MAGNETIC FIELD EFFECTS ON THE HEAD STRUCTURE OF PROTOstellAR JETS

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ABSTRACT

We present the results of three-dimensional smooth particle magnetohydrodynamics numerical simulations of supermagnetosonic, overdense, radiatively cooling jets. Together with a baseline nonmagnetic calculation, two initial magnetic configurations (in approximate equipartition with the gas) are considered: (1) a helical field and (2) a longitudinal field, both of which permeate both the jet and the ambient medium. We find that magnetic fields have important effects on the dynamics and structure of radiative cooling jets, especially at the head. The presence of a helical field suppresses the formation of the clumpy structure that is found to develop at the head of purely hydrodynamical jets by fragmentation of the cold shell of shocked material. On the other hand, a cooling jet embedded in a longitudinal magnetic field retains clumpy morphology at its head. This fragmented structure resembles the knotty pattern commonly observed in HH objects behind the bow shocks of protostellar jets. This suggests that a strong (equipartition) helical magnetic field configuration is ruled out at the jet head. Therefore, if strong magnetic fields are present, they are probably predominantly longitudinal in those regions. In both magnetic configurations, we find that the confining pressure of the cocoon is able to excite short-wavelength MHD Kelvin-Helmholtz pinch modes that drive low-amplitude internal shocks along the beam. These shocks are not strong however, and it is likely that they could only play a secondary role in the formation of the bright knots observed in protostellar jets.

Subject headings: ISM: jets and outflows — MHD — stars: mass loss — stars: pre–main-sequence

1. INTRODUCTION

While magnetic fields seem to play a fundamental role in the production and initial collimation of astrophysical jets (see, e.g., Königl & Ruden 1993; Shu et al. 1995), they have been neglected in most of the analytical and numerical modeling of the structure of protostellar jets because the inferred estimates of their magnitude \( B \sim 10^{-6} - 10^{-5} \) G suggest that they may be not dynamically important along the flow (see, e.g., Morse et al. 1993). However, after amplification by compression behind the shocks at the jet head, they may become relevant as they are carried backward with the shocked gas to fill the cocoon that envelopes the jet. Moreover, as the magnetized beam propagates through the surrounding medium (which is possibly also magnetized), it may be stretched or bent and the associated compression of the field lines may lead to significant changes in the beam dynamics and the jet head structure. A considerable amount of theoretical and numerical work on magnetized, adiabatic, light jets has been done to study the structure and evolution of extragalactic jets (see, e.g., Birkinshaw 1997 for a review). Most of that work has focused on the study of the stability properties of the beam against the development of the Kelvin-Helmholtz (K-H) instability at the contact discontinuity between the jet and the surrounding medium. Such studies indicate that adiabatic, supermagnetosonic jets are generally unstable to the K-H pinch and helical modes, which can successfully explain the formation of structures such as knots, wiggles, and filaments in those jets (see, e.g., Hardee et al. 1992). Lately, these MHD studies have been extended to heavy, adiabatic jets (Todo et al. 1993; Hardee & Clarke 1995; Hardee, Clarke, & Rosen 1997), but the general effects of \( B \) fields on the global evolution and morphology of radiatively cooling jets have not yet been explored in numerical studies.

In the limit of zero magnetic field, numerical simulations of radiatively cooling, heavy jets (i.e., denser than their surroundings)—a picture believed to be consistent with protostellar jets—have shown that thermal energy losses by the jet system have important effects on its dynamics (see, e.g., Blondin, Fryxell, & Königl 1990, hereafter BFK). This early work was extended to three-dimensional simulations in a series of papers (Stone & Norman 1993a, 1993b; de Gouveia Dal Pino & Benz 1993, hereafter GB93; de Gouveia Dal Pino & Benz 1994; Chernin et al. 1994; de Gouveia Dal Pino, Birkinshaw, & Benz 1996; de Gouveia Dal Pino & Birkinshaw 1996, hereafter GB96). All these studies have revealed that the cooling jet develops a dense, cold shell of shocked material at the head that is violently fragmented into clumps by the Rayleigh-Taylor (R-T) instability. Moreover, BFK and GB93 have found that the development of K-H modes along the beam are inhibited by the presence of cooling. Recently, Hardee & Stone (1997) and Stone, Xu, & Hardee (1997) (see also Massaglia et al. 1992) have examined the dynamics of K-H unstable cooling jets. In the case of a supermagnetosonic jet with longitudinal magnetic field, the linear analysis of Hardee & Stone indicates that as long as it does not dominate the pressure, the magnetic field does not significantly impact the qualitative differences in K-H stability properties between adiabatic and cooling jets.

In the present work, we aim to extend these prior studies by examining the nonlinear effects of magnetic fields (close to equipartition with the gas) in the structure of radiatively cooling, heavy jets and by testing their importance on the dynamics of protostellar jets. A preliminary step in this direction was

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made in a previous work (de Gouveia Dal Pino & Cerqueira 1996). Here we mainly concentrate on the effects of the magnetic field in the jet head structure. In a forthcoming paper, we will explore the details of the magnetic field effects over the whole structure of the jet, covering an extensive range of parameters (Cerqueira & de Gouveia Dal Pino 1998, hereafter CG98). In § 2 the numerical method is briefly described, and in § 3 the results of the simulations are shown. The conclusions and the possible implications of our results to protostellar jets are addressed in § 4.

2. NUMERICAL METHOD, INITIAL AND BOUNDARY CONDITIONS

To simulate the jets in the presence of magnetic fields, we have employed the smooth particle magnetohydrodynamics (SPMHD) technique (for an overview of the method, see, e.g., Stellingwerf & Peterkin 1990; Meglicki 1995). We solve the MHD equations in the ideal approximation using a modified version of the three-dimensional SPH code previously employed by GB93 and GB96 in the investigation of the evolution of purely hydrodynamical (HD) jets. (A more detailed discussion with validation tests of the SPMHD will be presented in CG98.)

Our computational domain is a three-dimensional rectangular box filled with particles that are initially distributed in a cubic lattice array and that represent the ambient gas. The jet of radius \( R_j \) is continuously injected into the bottom of the box and propagates through the ambient medium up to a distance of \( x \approx 30R_j \). In the transverse directions (\( y \) and \( z \)) the box has dimensions \( \approx 24R_j \). We use outflow conditions for the box boundaries (see, e.g., GB96). The initial resolution, as defined by the initial smoothing length of the particle, is \( 0.4R_j \) and \( 0.2R_j \) in the ambient gas and the jet, respectively. The adiabatic index of the ambient medium and the jet was assumed to be \( \gamma = 5/3 \), and an ideal equation of state is used. The radiative cooling, due to collisional excitation and recombinations, is implicitly calculated using a time-independent cooling function for a gas of cosmic abundances cooling from \( T = 10^4 \) to \( 10^9 \) K (the cooling is set to zero for \( T < 10^4 \) K; see GB93).

We assume two different initial configurations for the magnetic field. In one case, we consider an initially constant longitudinal magnetic field permeating both the jet and the ambient medium \( B = (B_z, 0, 0) \). This kind of configuration is suggested by observations that some protostellar jets appear to be aligned with the main direction of the local interstellar magnetic field (see, e.g., Appenzeller 1989). The second geometry adopted here is a force-free helical magnetic field that also extends to the ambient medium and whose functional dependence is given by equations (19)–(21) of Todo et al. (1993). In these equations, the maximum strength of the magnetic field in the system corresponds to the magnitude of the longitudinal component of the field at the jet axis. The azimuthal component attains a maximum value \( (B_z = 0.39B_0) \) at \( \sim 3R_j \) (see CG98). The pitch angle at \( 1R_j \) is \( \sim 19^\circ \).

The parameters of the simulations were chosen to resemble the conditions found in protostellar jets. In order to compare with previous purely hydrodynamical simulations (see, e.g., GB96), we adopt a number density ratio between the jet and the ambient medium \( n_j/n_a = 3 \), \( n_j = 600 \) cm\(^{-3} \), an ambient Mach number \( M_a = v_j/c_s = 24 \) (where \( v_j \) is the jet velocity and \( c_s \) is the ambient sound speed), \( v_j = 398 \) km s\(^{-1} \), and \( R_j = 2 \times 10^{15} \) cm. In the MHD simulations, we assume an initial \( \beta_j = p_{\text{th}}/p_{\text{mag}} = 1 \) (the thermal to the magnetic pressure ratio at the jet axis), which corresponds to a maximum initial value \( B_0 \approx 83 \) \( \mu \)G. The corresponding initial Alfvén and magnetosonic jet Mach numbers are \( M_{A,j} = v_j/B_0 \approx 38 \) and \( M_{m,j} = v_j/(c_s^{2} + c_{\text{A}}^{2})^{1/2} \approx 28 \), respectively. (See CG98 for a wider range of parameters.)

3. RESULTS

Figure 1 (Plate L17) depicts the density in the midplane section of the head of three supermagnetosonic, radiatively cooling jets after they have propagated over a distance \( \approx 30R_j \) at \( t_{\text{front}} = 1.65 \) (where \( t_{\text{front}} = R_j/c_s \approx 38 \) yr). The top jet is purely hydrodynamical (HD) (\( \beta_j = \infty, M_{m,j} = 42 \)), the middle jet has an initial constant longitudinal magnetic field configuration (with \( \beta = 1, M_{m,j} = 28 \)), and the bottom jet has an initial helical magnetic field (with axial \( \beta = 1 \) and \( M_{m,j} = 28 \)). In the HD case, the ratio of the radiative cooling length in the postshock gas behind the bow shock to the jet radius is \( q_{\text{sh}} = d_{\text{cool,sh}}/R_j \approx 8 \) and the corresponding ratio behind the jet shock is \( q_{\text{sh}} \approx \eta^{-1}q_{\text{sh}} \approx 0.3 \) (GB93). These cooling length parameters imply that within the head of the jet, the ambient shocked gas is almost adiabatic, whereas the shocked jet material is subject to rapid radiative cooling. Similar initial conditions are obtained for the MHD cases. The time evolution of the corresponding velocity distribution is presented in Figure 2.

In the pure HD jet (Figs. 1 and 2, top), we can identify the same basic features seen in previous work (see, e.g., GB93). At the head of the jet, the working surface develops a cold dense shell with maximum density \( n_{\text{sh}}/n_a \approx 210 \) at \( t_{\text{front}} = 1.65 \) due to the cooling of the shock-heated jet material. This shell is responsible for most of the emission of the jet. It becomes R-T unstable (GB93) and breaks into clumps that spill into the cocoon. The density of the shell also undergoes oscillations with time which are caused by global thermal instabilities of the radiative shocks (see, e.g., Gaetz, Edgar, & Chevalier 1988; GB93).

The cold clumps seen in the HD jet also develop in the shell of the MHD jet with longitudinal field (Figs. 1 and 2, middle), but in this case they detach from the beam as they are expelled backward to the cocoon. The fragmentation of the shell is also accompanied by density oscillations (due to the global thermal instability) but with a maximum amplitude smaller than that of the HD jet (\( n_{\text{sh}}/n_a \approx 155 \), at \( t_{\text{front}} = 1.65 \)).

In the MHD jet with helical magnetic field (Figs. 1 and 2, bottom), a cold shell also develops initially at the jet head, but the toroidal component, which is initially less intense than the longitudinal component (by a factor \( \leq 2.5 \)), is amplified by compression in the shocks at the head (by a factor \( \approx 5 \)). This amplification reduces the density enhancement and increases the cooling length behind the jet shock. As a consequence, the shell tends to be stabilized against the R-T instability and the fragmentation and formation of clumps is thus inhibited (see also CG98). The dense shell with clumps seen in the pure HD jet (Fig. 1, top) is replaced in this helical field case by an elongated, narrow plug of low-density material (\( n_{\text{sh}}/n_a \approx 5 \)), which is pushed by magnetic forces toward the jet axis and is mixed with the beam material.

Figure 2 also shows the development of some pinching along both MHD jets. In the pure HD case, constriction occurs only close to the jet head where the beam is overconfined by the gas pressure of the cocoon. In the MHD jet with helical field, the toroidal component \( p_{\text{mag}} \) is amplified by compression in the shocks at the head, and advected back with the shocked jet.
material to the cocoon. The associated magnetic pressure \(\sim B^2/8\pi\) causes an increase in the total pressure of the cocoon, relative to the pure HD case. The increase in the total pressure and the inherent discreteness of the SPH code in the beam excites (the fastest growing) small-wavelength pinch modes of the K-H MHD instability (see, e.g., Birkinshaw 1997; Cohn 1983). These modes overconfining the beam and drive the approximately equally spaced internal shocks seen in the MHD jet with helical field at the positions \(x = -1R_j, 3R_j,\) and \(7R_j\) (Fig. 2, bottom). The fact that both the gas pressure and the magnetic pressure in the cocoon have approximately the same magnitude, and that the toroidal magnetic field exceeds the longitudinal component, suggests that the unstable modes are driven by both magnetic field effects and the velocity discontinuity at the interface between the jet and the cocoon. It is interesting to note that the numerical study of Todo et al. (1993) employed a similar helical field geometry. In that case, however, the collision of the jet with the ambient cloud led to an MHD kink instability that is not seen in our simulations.

Along the MHD jet with longitudinal field (Fig. 2, middle), the increase in the total confining pressure of the cocoon also drives the development of K-H MHD instabilities, which produce the beam pinching and internal shocks seen in the figure. Consistent with the linear theory for K-H modes in the supermagnetosonic regime, they begin to appear at a distance \(\approx M_{\infty} R_j\). As expected, this destabilization length is smaller than that for the pure HD jet. Also, we found a close correlation between the pinching zones and the appearance of more intense reversed magnetic fields at the contact discontinuity between the jet and the cocoon. The originally uniform longitudinal

![Diagram of midplane velocity field distribution evolution of the head region of the jets of Fig. 1: hydrodynamical jet (top); MHD jet with longitudinal magnetic field (middle); and MHD jet with helical magnetic field (bottom). The initial parameters are the same as in Fig. 1. The times and the jet head positions are \(t/t_j = 1.40\) and \(x = 25R_j\) (left); \(t/t_j = 1.60\) and \(x = 29R_j\) (middle); \(t/t_j = 1.65\) and \(x = 30R_j\) (right).](image)
fields are reoriented in the nonparallel shocks at the head and swept back into the cocoon. As a consequence, a predominantly toroidal current density distribution develops around the jet radius \( \mathbf{J} = J_z \). Such configuration creates a \( \mathbf{J} \times \mathbf{B} \) force \( \sim -J_z B_z \) that constricts the beam (this is analyzed in detail in CG98).

4. DISCUSSION AND CONCLUSIONS

We have presented the results of fully three-dimensional simulations of supermagnetosonic, overdense, radiatively cooling jets with two different initial magnetic field configurations (with magnitude in close equipartition with the gas). Our results indicate that magnetic fields can have significant effects on the morphology and dynamics of radiatively cooling jets, particularly at the head structure.

As in previous adiabatic MHD calculations (Todo et al. 1993; Frank et al. 1997), the helical field in the cooling jet is amplified and reoriented by the shocks at the head. This reduces the postshock compressibility and thus increases the postshock cooling length relative to the pure hydrodynamical (HD) jet. This stabilizes the shell at the head against the R-T instability. As a result, the clumps that develop by fragmentation of the dense shell at the head of the HD jet do not appear in the helical magnetic jet. Instead, the clumpy, dense shell is replaced by an elongated plug of low-density material that is pushed to the jet axis by the development of \( \mathbf{J} \times \mathbf{B} \) forces. This structure resembles the nose cone seen in previous adiabatic simulations of strongly magnetized jets with toroidal fields (see, e.g., Clarke, Norman, & Burns 1986; Kössl, Müller, & Hillebrandt 1990). On the other hand, a cooling jet embedded in a longitudinal magnetic field retains the clumps seen at the head of the HD jet. The fact that the fragmented, clumpy shell resembles the knotty structure often observed in Herbig-Haro objects behind the bow shocks of protostellar jets (e.g., HH 1, HH 2, HH 19, HH 12, HH 95, HH 45, HH 47D—Herbig & Jones 1981; Brugel et al. 1985; Reipurth 1989; Heathcote et al. 1996) suggests that a strong helical magnetic field geometry is unlikely in these jets. If the jet is permeated by strong magnetic fields, these are probably predominantly longitudinal, at least in the outer regions of the jet far from the driving source.

Over the simulated time and length scales, in both initial magnetic field configurations but not in the HD run, approximately equally spaced internal shock are produced by K-H MHD reflection modes. These shocks propagate forward with velocities similar to that of the head of the jet (\( v_h \approx 250 \, \text{km} \, \text{s}^{-1} \)). The mean distance between the internal shocks \( \approx 3R_j \) is in agreement with the observed jet knots. However, the weakness of these shocks \( (n_s/\langle n_s \rangle \lesssim 10) \) makes it doubtful that they could produce by themselves knots as bright as those observed in protostellar jets.

Finally, we note that the beam pinching seen in the MHD cooling jets discussed here is also found in adiabatic jets with similar initial conditions (see CG98). Their strength is, however, larger in the adiabatic case. This result is consistent with previous numerical analyses comparing pure HD jets with and without cooling (see, e.g., BFK; GB93), which have indicated that the presence of radiative cooling tends to reduce the strength and the number of internal shocks in the jets. This result is also compatible with the predictions of the linear stability theory (Hardee & Stone 1997) when applied in the context of the cooling function employed in the present work.

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Fig. 1.—Color-scale representation of the midplane density of the head of a hydrodynamical jet (top), an MHD jet with initial longitudinal magnetic field configuration (middle), and an MHD jet with initial helical magnetic field configuration (bottom), at a time $t/t_d = 1.65$ ($t_d = R/c_s \approx 38$ yr). The initial conditions are $\eta = n_z/n_s = 3, n_s = 200 \text{ cm}^{-3}, M_s = 24, v_i \approx 398 \text{ km s}^{-1}, q_{\eta} \approx 8$, and $q_{\mu} \approx 0.3$ The initial $\beta = 8\pi \rho B^2$ for the MHD cases is $\beta \approx 1$. The color scale (from minimum to maximum) is given by black, grey, white, orange, yellow, and blue. The maximum density reached by the shell at the head of the jets is $n_z/n_s \approx 210$ (top), $n_z/n_s \approx 153$ (middle), and $n_z/n_s \approx 160$ (bottom).

Cerqueira et al. (see 489, L186)