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# MHD IONIZATION FRONTS

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RESUMEN

Describimos los efectos de un campo magnético en la evolución de un frente de ionización (FI). La clasificación usual de FI se ramifica, con clases separadas de las soluciones tipo R y D en cada una de las velocidades críticas magnetosónicas. Esto es confirmado con cálculos de la estructura interna.

ABSTRACT

We describe the effect of magnetic fields threading the interstellar medium on an ionization front (IF) moving through it. The standard classification of IF breaks down, with separate classes of R- and D-type solutions appearing about each of the fast and slow magnetosonic critical speeds. Internal structure calculations confirm the results derived from evolutionary constraints.

*Key Words:* **HYDRODYNAMICS — ISM: HII REGIONS — MHD**

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## 1. INTRODUCTION

Massive young stars irradiate the gas which surrounds them, producing spectacular emission nebulae illustrated elsewhere in this volume. The gas is heated and ionized, and produces emission lines which are important diagnostics of its composition and kinematics.

Where the upstream neutral gas is unmagnetized, the dynamical effects of the sudden increase in gas pressure which results are reasonably well understood. If an ionizing radiation field turns on rapidly in neutral gas which is not too centrally concentrated, an IF at first moves out far faster than the sound speed in the ionized gas (the R-type phase). Eventually, the IF slows, and a shock is driven into the neutral gas leaving behind an IF which moves subsonically with respect to the upstream gas, and decreases the density of the gas which flows through it by a substantial factor (the D-type phase).

However, despite some significant early work (notably by Lasker 1966), the effects of the magnetic field in the upstream gas have often been neglected, even though the dynamically important magnetic fields are found in many molecular clouds (Crutcher 1999). In a series of papers (Redman et al. 1998; Williams, Dyson, & Hartquist 2000; Williams & Dyson 2001), we have been studying the nature of MHD IF: the jump conditions which determine the range of solutions which are possible for plane-parallel IF, and the internal structures of the fronts.

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## 2. JUMP CONDITIONS

Evolutionary constraints allow one to determine which solutions of the jump conditions across an IF correspond to physically realizable structures. Applied to hydrodynamical IF, these conditions isolate the classes of weak-R (supersonic to supersonic) and weak-D (subsonic to subsonic) solutions. They also allow the possibility of some strong-D solutions, in which the IF structure has an internal critical point.

In MHD, instead of a single critical speed (the sound speed), there are three: the slow and fast magnetosonic speeds, together with the Alfvén speed. We find (Williams et al. 2000) that the evolutionary conditions allow four classes of weak solution, which can be classified as fast-R, fast-D, slow-R and slow-D, depending on whether they increase (R) or decrease (D) the upstream density. At the boundary between fast-D and slow-R solutions, the flow remains at the Alfvén speed throughout the front and the density is constant.

## 3. INTERNAL STRUCTURES

The evolutionary conditions are necessary, but not sufficient, to prove that physically feasible internal structures exist. We have therefore studied the internal structures of MHD IF, using a simplified treatment of radiative transfer and internal energy terms, to find out whether the allowed regions corresponded to real solutions of the steady state equations (for full details, see Williams & Dyson 2001).

The boundaries of regions allowed by the evolutionary conditions are so-called critical solutions, for which the gas leaves at a critical speed. It is known from studies of hydrodynamical IF solutions that ‘overheating’ within the front can mean that

(a) (b)

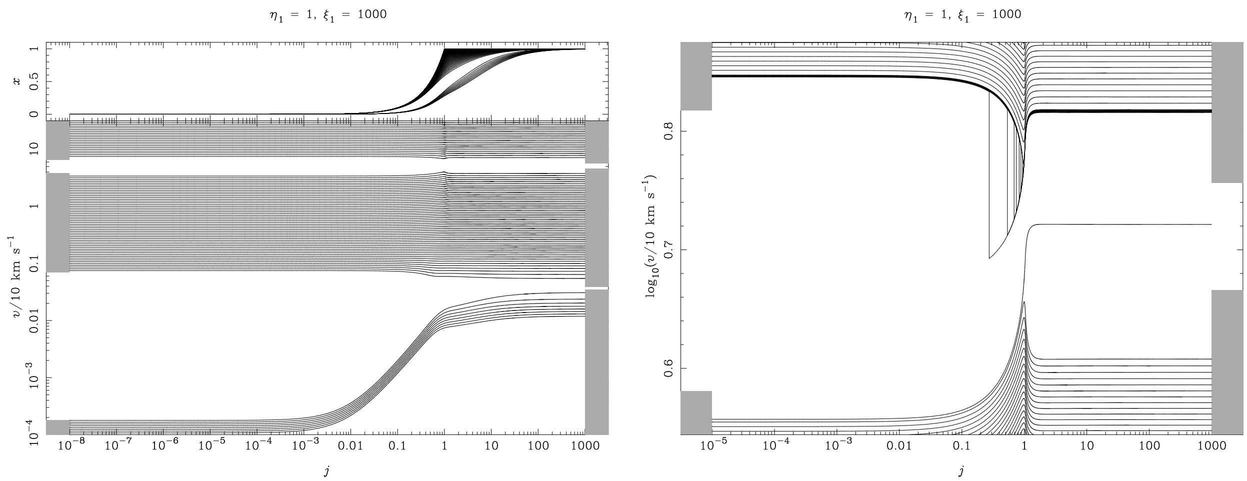


Fig. 1. Internal structures of MHD IF. (a) Overall view, showing all the classes. (b) Magnification of fast-critical region, showing strong-D solutions. The gray bars show the solutions allowed by the jump conditions: note that the strong-D solution forms a more restrictive limit than the jump conditions.

solutions close to criticality do not form in practice: instead, the upper boundary of the D-type solutions becomes a strong-D type solution which takes the flow to significantly supersonic speeds, while at the lower boundary of the R-type solutions, a range of cases appear which contain viscous subshocks.

In Figure 1, we show solutions for one choice of upstream flow parameters and varying IF velocity. These confirm our analysis of the jump conditions, as they all start within the gray regions of allowed upstream velocities. In Figure 1b, we magnify the fast-critical region. At the top of the fast-D solutions, a single fast-strong-D solution continues to accelerate, reaching large $j$ at a speed larger than the fast-mode speed. At the bottom of the fast-R solutions, a viscous subshock appears when the solution passes through the fast-mode speed, and moves upstream in the steady structure as the IF slows.

## 4. CONCLUSIONS

Magnetic fields with strengths comparable to those observed can have significant dynamical effects on the development of ionized nebulae. We have classified the range of solutions which are possible, and verified that these correspond to reasonable internal structures. In work in progress, we are modeling the photoevaporation of a magnetized core using a time-dependent MHD code to look at the effects that magnetic fields may have on observed examples, and to study the form of MHD IF in a less restricted geometry than discussed here.

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