational collapse, both in the low mass source NGC1333 IRAS 4 (Girart *et al.* 2006), and in the massive star forming regions G31.41+0.31 (Girart *et al.* 2009) and W51 (Tang *et al.* 2009). In G31.41+0.31 there is also evidence of magnetic braking by a strong magnetic field. In W51, the polarization maps obtained with BIMA show a uniform, large-scale magnetic field while the SMA map shows the small-scale dragged field in the individual sources e2 and e8. Recently, Crutcher *et al.* (2009) measured the core and envelope mass-to-flux ratio of 4 low-mass star forming clouds and did not find the increase of λ in the cores predicted by ambipolar diffusion models. It is important to note that their observations used the Arecibo and Green Bank telescopes which have very low angular resolution of several arc minutes. In contrast, the dust polarization SMA observations mentioned above probe scales of hundreds to thousands of AU (angular scales of arc seconds) and find the predicted behavior.

2. Gravitational Collapse and Magnetic Field Dissipation

Ideal MHD models of the gravitational collapse of magnetized rotating clouds show that the magnetic field tends to acquire a “split monopole” geometry, with $B \sim a^3 t/(G^{1/2} r^2)$, where a is the sound speed and r is the radial coordinate (Galli *et al.* 2006). The magnetic field trapped in the central star becomes so large that it brakes the rotating infalling material such that the azimuthal velocity goes to to zero at the origin, i.e., no centrifugally supported disk is formed. This behavior was found in numerical models by Allen *et al.* (2003). Recent numerical simulations of Hennebelle & Fromang (2007) and Mellon & Li (2008) showed that centrifugal disks can only be formed in ideal MHD conditions for $\lambda > 20 - 80$. Since $\lambda < 4$ is observed in molecular clouds, field dissipation is a prerequisite for disk formation. Moreover, stars have $\lambda_* \sim 10^3 - 10^4$, thus, the magnetic field has to be dissipated by even larger amounts to form stars, which is the classical flux problem. Nevertheless, at densities $n > 10^9$ cm^{-3}, Ohmic dissipation is efficient. Shu *et al.* (2006) showed that the process of Ohmic dissipation occurs at scales of ten’s of AU, i.e., disk size scales, and that enough flux can be lost during the gravitational collapse phase to form stars. Recently, Gonçalves *et al.* (2008) successfully applied this model to the submillimeter dust polarized emission from the low mass protostar NGC1333 IRAS 4A.

3. Magnetized Protoplanetary Disks

When an accretion disk forms during the gravitational collapse phase it will drag the magnetic field from the parent core. The disk will evolve subject to two diffusive processes: viscosity, ν, due to turbulent and magnetic stresses, that produces accretion towards the star and transfer of angular momentum outside, and resistivity, η, due to microscopic collisions and the magnetorotational instability (MRI), which allows matter to slip across field lines. Shu *et al.* (2007) studied the structure of steady state models of magnetized disks and found that their masses, sizes and magnetic field strengths are consistent with observations of disks around young stars. In these disks, the dragging of field lines by accretion is balanced by the outward field diffusion only if the ratio $\eta/\nu \sim A \ll 1$, where A is the disk aspect ratio. Moreover, the magnetic tension due to a poloidal magnetic field threading the disk will produce subkeplerian rotation. Subkeplerian rotation poses a problem to launch disk winds: they either have to be warm to overcome the potential barrier or they need a dynamically fast diffusion across the magnetic field lines. Nevertheless, such a large diffusion also produces sonic accretion speeds which imply too short a lifetime for the disks, less than 5000 yr (Shu *et al.* 2008). Another important effect of subkeplerian rotation in protoplanetary disks is that, at a given radius, an embedded protoplanet orbits with keplerian speed and thus, experiences a headwind from the slower gaseous disk. The resulting velocity mismatch results in energy loss from the orbit and inward migration (Adams et al. 2009). In particular, subkeplerian migration reduces the migration time and dominates over Type I migration for small planets (less than one Earth mass), and/or close orbits ($\lesssim 1$ AU).

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