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Toroidal Fields: a Driving Mechanism for Protostellar Jets

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Abstract. We propose that a toroidal magnetic field is the main driving component of a protostellar jet. We discuss how the ram pressure of the jet may damp a Parker-like instability and provide a stable environment for a jet flow.

Two basic mechanisms for protostellar jets have been proposed: the centrifugal wind model (CWD) (Blandford and Payne (1982)), and the magnetic pressure driven model (MPD) (Uchida and Shibata (1985)). The CWD model is currently the most popular model, partly because toroidal fields in MPD models are confined by gravity and are thereby subject to the Parker instability (Parker (1966)). In this paper, we study the possibility that the ram pressure of the jet may be a more appropriate confinement mechanism for such toroidal fields.

We adopt Freeman's model for a protostellar system (Freeman (1977)), where the dipole magnetic field of a protostar threads a surrounding accretion disk and is "wrapped up" by the Keplerian motion of the disk, *i.e.*, the purely poloidal magnetic field of the protostar is converted into a toroidal field in the disk, where the sign of the field changes as one passes through the disk. This magnetic structure suggests that the midplane of the accretion disk may become a zone of magnetic reconnection. In Figure 1 we show the expected disk magnetic field structure on one side of the disk midplane.

Suppose we have a jet flow, where the gas and magnetic pressures balance the ram pressure of the jet, and the gravitational pressure is negligible relative to the ram pressure *i.e.*

$$\frac{\overline{\rho}_{disk} k\overline{T}}{m_g} + \frac{\overline{B}^2_{disk}}{2\mu_o} = \overline{\rho}_{wind} v^2_{wind} , \tag{1}$$

with k being the Boltzmann constant, $\overline{T}$ is the "average" gas temperature, m_g the mean molecular mass of the gas, $\overline{B}_{disk}$ the average magnetic field strength in the disk, μ_o the magnetic permeability of free space, $\overline{\rho}_{disk}$ and $\overline{\rho}_{wind}$ the average gas mass-density in the disk and wind, respectively.

We assume that a destructive instability in the toroidal field occurs when $P_{mag} \geq \alpha P_{gas}$, where α is some constant. So, at the point of destructive insta-

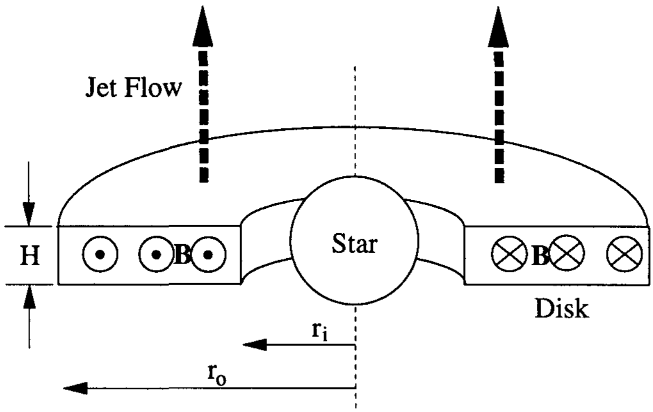

Figure 1. Schematic of the jet formation region in the "top" half of an accretion disk surrounding a protostar, where r_i and r_o are the inner and outer radii of the jet formation region, with $r_o, r_i \ll r_{disk}$. H is the disk scale height, where $H/r_i \ll 1$, and it is assumed that $H(r_i) \approx H(r_o)$

bility ($P_{mag} = \alpha P_{gas}$), Eq. (1) implies, $P_{gas} = P_{wind}/(1+\alpha)$ or

$$v_T^2 = \frac{2k\overline{T}}{m_g} = \left(\frac{\overline{\rho}_{wind}}{\overline{\rho}_{disk}}\right)\frac{2v_{wind}^2}{(1+\alpha)} , \tag{2}$$

where v_T is the thermal gas speed, which has the parametrized form

$$v_T \approx 4\sqrt{\left(\frac{\overline{T}}{10^3\ \mathrm{K}}\right)\left(\frac{m_H}{m_g}\right)}\ \mathrm{km\ s^{-1}} , \tag{3}$$

with m_H the mass of a hydrogen atom.

For a protostellar jet to occur, we must have

$$v_{wind} \sim v_{esc} = \sqrt{\frac{2GM}{\overline{r}}} \approx 133\sqrt{\left(\frac{M}{M_\odot}\right)\left(\frac{0.1\ \mathrm{AU}}{\overline{r}}\right)}\ \mathrm{km\ s^{-1}} , \tag{4}$$

where M is the mass of the protostar, and $\overline{r}$ is the mean distance of the jet formation region from the centre of the protostar.

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Combining Eqs (2)-(4), we obtain the required ratio of gas densities such that the wind can reach escape velocity:

$$\frac{\overline{\rho}_{wind}}{\overline{\rho}_{disk}} = (1+\alpha)\frac{v_T^2}{2v_{wind}^2} \approx 4.5 \times 10^{-4}\ (1+\alpha)\frac{(\overline{T}/10^3\mathrm{K})(\overline{r}/0.1\ \mathrm{AU})}{(M/\ \mathrm{M}_\odot)(m_g/m_H)} \tag{5}$$

For $\alpha \sim 1$, this density ratio becomes $\overline{\rho}_{wind}/\overline{\rho}_{disk} \sim 10^{-3}$.

The magnetic pressure - at the point of destructive instability - is simply $P_{mag} = P_{wind}\ \alpha/(1+\alpha)$ or

$$C_{A,wind}^2 = \frac{\overline{B}_{wind}^2}{\mu_o \overline{\rho}_{wind}} = \left(\frac{2\alpha}{\beta^2(1+\alpha)}\right) v_{wind}^2 \sim \left(\frac{2\alpha}{\beta^2(1+\alpha)}\right) v_{esc}^2 \tag{6}$$

where we have set $\overline{B}_{disk} = \beta \overline{B}_{wind}$. Using Eqs (5) and (6) one can show that

$$C_{A,disk}^2 = \frac{\overline{B}_{disk}^2}{\mu_o \overline{\rho}_{disk}} = \alpha v_T^2 \tag{7}$$

Thus, for $\alpha \sim 1$ (and $\beta^2 \lesssim 2\alpha/(1+\alpha)$) we have that $C_{A,wind} \gtrsim v_{esc}$, and $C_{A,disk} \sim v_T$, *i.e.*, one can obtain sensible Alfvén speeds for the jet and the disk by assuming that $\overline{\rho}_{wind}/\overline{\rho}_{disk} \sim 10^{-3}$ and that the destructive instability occurs when $P_{mag} \approx P_{gas}$. Note that our upper bound on β allows the possibility that $\overline{B}_{disk} \ll \overline{B}_{wind}$, which is what one would expect for a region of magnetic reconnection.

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