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## MAGNETIC COLLIMATION OF PROTOSTELLAR WINDS INTO BIPOLAR OUTFLOWS

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**Abstract:** We describe self-consistent 2-D MHD simulations of the collimation of an isotropic protostellar wind into bipolar outflows by magnetic stresses in the ambient medium. A variety of ambient field strengths, wind luminosities, and density profiles have been studied. Collimation occurs when the energy of the magnetic field swept up by the expanding bubble approaches the bubble thermal energy. Measured axial and radial expansion rates are in good agreement with the analytical predictions of Königl (1982).

**Introduction:** Energetic mass ejection, frequently in the form of bipolar outflows, is now a well-established characteristic of low-to-intermediate mass star formation in our Galaxy (Lada 1985). The collimating mechanism for these outflows is uncertain, however, as is the physical relationship between the high-velocity molecular lobes, ionized jets, Herbig-Haro objects, water masers, etc. One possibility suggested by Königl (1982) which we explore here is that an isotropic protostellar wind may be collimated into bipolar outflows by a strong magnetic field which threads the ambient molecular cloud. This mechanism is attractive due to the good correlation between observed molecular outflow axes and magnetic axes inferred from optical polarization measurements of background stars (e.g., Vrba, Strom and Strom 1976).

**Simulations:** Here we solve the time-dependent equations of ideal MHD in axisymmetric, cylindrical (RZ) geometry for an unmagnetized, isotropic wind inflating a cavity within a magnetized external medium. In this preliminary study, radiative cooling is not included, hence both media are assumed adiabatic with  $\gamma=5/3$ . The ambient magnetic field is taken to be uniform with strength  $B_0$  parallel to the Z axis. The ambient gas is isothermal with sound speed  $C_0$  and plane-stratified according to  $\rho(Z)=\rho_0/[1+(Z/a)^2]^{m/2}$ ,  $0 \leq m \leq 2$ , where  $a$  is the core radius. The stellar wind is modeled by continuously adding mass into a small spherical source region with internal energy  $\epsilon_w=C_0^2/\eta$ , with  $\eta=.01$  and at a rate such that the desired mechanical luminosity is produced. The initial source region excludes magnetic flux. Because of the adiabatic assumption, the simulations are parameterized by two dimensionless ratios involving the ambient conditions and the source radius  $r_0$ :  $\beta=(\rho_0 C_0^2/\gamma)/(B_0^2/8\pi)$  -- the plasma parameter, and  $L=\dot{m}_w \epsilon_w/(4\pi \rho_0 V_{ms}^3 r_0^2)$ , where  $V_{ms}=(C_0^2+B_0^2/4\pi\rho_0)^{1/2}$  is the magnetosonic speed.

The simulations were performed using the ZEUS-2D code developed by the authors, which incorporates the hydrodynamic algorithms described in Norman and Winkler (1986) as well as the CT method of Evans and Hawley (1988) for magnetic field evolution. ZEUS-2D is a time-explicit, Eulerian ideal MHD code which has been tested against a battery of problems including the 1-D magnetic Riemann problem of Brio and Wu (1988), a 1-D Weber-Davis (1967) wind solution, and the 2-D solar transient solution of Low (1984). Typically, a grid of 256x128 zones were used in these calculations.

**Results:** The effects of varying field strength and wind luminosity on collimation in a constant density medium ( $m=0$ ) were investigated in a series of runs having parameters  $(\beta, L)=(0.2, 1), (1, 1), (5, 1), (1, 0.1), (1, 10)$ . Magnetic collimation occurs in each case, producing a smooth-surfaced bubble elongated in the direction of the magnetic field with eccentricity increasing in time at a rate determined by  $\beta$  and  $L$ . Fig. 1 shows a case with parameters representative of observed bipolar outflows. The early expansion of the bubble is quasi-spherical and drives a shock wave into the surrounding gas. The shock propagates faster perpendicular to the magnetic field lines than along them because  $V_{ms} > C_0$  and soon becomes highly oblate. At later times, the shock is quasi-planar and advances parallel to the field lines with the tip of the bubble. Behind the shock, a dense cap of material is accumulated near the bubble apex. The wind density distribution inside the bubble is smooth, however the velocity field contains eddies.

The bubble eccentricity is found to increase linearly in time, in agreement with the analytical predictions of Königl (1982; cf. Appendix). Fig. 2 shows this result for three values of  $\beta$ . The linear behavior is due to the fact that at late times, the bubble elongates at a constant rate while maintaining a constant equatorial radius. This result is only true in uniform density ( $m=0$ ) clouds; for  $m>0$ , both the equatorial and axial radii obey separate expansion laws (Königl 1982):

$$Z_0(t) \propto t^{2/(2-m)}; \quad R_0(t) \propto t^{-m/(4-m)}; \quad (0 \leq m < 2).$$

We have confirmed these relations numerically for  $m=1$ , and have also computed the case  $m=2$ . In both cases, the bubble tip accelerates whereas the equatorial radius eventually decreases (cf. Fig. 3). Despite the reduced pressure at large  $Z$ , the bubble does not flare and "blow out" owing to the strong lateral magnetic confinement.

**Future prospects:** We have demonstrated that an ambient magnetic field is capable of collimating an isotropic protostellar wind into an elongated bubble resembling bipolar outflows. Future work will consider radiative cooling in the wind and cloud regions, and different magnetic field geometries. However, using the simplified assumptions of the present model, we are already able to obtain collimation ratios  $R_{coll}=Z_0/R_0$  well within the observed range of 2-4 for majority of highly-collimated flows (Lada 1985).

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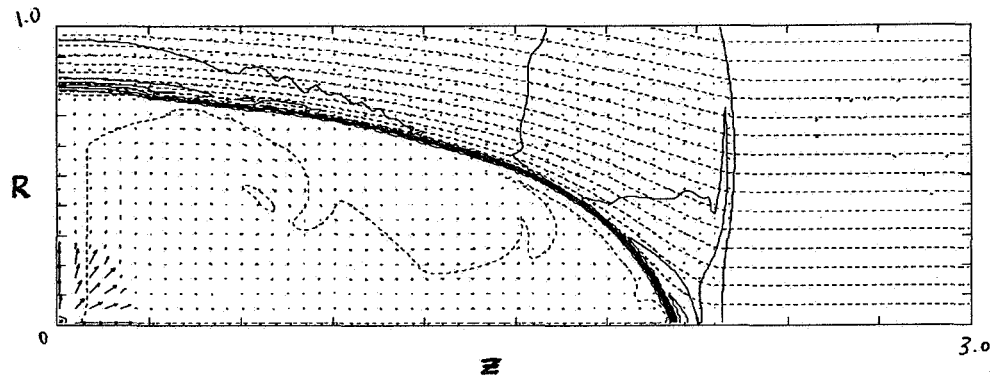
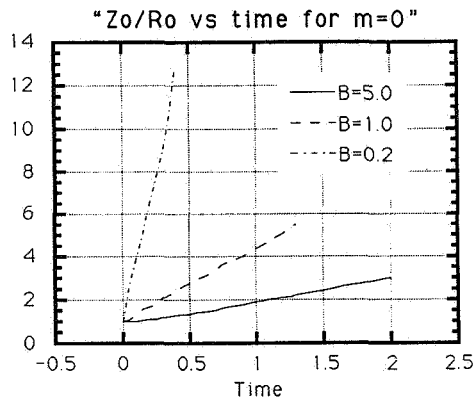


Fig. 1 - Magnetic collimation of a protostellar wind creates an elongated bubble in the direction of the ambient magnetic field. Density contours (solid lines) are superposed on the displaced magnetic field lines (dashed lines) and velocity vectors, and show the near planar MHD shock being driven by the advancing bubble apex. The parameters are  $\beta=1$ ,  $L=10$ .



Figs. 2 - Ratio of axial to equatorial radius versus time for  $L=1$  varying  $\beta$  in constant density ( $m=0$ ) atmosphere.

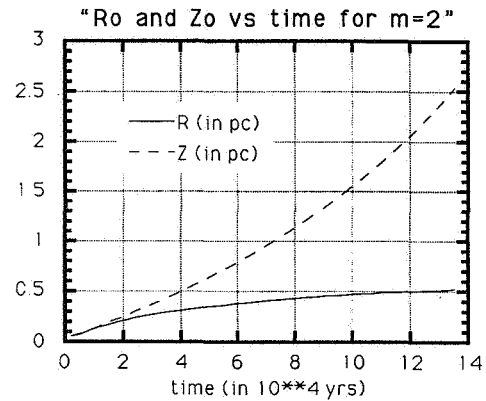


Fig. 3 - Axial and equatorial radius versus time for  $m=2$  atmosphere for  $L=1$ ,  $\beta=0.2$