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AMBIPOLAR RESISTIVITY AND THE FORMATION OF DENSE CORES

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RESUMEN

Las nubes moleculares están altamente estructuradas. Frecuentemente se asegura que gas altamente turbulento produce inhomogeneidades de alta densidad. Las simulaciones que siguen el comportamiento de una sola onda magnetosónica ciertamente muestran la generación de grandes contrastes de densidad que están asociados a ondas de modo lento. En estas simulaciones el fluido fue tratado como un plasma único ideal en el cual el gas está perfectamente acoplado con el campo magnético. Sin embargo, la baja fracción de ionización en las nubes moleculares implica que el gas y el campo magnético están débilmente acoplados y, por lo tanto, la resistividad ambipolar se vuelve importante. Usando simulaciones magnetohidrodinámicas de multifluidos con malla adaptiva examinamos el efecto de la resistividad ambipolar en la generación de perturbaciones de densidad. Nuestros resultados muestran que esto afecta ondas con longitudes de onda hasta dos órdenes de magnitud mayores que la escala de disipación, inhibiendo efectivamente la generación de estructuras densas. Esto impone un límite inferior al tamaño de los núcleos densos del orden de 0.1 pc.

ABSTRACT

Molecular clouds are highly structured. It is often asserted that highly turbulent gas produces the high-density inhomogeneities. Simulations following the behaviour of a single magnetosonic wave indeed showed the generation of large density contrasts which are associated with slow-mode waves. In these simulations the medium was treated as a single ideal plasma in which the gas is perfectly coupled with the magnetic field. However, the low ionisation fraction within molecular clouds implies that the gas and the magnetic field are actually weakly coupled and, thus, ambipolar resistivity becomes important. Using multifluid adaptive mesh magnetohydrodynamic simulations, we examine the effect of ambipolar resistivity on the generation of density perturbations. Our results show that it affects waves with wavelengths up to two orders of magnitude larger than the dissipation length scale, effectively inhibiting the generation of dense structures. This sets a lower limit on the size of dense cores of order 0.1 parsec.

Key Words: ISM: clouds — MHD — stars: formation

1. INTRODUCTION

Observations show that molecular clouds are highly structured and emission-line profiles of molecular traces such as CO and CS are considerably broader than their thermal line-widths indicating the presence of highly turbulent motions (e.g. Falgarone & Phillips 1990). As molecular clouds are threaded by magnetic fields, it is natural to suppose that these observed line-widths are due to magnetohydrodynamic waves (Arons & Max 1975). Large scale simulations of turbulent gas (e.g. Ballesteros-Paredes & Mac Low 2002) show that the presence of waves leads to dense cores formation. Furthermore, the analysis of Falle & Hartquist (2002) showed that dense cores are generated by the excitation of slow-mode waves.

All these simulations treat the gas as a single ideal plasma in which the gas is perfectly coupled with the magnetic field. However, the low ionisation fraction in molecular clouds implies that the gas and the magnetic field are actually weakly coupled. The drift of the charged particles through the neutral fluid gives rise to ambipolar diffusion (Mestel & Spitzer 1956). Lim et al. (2005) investigated in 1D the effect of ambipolar resistivity on the evolution of a single MHD wave. They found that ambipolar diffusion affects waves with wavelengths up to a thousand times the dissipation length and thus has a significant effect on much of the observed structure in star formation. We extend the Lim et al. model to 2D and discuss the relevance of these results.

2. NUMERICAL MODEL

A quiescent, uniform plasma in which the thermal to magnetic pressure ratio β is small is perturbed by a fast-mode wave. This adequately describes the

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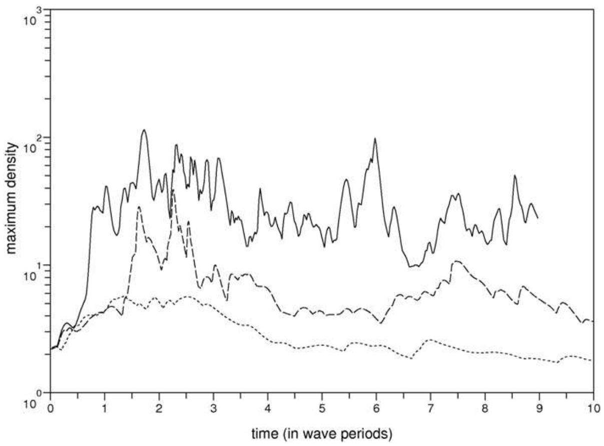

Fig. 1. Temporal evolution of the maximum density for $\lambda \approx 10^2 l_d$ (dotted), $\lambda \approx 10^3 l_d$ (dashed), $\lambda \approx 10^4 l_d$ (solid) with a wave-amplitude of 1.5 times the Alfvén speed.

formation of dense cores in a clump which is perturbed at its edge. We follow the evolution of the fast-mode wave using a 2D multifluid AMR MHD code.

The background plasma consisting of neutrals, ions and electrons has similar properties to a translucent clump of $A_V = 3$ and $n_H = 1000$ cm^{-3}. The ionisation fraction in such a clump is roughly 10^{-4} and decreases as the neutral density increases. We assume that the ionisation fraction follows a $1/n_H$ law.

The superposed fast-mode wave propagates in the positive x-direction at a small angle with the magnetic field. The wave front is phase shifted as a function of y to make the flow 2D. The wave-amplitude of the fast-mode wave is defined as the total velocity perturbation and is chosen to be sub-, trans- or super Alfvénic.

3. FORMATION OF DENSE CORES

Fast-mode waves with wavelengths larger than 1000 times the dissipation length l_d (=100 AU) are not affected by ambipolar diffusion (see Lim et al. 2005). Slow-mode waves are excited due to the non-linear steepening of the fast-mode wave or its interaction with denser regions. In regions with a low β, slow-mode waves are associated with large density perturbations. Fast-mode waves with wavelengths of the order of a clump size thus produce dense cores with $n_H \approx 10^4 - 10^5$ cm^{-3} (see Figure 1) and sizes of the order of 0.1 pc (see Figure 2) which are similar to observed ones.

Fast-mode waves with wavelengths up to 100 l_d are strongly affected by ambipolar diffusion. These

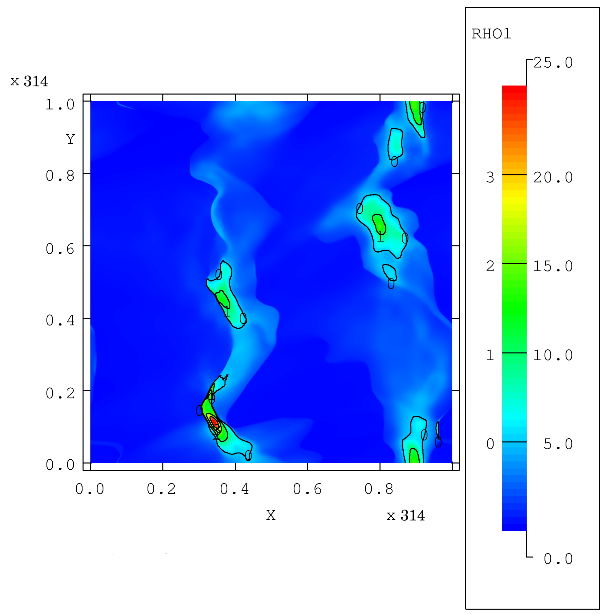

Fig. 2. The density structure after 3 wave periods for $\lambda \approx 10^4 l_d$ with a wave-amplitude of 1.5 times the Alfvén speed. (rho1 = 1 corresponds to $n_H = 1000$ cm^{-3}).

fast-mode waves do not produce large density enhancements (see Figure 1). This is because ambipolar diffusion causes rapid decay of both the fast-mode wave and the y-dependent contribution of the perturbation. The shock wave loses its energy within a few wave periods. Only if the y-dependent contribution of the initial perturbation is large enough to develop any significant variation in that direction, will cores with moderate density form. This requires the flow to be highly turbulent.

4. SUBSTRUCTURE IN CORE D OF TMC-1

The results for the formation of cores can also be used to explain the substructure in Core D of TMC-1. With a core density of $n_H \approx 6 \times 10^4$ cm^{-3}, a fractional ionisation $X_i \approx 10^{-6}$ (Caselli et al. 1998) and a magnetic field $B \approx 15$ μ G, l_d is about 10 AU which is considerably smaller than its 0.1 pc size. Then, waves with wavelengths up to 3 orders of magnitude larger than l_d can be present in the core. Such waves can easily generate large-density variations, even for sub-Alfvénic velocity perturbations. This fits well with the emission line observations of e.g. CS And CO Which show a non-thermal broadening that is not highly supersonic with respect to the sound speed in H_2 (e.g. Fuller & Myers 1992).

Most dense cores, however, have an ionisation fraction which is 1 to 2 orders of magnitude lower than in Core D of TMC-1. The dissipation length then increases by the same magnitude. This makes it unlikely that substructure can be produced in these cores.

5. FROM ALFVÉNIC TO SUBSONIC MOTIONS

Our results can also be used to qualitatively discuss the effect of ambipolar diffusion on the velocity structure. For typical clump properties the fast-mode and Alfvén waves with wavelengths corresponding to dense cores dissipate their energy quickly. Slow-mode waves, however, are not subject to dissipation (Balsara 1996). Thus, the velocity dispersion on small scales is dominated by the slow-mode waves while all types of waves contribute to the velocity dispersion at large scales. By examining the eigenvectors for the slow, fast and Alfvén waves in a low-β plasma, one can show that the velocity perturbation of a fast-mode wave with a moderate density perturbation is of the order of the Alfvén speed, whereas it is only of the order of the thermal sound speed for slow-mode waves. This agrees well with the observed transition from supersonic motions in molecular clouds to subsonic motions in dense cores (e.g. Myers 1983).

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