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MAGNETIZED ASTROPHYSICAL OUTFLOWS: CRADLE TO GRAVE, SOURCE TO EFFECT

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RESUMEN

Analizamos la propagación de jets y otros flujos MHD radiativos enfatizando los flujos impulsados por rotores magneto-centrífugos. Nuestro objetivo es ligar las propiedades de los jets con la física de la fuente que los produce. Encontramos que la estratificación de la densidad y del campo magnético (con el radio) en jets de rotores magnéticos lleva a un comportamiento nuevo, que incluye el desarrollo de un núcleo denso del jet y una envoltura de baja densidad. Reportamos también estudios más generales sobre difusión ambipolar y geometría de campos en jets pulsados. Finalmente, describimos un nuevo trabajo diseñado para el estudio de los efectos de vientos magnetizados sobre el ambiente circunestelar apropiado para YSOs (siglas en inglés: Young Stellar Object; Objetos Estelares Jóvenes) y PNe (siglas en inglés: Planetary Nebulae; Nebulosas Planetarias).

ABSTRACT

We discuss the propagation of radiative MHD jets and outflows focusing on outflows driven by magneto-centrifugal rotators. Our goal is to link the properties of the jets with the physics of the sources which produce them. We find that density and magnetic field stratification (with radius) in jets from magnetized rotators leads to new behavior including the development of a dense inner jet core and a low density collar. We also report on more general studies of ambipolar diffusion and field geometry in pulsed jets. Finally we describe a new work designed to study the effects of magnetized winds on circumstellar environments appropriate to YSOs and PNe.

Key Words: **ISM: JETS AND OUTFLOWS — MAGNETOHYDRODYNAMICS — PLANETARY NEBULAE — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

Hypersonic collimated flows (jets) are a ubiquitous phenomena in astrophysics occurring in wide variety of environments including young stars (YSOs) (Reipurth 1997) and evolved stars (PNe) (Soker & Livio 1994). In almost all cases magnetic fields are expected to play a key role in launching and collimating these outflows. In particular, magneto-centrifugal processes associated with magnetized, rotating stars (Bogovalov & Tsinganos 1999) and/or accretion disks (Pudritz 1991) are believed to lift material out of the gravitational well and provide at least some confinement, shaping the wind into a jet. There has been considerable effort in the study of collimated outflows over the last two decades both in terms of jet simulations and the study of magneto-centrifugal launching. Unfortunately, direct links between the observable jets (scales of $> 10^{15}$ cm) and the collimation processes (scales of $< 10^{13}$ cm) have yet to be established. Indeed, until recently the majority of jet propagation simulations have been purely hydrodynamic. Thus the role magnetic fields play in establishing the properties and behavior of radiative jets (appropriate to YSOs and PNe) remains an open issue. In addition, establishing links between the near-field (close to the star) magneto-centrifugal processes and the far-field jet behavior which can be readily observed must also be established.

In this contribution we describe the MHD behavior in radiative jets and outflows. The goal of our studies is to articulate how magnetic fields effect radiative jet/outflow behavior and to provide links between magneto-centrifugal processes occurring at the source with observable properties of the jets and outflows.

2. JET STRUCTURE AND THE PROBLEM OF INITIAL CONDITIONS

Magnetic fields imposed on the flow during the launching process may bleed out the beam by *ambipolar diffusion* (where ions and the field slip past neutrals. Frank et al. (1999) have shown that the ambipolar diffusion timescale in YSO jets can be written as

$$t_{\rm ad} \approx 10^4 \left(\frac{n_{\rm j}}{10^3~{\rm cm}^{-3}}\right)\left(\frac{R_{\rm j}}{10^{15}~{\rm cm}}\right)^2\left(\frac{10^4~{\rm K}}{T_{\rm j}}\right) Q(\beta)$$

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where β is the ratio of gas to magnetic pressure, $Q(\beta) = \beta/(\beta+1)$, and $n_{\rm j}$ refers to the neutral fraction in the jet beam. Since the largest scale YSO jets have dynamical times of order a few 10^4 to 10^5 years (Reipurth 1997) our result shows that fields will remain in the beam for much of the jet's lifetime. The characteristic ambipolar diffusion timescale of 10^4 years is also suggestive. Its approximate equivalence with the age of parsec-scale jets may indicate that these structures remain intact as long as the collimating fields remain in the beam. This issue needs further study.

Establishing initial equilibria for MHD jet simulations is non-trivial. This is not the case for hydrodynamic jets where the required force balance across the jet and ambient medium interface allows for the use of so-called *top-hat* profiles (i.e., the hydro variables are constant across the jet cross section). Such distributions may not be tenable in MHD jet studies. The difficulty can be seen by decomposing the Lorentz force into a tension term and a pressure term. $\mathbf{F}_{\rm L} \propto -\nabla \mathbf{B}^2 + 2(\mathbf{B}\cdot\nabla)\mathbf{B}$. In a steady, cylindrically collimated jet only B_ϕ and B_z components of the field are possible. Jets with purely longitudinal fields, $B = B_z$, can be easily set in pressure balance with the environment and top-hat profiles may be used. Toroidal or helical field geometries require more complicated initial conditions unless the field is assumed to take on a force free configuration. If the field is not force free, MHD jets must have variable distributions of gas pressure and, perhaps, other variables in order to balance the *hoop stresses* associated with the tension force.

Faced with the problem of initial conditions researchers studying radiative MHD jets have, in general adopted one of two strategies: (i) use force-free fields (Cerqueira et al. 1998, 1999); (ii) use ad-hoc gas pressure and magnetic field distributions configured to be in initial force balance (Frank et al. 1999; Stone & Hardee 2000; O'Sullivan & Ray 2000). The results of these studies for both steady and time-variable (pulsing) jets reveal a number generic features:

• Jets with purely longitudinal B-field geometries do not show propagation characteristics which differ significantly from the hydrodynamic case (Cerqueira et al. 1998; Gardiner et al. 2000). The presence of poloidal fields does however allow for the possibility of field reversals at the head of the jet, which are likely to be unstable to reconnection (Gardiner et al. 2000). The transfer of magnetic energy into thermal energy at reconnection sites may alter the emitted spectrum away from that associated with shocks. Given the importance of shock diagnostics for interpretation of spectra the additional source of excitation provided by reconnection requires further study.

• Jets with a toroidal field component will be subject to strong hoop stresses especially in the region between the jet and bow shocks (Clarke, Norman, & Burns 1986; Frank et al. 1998). In 2.5-D axisymmetric calculations pinch forces associated with the toroidal fields lead to the development of streamlined, high field *nose-cones*. Recent simulations have shown such nose-cones may be unstable in 3-D (de Gouveia Dal Pino & Cerqueira 2002). While this result still needs further study, it may be correct for jets with top-hat density profiles. As we will show in the next section, more realistic initial conditions for jets from magneto-centrifugal rotators may not have unstable nose-cones.

While the studies discussed above have yielded significant progress in our understanding of heavy, radiative MHD jet behavior, the initial conditions are still unconnected to the processes believed to create the jets. We turn to this issue in the next section.

3. JETS FROM KEPLERIAN ROTATORS

Recently we have simulated jets whose initial conditions are taken directly from a (simplified) model of the magneto-centrifugal launching/collimation process. The model, known as the *Given Geometry Method* (GGM) allows asymptotic MHD jet equilibria to be linked to the properties of a rotating source (Lery et al. 1999; Lery & Frank 2000). The GGM assumes a time-independent, axisymmetric flow. It further simplifies the problem of magneto-centrifugal launching/collimation by assuming that the nested magnetic flux surfaces defining the flow possess a shape which is known a priori inside the fast critical surface (the locus of points beyond which the flow is kinetic energy dominated). The flux surfaces are assumed to be conical and, as an additional simplification, an equilibrium across the surfaces is assumed at the Alfvén point. The final asymptotic solution for the collimated jet is solved by assuming pressure balance with the ambient medium.

In terms of dynamics, The most important properties of the jets derived via the GGM are the radial variations in the density $\rho(r)$ and the toroidal component of the magnetic field $B_\phi(r)$. In particular, when the source is composed of a rapidly rotating disk truncated some distance from a rigidly rotating star, the emitted jets can have strong density stratifications, i.e. a high density axial *core* surrounded by a lower density *collar*. The strongest toroidal field is located at the boundary of the core and collar creating a magnetically confined jet-within-a-jet structure. Note that the bulk of the jet's momentum resides in the core. Hence we expect this portion of the beam to penetrate more easily into the ambient medium during the jet's propagation while the collar will be more strongly decelerated.

Figure 1 (top) shows a frame from a jet simulation with a high core to collar density ratio (~ 100, see Frank et al. (2000)). As expected, the jet core propagates faster through the grid then the outer collar. In these simulations, (which do not include radiative losses), the collar is diverted by shocks at the initial head of the jet. The collar peels away as the jet propagates down the grid. A distinct nose-cone forms at the head of the jet core due to its strong confining toroidal magnetic field. Nose-cones associated with this high density core may not be unstable. Also of particular interest are the apparent pinch mode ($m = 0$) instabilities seen in the core. A stability analysis of the initial conditions effectively predicts the wavelength of these modes ($\lambda = 0.3R_{\rm j}$) and suggests these they are current driven rather hydrodynamic Kelvin-Helmholtz instabilities.

Since many jets are seen to be episodic we can also use the GGM method to derived a sequence of jet solutions appropriate to a time variable flow. Figure 1 (bottom) shows the density in a radiative pulsed jet simulation (Gardiner, Frank, & Lery 2002) from a Keplerian rotator. Here again we see the core/collar structure which now persists in the internal working surfaces. The collar is not seen to peel away from the core in these models, a result which may be due to the pulsing or to the lower core to collar density ratio obtained from the GGM model in this case. The eventual goal of these studies will be to model jets emitted by sources undergoing some form of FU Ori type outburst and hence connect the properties of variable jets to theoretical models of variations at the source.

4. THE MAGNETIC GEOMETRY OF PULSED JETS

The most general magnetic geometry for cylindrically collimated jets is a helical field. Indeed, this is the geometry which is to be expected from magneto-centrifugal launching. Since many jets are observed to episodic, it is of interest to understand how variations in the flow at the source will effect the subsequent downstream field geometry of the jets. In Gardiner & Frank (2001a) a simple, universal relation was derived for the field configuration which would evolve in a helically-magnetized, pulsed jet.

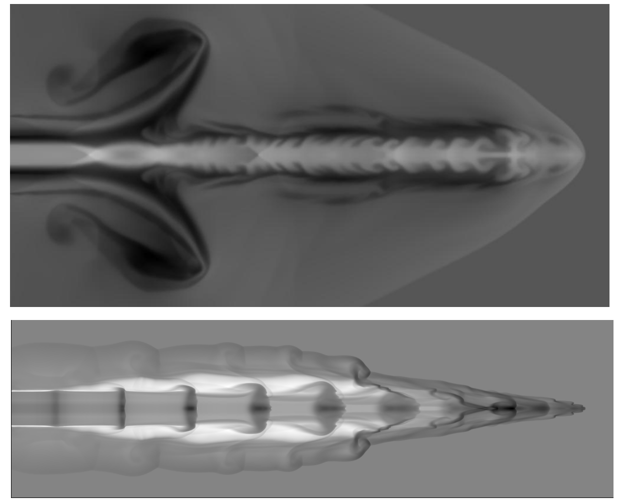

Fig. 1. Top: Grey-scale map of the density in steady jet calculation from a disk+star rotator (see Frank et al. 2000 for details). Bottom: Pulsed jet simulation. Initial conditions derived from a sequence of GGM Keplerian rotator models (Gardiner, Frank, & Lery 2002).

Consideration of the governing flow equations reveals that the toroidal field component B_ϕ will evolve in manner similar to the gas density. Thus, downstream compressions produced by internal working surfaces will also lead to compression in the toroidal field. Likewise, regions of gas rarefactions will also become regions of weak toroidal field. Gardiner & Frank (2001a) derived an expression for the ratio of the toroidal to poloidal field components at a time t based on a Burger's equation analysis,

$$\frac{B_\phi}{B_z} = \frac{B_{\phi,0}}{B_z}\left(\frac{1}{1-k(t-t_0)}\right),$$

where t_0 is the time when the gas parcel was ejected and k is the ratio of the derivative of the jet ejection velocity at t_0 to the value of the velocity at that time: $k = v_{\rm j}'(t_0)/v_{\rm j}(t_0)$.

The relation above shows that pulsed helical jets will develop alternating regions of toroidal and poloidal domination in the beam. High density knots associated with the internal working surfaces will be toroidally dominated and the inter-knot rarefied regions will be poloidally dominated. Figure 2 shows a plot of B_ϕ at two different times from a pulsed jet simulation. The development of strong field regions is clearly seen as the pulses steepen into internal shocks.

5. MAGNETIZED WIND BLOWN BUBBLES:YSO AND PNE

In previous sections we discussed the behavior of fully collimated jets. In both YSOs and PNe, how-

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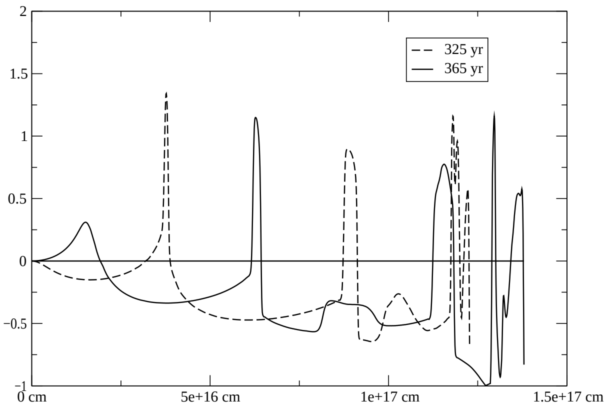

Fig. 2. $\log_{10}(B_\phi/B_{\phi,0})$ at two different times in a pulsed radiative MHD jet simulation with an initial helical field. For details see Gardiner & Frank (2001a).

ever, the outflows may include a significant *wide-angle* magnetized wind component. Numerous studies have shown that the pure hydrodynamical interaction of a wide-angle wind with an aspherical ambient density distribution can lead to highly collimated bipolar flows (Icke et al. 1992; Delamarter, Frank & Hartmann 2000). Since the environment surrounding both YSOs and PNe is expected to include an aspherically shaped density distribution, the additional effect of magnetic fields in shaping the outflows is of great interest.

A number of authors have explored a model whereby a weak toroidally magnetized wind is collimated by hoop stresses after passage through a wind shock (Chevalier & Luo 1994; García-Segura et al. 1999). This so-called *magnetized wind bubble* (MWB) model shows some promise in that highly collimated outflows can be obtained even when purely hydrodynamic flows would only yield rather wide bipolar lobes. Precession of the sources' magnetic axis also allows for point-symmetry, (observed in many PNe), to be imposed on the flows (Sahai 2000).

Recently however (Gardiner & Frank 2001b) have shown that the MWB fails to account for collimation which would occur *before* the wind is shocked. The toroidal field in the wind produces an unbalanced collimating force which can redirect the wind as it freely expands. Thus a proper treatment of this model must include the full history of the wind starting close to the source. It is also noteworthy that the MWB model is consistent with a wind accelerated by some means other than magneto-centrifugal launching.

Figure 3 shows a simulation of a magnetized wind blown bubble appropriate to YSOs (Gardiner, Frank & Hartmann 2002). In this model a *pre-collimated* wind with a pole to equator density ratio of 10 is driven into a collapsing sheet-like environment. The initial conditions capture many of the salient properties of magneto-centrifugal flows such as the X-wind (Shu et al. 1994; Matzner & McKee 1999). The figure shows a strongly collimated flow, including a jet, forming along the axis. Note that though the flow begins with a strong axial condensation it is not visible until after the wind passes through the shock. As

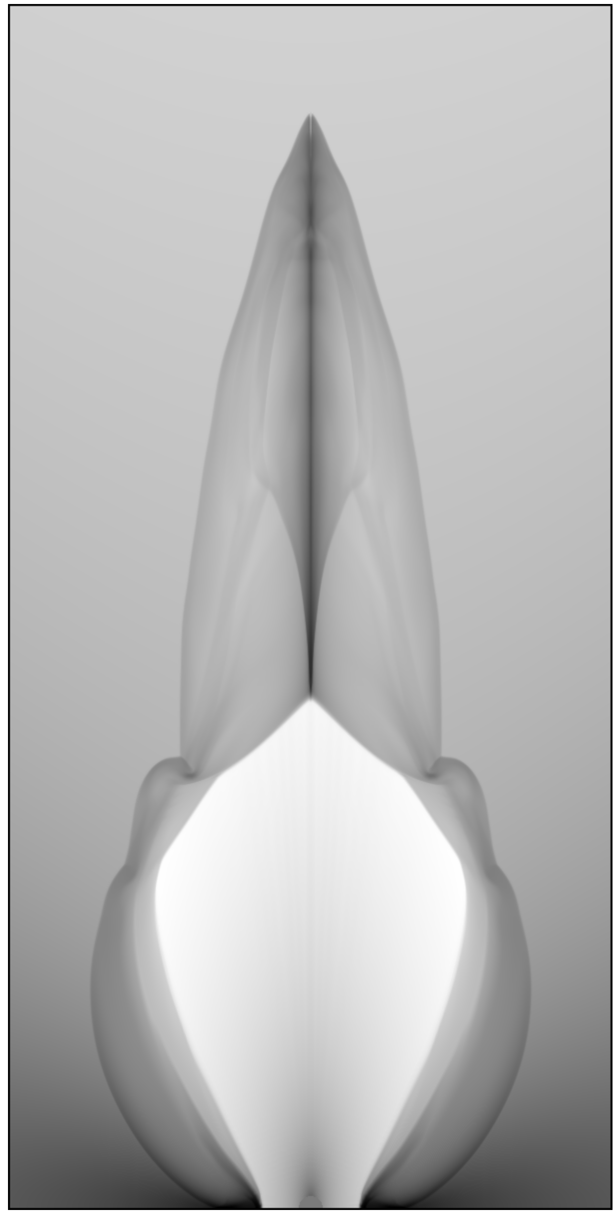

Fig. 3. Simulation of MWB model in a collapsing environment appropriate to YSOs. The simulation begins with a wind with properties similar to those from magneto-centrifugal flows.

with previous studies of the MWB model this occurs due to strengthening of hoop stresses associated with the toroidal field after the wind has been shocked.

6. CONCLUSIONS

Magnetic fields offer a theoretically attractive means for producing and shaping much of the outflow behavior observed in both young and evolved stars. An obvious impediment to the development of magnetic models rests in the unfortunate reality that the fields themselves are, in most cases, unobservable with current techniques. Thus the presence and effect of the these important players on the stage of stellar evolution must be inferred by other means. Currently it is not clear if YSO jets, the structures most likely associated with stellar or disk magnetic fields, show any behaviors, such as nose-cones, which can be clearly linked to the presence of magnetic stresses. It would be an ironic situation indeed if the most favored model of jet launching and collimation leaves us with no signature with which to confirm its veracity.

It is still too early to know if simulation studies can provide proxy links between outflows and magnetic fields. We believe, however, that the use of initial conditions which come directly from MHD launching and collimation models should provide the quickest route to a final answer.

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