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A HELICAL MAGNETIC FIELD MODEL OF THE JETS

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ABSTRACT. A hydromagnetic model is presented for the bipolar flow of molecular gas from newborn stars and for the radio jet emerging out of active galactic nuclei. We assume a tightly-twisted helical magnetic field in the jet, which can collimate and accelerate the gas along the jet axis. The Lorentz force is also shown to rotate the gas around it.

1. ACCELERATION AND COLLIMATION

When the magnetic field in the jet is tightly-twisted and the gas moves mostly along it, we have

$$|B_\phi| \gg |B_r|, |B_\theta|, \quad (1)$$

$$|u| \gg |v|, |w| \quad . \quad (2)$$

Assuming a steady and axisymmetric structure, we can derive the following equations from the cold MHD equations by using the extreme-inequality conditions (1) and (2)

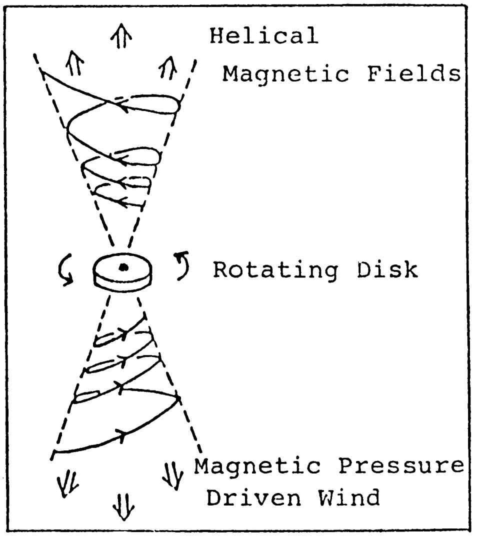

Fig. 1

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$$u \frac{du}{dr} = \frac{1}{4\pi \rho(r)} \cdot \left\{ - \frac{\partial}{\partial r} \left(\frac{B_\phi^2(r)}{2} \right) - \frac{B_\phi^2(r)}{r} \right\} - \frac{GM}{r} \quad , \tag{3}$$

$$B_\phi(r,\theta) = B_\phi(r) \cdot \frac{1}{\sin\theta} \quad , \tag{4}$$

$$\rho\ (r,O) = \rho\ (r) \cdot \frac{1}{\sin^2\theta} \quad , \tag{5}$$

$$B_\phi(r)ur = \text{constant } (\equiv f_b), \tag{6}$$

$$\rho\ (r)ur^2 = \text{constant } (\equiv f_m), \tag{7}$$

where (u,v,w) is the velocity in the spherical coordinate system (r,θ,ϕ). The gas is accelerated by the magnetic pressure gradient in the r direction [equation (3)], and is collimated by the magnetic tension [equations (4) and (5)]. Substituting equations (6) and (7) into equation (3), we have

$$(u - \frac{1}{u^2} \cdot \frac{f_b^2}{4\pi f_m}) \cdot \frac{du}{dr} = - \frac{GM}{r^2} \quad . \tag{8}$$

Integrating over r, we have Bernoulli's equation

$$\frac{u^2}{2} + \frac{u_A^3}{u} - \frac{GM}{r} = constant\ (\equiv h) \ , \tag{9}$$

where

$$u_A \equiv \left(\frac{f_b^2}{4\pi\ f_m} \right)^{1/3} \quad : \text{Alfvén velocity at infinity}$$

$$= \frac{B_\phi(\infty)}{\sqrt{4\pi\ \rho(\infty)}} = 22 \left(\frac{B_\phi(\infty)}{10^{-4}\ gauss} \right) \left(\frac{n(\infty)}{10^2 cm^{-3}} \right)^{-1/2} km\ s^{-1}. \tag{10}$$

In the case $h = 3u_A^2/2$, the velocity of the outward flow reaches the Alfvén velocity u_A at infinity. The characteristic length of the accelerating region (the distance from the origin to the point where the velocity becomes half of the final one), is given as

$$r_{1/2} = \frac{8GM}{5\ u_A^2}$$

$$= 1.7 \times 10^{-4} \left(\frac{M}{10\ M_\odot} \right) \left(\frac{u_A}{20\ km\ s^{-1}} \right)^{-2} \quad pc \ . \tag{11}$$

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2. ROTATION

Next we determine the components of smaller magnitude (B_r, B_θ, v, w) by using (B_ϕ, u, ρ) in the previous section. Substituting equations (4) through (7) into the MHD equations and neglecting the higher order terms of (B_r, B_θ, v, w), we have

$$rw - r \cdot \frac{B_\phi B_r}{4\pi\rho u} = \text{constant} \ (\equiv \ell\phi) \ , \qquad (12)$$

$$B_r(r,\theta) = B_r(r_0) \cdot \left(\frac{r_0}{r}\right)^2 \cdot \frac{1}{\sin\theta} \ , \qquad (13)$$

$$v = 0 \ , \quad (14) \quad : \quad B_\theta = 0 \ , \quad (15)$$

where r_0 is an arbitrary constant with the same dimension as r. The gas is rotated by the magnetic torque [equation (11)].

3. CORE JET

The cold magnetic jet has intrinsically a slender gaseous core along the symmetry axis as suggested by equations (4) and (5). This core gas is assumed to have no magnetic field in it, and to be hot enough to balance laterally the outside magnetic pressure due to B, i.e.

$$P_c(r) = \frac{1}{8\pi} B_\phi^2 (r, \theta_c) .$$

The spatial gradient of P_c accelerates the core gas like the "melon seed" effect. Numerical computations show that this core jet has a larger velocity than the cold magnetic one has and it is accelerated as log r. See the detailed discussions and conclusions in the reference.

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COLLIMATION OF STELLAR WINDS BY THE MAGNETIC FIELD

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The pinching effect of the magnetic field is studied as a possible mechanism for collimating stellar winds into bipolar flows in star-forming regions. Axisymmetric, steady, polytropic stellar wind models

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