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CAN MAGNETIC FIELDS SUPPORT MOLECULAR CLOUDS?

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RESUMEN

Las observaciones sugieren que los campos magnéticos juegan un papel dominante en la dinámica interna de los núcleos de nubes moleculares. Debido a que una parte importante del campo que atraviesa a los núcleos se debe perder antes de que estos puedan colapsarse para formar estrellas, se considera que el proceso de pérdida del campo magnético es un factor importante que controla la tasa de formación estelar.

En este trabajo presentamos modelos detallados del proceso de pérdida del campo magnético. Estos tienen implicaciones para la tasa global de pérdida del campo, para el origen de los movimientos aleatorios observado dentro de los núcleos y para el tratamiento de la difusión ambipolar en simulaciones numéricas.

ABSTRACT

Observations suggest that magnetic fields play a dominant role in the internal dynamics of molecular cloud cores. As much of the magnetic field threading the cores must be lost before they can collapse to form stars, field loss is thought to be an important factor in controlling the rate of star formation.

We present models of the detailed process of magnetic field loss. These have implications for the overall rate of field loss, the origin of the random motions observed within cloud cores and the treatment of ambipolar diffusion in numerical simulations.

Key Words: **DUST, EXTINCTION — INSTABILITIES — ISM: CLOUDS — ISM: KINEMATICS AND DYNAMICS — MHD**

1. INTRODUCTION

The simplest theoretical picture of quiescent star formation is that as the mass of a spherical core (or the external pressure) increases, it evolves through a series of quasi-equilibrium states. Eventually the Jeans limit is passed: internal pressure can no longer support the gas against the external forces and its own self-gravity, and it undergoes dynamical collapse to form a star.

This simple picture will be complicated by the effects of the angular momentum of the gas and magnetic fields. Angular momentum acts to prevent the gas collapsing to small radii, unless it can be removed. Magnetic fields can support to the gas, but can also help remove angular momentum by connecting the gas to its surroundings.

The observational data on magnetic field strengths of molecular clouds, on scales from hundredths of a parsec to tenths of a parsec, suggests several general features (see, e.g., Crutcher 1999 for a review). The observed line widths suggest motions in the range of 3–10 times the thermal sound speed, but comparable to the Alfvén speed $v_{\rm A} = B/(4\pi\rho)^{1/2}$ characteristic of MHD wave propagation. There is a weak tendency for the ratio of the line width to the Alfvén speed to increase with the ratio $M/\Phi_{\rm B}$ of cloud mass to magnetic flux: magnetic fields can prevent collapse until a critical value of this ratio is reached. Support by organized magnetic fields would seem more likely to lead to oblate structures threaded by magnetic fields through their short axes; however, polarimetric evidence (Ward-Thompson et al. 2000) confirms that the mean magnetic field is organised on the size scale of the whole core, but not at any special angle to the symmetry axes of the core, and observations suggest a preponderance of prolate cores (Curry 2002).

Mestel & Spitzer (1956) suggested that the magnetic field could be removed from the cloud core by ambipolar diffusion, in which neutral gas drifts under the influence of gravity through ionized material tied to the magnetic fields. Mouschovias (1976) and Nakano (1976) developed this model, realizing that the concentration of material at the centre of a molecular cloud could allow the gas to become locally supercritical on timescale shorter than that for the cloud as a whole. The ambipolar diffusion timescale was still long, but this was in reasonable agreement with the timescale derived from compar-

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ing the amount of molecular cloud material in the Galaxy with the inferred star formation rate.

This picture was developed in detail in a series of papers by Mouschovias and collaborators. For example, Fiedler & Mouschovias (1993) show the development of oblate, flattened cores in their MHD simulations. They find the typical lifetime of cores to be $\tau_{\rm ff}^2/\tau_{\rm ni} \simeq 10\tau_{\rm ff}$ (where $\tau_{\rm ff}$ is the cloud free-fall time and $\tau_{\rm ni}$ is the ion-neutral collision time), although Ciolek & Basu (2001) suggest that the effects of charged grains may decrease this somewhat.

These models do not address the origins of the observed broad turbulent line widths. While initial theoretical studies suggested that cushioning by magnetic fields could allow supersonic (but sub-Alfvénic) turbulence to be long-lived and contribute to the support of the clouds (Arons & Max 1975), simulations have shown that turbulence in MHD systems decreases to a velocity comparable to the sound speed in the neutral gas within a dynamical timescale (Mac Low et al. 1998, Stone et al. 1998, Padoan & Nordlund 1999).

This efficient damping when the magnetic pressure is significantly greater than the thermal pressure appears to result from the formation of dense knots by waves of non-linear amplitude (Falle & Hartquist 2002), a process which may also have a role in the initial formation of the dense cores. Indeed, it is now suggested that individual dense cores have a relatively short lifetime (Elmegreen 2000, Pringle et al. 2001). The large overall ratio of molecular gas mass to star formation rate results not from the long lifetimes of cores, but rather because both the fraction of gas in self-gravitating cores and the efficiency of the star-formation process from them are small.

2. LOCAL STABILITY STUDIES

When studies have been made of ambipolar flows, the neutral gas has generally been assumed to slip through the ions at a quasi-equilibrium rate, found by equating the differential force on the ionized and neutral fluids to the drag force between them. This seems like a reasonable assumption, as the timescale for dissipation of motions by interphase drag is generally very small compared to the global evolution timescales of interest.

We have recently investigated whether this assumption is valid (Tytarenko et al. 2002), prompted in this investigation by the analogy between ambipolar flows and fluidized beds. In the latter case, slip between two phases is known to cause phase separation, with bubbles of the suspension fluid separated by agglomerated 'slugs' of dense particles.

Analysing local stability for a model form of the equations of ambipolar flow, we found that unstable linear modes also existed in this case. These modes were found at resonances between the sound and shear waves in the neutral gas and the fast- and slow-mode waves in the ionized gas. They grow on a timescale comparable to the damping rate of waves passing through gas in which there is no ambipolar flow: *a rate which is so rapid that it was assumed the ambipolar flow could be considered quasi-static.*

Ambipolar flow is a particularly promising environment for the growth of these waves, as the low phase velocity of the slow-mode waves in directions perpendicular to the mean magnetic field means that slip at any rate in (essentially) any direction between the ionized and neutral phases is sufficient to find a resonance and drive an instability.

This conclusion can be made more intuitive, if one considers that the slip between the two phases constitutes a local source of free energy, much like the wind across the surface of water. In the latter case, this leads to the growth of ocean waves and the motion of sailing craft, in the former to the instabilities we describe.[4] These instabilities will likely have an important role to play in a variety of astrophysical circumstances, from the winds of late-type stars (Tytarenko et al. 2002) to the fine-scale structure of the interstellar medium (e.g., Price et al. 2001).

3. NUMERICAL SIMULATIONS

In the previous section, we have briefly described the analytic results of Tytarenko et al. (2002). This study left various questions unanswered, such as what the form of the flow is when the unstable modes reach non-linear amplitudes. To address these questions, we performed two-dimensional numerical simulations of the flow, including explicit time-dependent solvers for both the hydrodynamic flow of the neutral material and the MHD equations for the ionized material, together with differential forces on the phases and a Stokes-law drag between them. The simulations were performed on a uniform grid with periodic boundary conditions.

In the Figure, we show the state of the flow at two timesteps. The initial conditions for this simulation were given by the quasi-steady slip solution, with small random perturbations. In the first panel, the perturbations have grown to form nearly plane waves in a direction consistent with the resonance condition found in our linear analysis. At this time, the amplitude of the waves is growing exponentially.

[4] A loop of superconducting material might even function as an effective keel if one were to attempt to travel using an interstellar sail!

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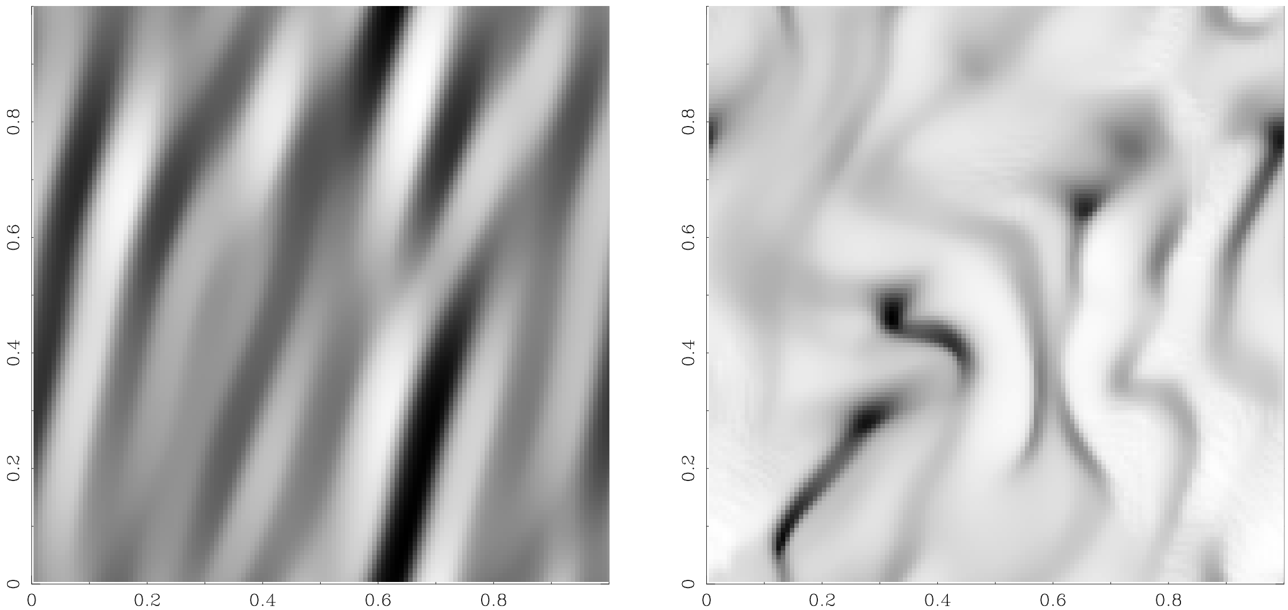

Fig. 1. Development of the MHD slip instability in a time-dependent code, showing the density in the ionized gas (dark regions, but the range is set by the range of values present). For the initial conditions, the slip between phases is in the vertical direction, perturbed by a small random noise. The left hand frame shows the development of the instability at 10 per cent amplitude, while the right hand frame shows a later time where the ions have been collected into small regions.

Eventually, however, the waves grow to nonlinear amplitude and begin to break, with ionized and neutral gas segregating into separate clumps. By this time, the mean flow of the phases through each other is at a far greater velocity than in the initial equilibrium. While the periodic boundary conditions on the grid ensure that the mean large-scale magnetic field is conserved, considerable small-scall structure has appeared.

4. CONCLUSIONS

We have shown that a local treatment of the structure of ambipolar flows naturally leads to properties of magnetically supported cores such as the large velocity dispersion observed on small-scales, and short cloud lifetimes. It remains to develop the simulations further, to include these local effects in a model of the gravitational collapse of a large-scale cloud with a more complete treatment of the properties of the gas.

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