FORMATION OF ASTROPHYSICAL JETS BY A CONTRACTING MAGNETIC ACCRETION DISK*

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Abstract. In the present paper, we discuss an MHD model for the formation of astrophysical jets, in which the directed flows are ejected along the rotation axis of an accretion disk formed from a cloud having a large scale magnetic field parallel to the angular momentum axis of the disk. The acceleration of jets is due to the $\mathbf{j} \times \mathbf{B}$ force in the relaxing magnetic twist which is produced by the rotation of the disk. The characteristic features of the jets, predicted by our mechanism and hopefully to be proven by observations, are the helical velocity and the hollow cylindrical shape of the jet, with a diameter of roughly the size of the region from which the accretion disk collected its mass. Justification for the assumption of the perpendicular orientation of the disk, or the parallelism of the jets, to the external magnetic field may be provided by the fact that the component of rotation whose axis is perpendicular to the field may have been damped in the earlier phase of the cloud contraction.

1. Introduction

Astrophysical jets form one of the categories of cosmic phenomena established recently. Well-known examples are jets with double radio lobes of active galaxies (Begelman *et al.*, 1984). The radio lobes above the nucleus of our Galaxy recently reported by Sofue and Handa (1984) may be related to these astrophysical jets in the galactic scale. It has also been revealed recently that there are jet-like phenomena having bipolar configuration in the stellar situation. Examples are the bipolar flows observed in star forming regions (Snell *et al.*, 1980; Bally and Lada, 1983), the jets from SS433 (Margon, 1982), and the double lobes of Sco X-1 (Fomalont *et al.*, 1983).

In spite of the progress in the observation, the origin of these astrophysical jets is not yet well explained theoretically (e.g., Begelman *et al.*, 1984). There are still several hypotheses as to the source of energy and the acceleration and collimation mechanisms. As for the collimation of the flow, mechanisms including the collimation of the strong 'wind' by polar funnels in a thick accretion disk (Koenigl, 1982; Fukue, 1982; Ferrari *et al.*, 1984), or collimation by blockading the isotropic flow in the direction of the high density disk (Sakashita *et al.*, 1984; Okuda and Ikeuchi, 1984) have been discussed; though the origin of the 'wind' remains unclear. It is, however, not easy to explain the high collimation of a flow by considering a funnel of small aspect ratio, and it is more

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difficult to explain the helical motion suggested in some observations. In this connection, we have proposed a mechanism in which both the acceleration and the collimation are caused by the action of a magnetic field. The magnetic field acts as an efficient converter for the gravitational energy of the contracting disk rotating around the center of gravity into that of the directed flow (Uchida and Shibata, 1984a, b, 1985; Shibata and Uchida, 1984).

We consider a cool gaseous disk rotating with a sub-Keplerian velocity around the central object. If there is a magnetic field penetrating the disk, the contraction of the rotating disk drags the magnetic field lines towards the center as well as towards the azimuthal direction. The magnetic field is thus twisted up around the axis of rotation, and after some time, the accumulated magnetic twists begin to relax along the external magnetic field and drive out the plasma by the $\mathbf{j} \times \mathbf{B}$ force helically towards the polar directions. In our model, the source of energy is the gravitational potential energy released in the contracting motion of the rotating disk. In the following we show that jets having a bipolar configuration can actually be created by our proposed mechanism.

2. Numerical Simulations

Assumptions in the calculations are (i) axial symmetry, but allowing B_φ and v_φ, (ii) ideal MHD, (iii) non-relativistic, and (iv) the self-gravity of the disk neglected. The basic equations are standard ideal MHD equations with the gravity source, the central star, located at the origin of cylindrical coordinates (r, φ, z).

As for the initial condition, we assume a cool accretion disk rotating around the z-axis with a velocity smaller than the Keplerian velocity in the gravitational potential of the central point mass. We further assume a hydrostatic corona and a uniform magnetic field which penetrates the disk vertically as the initial condition. These assumptions are for the sake of simplicity at this moment, but we know from observations that bipolar flows tend to be parallel to the external magnetic field, and the accretion disk lies perpendicular to both (Kaifu *et al.*, 1984).

Boundary conditions on the inner spherical boundary (for practical reasons in the calculation we cannot cover too wide a range of scales at a time) and on the top and side surfaces of the cylindrical region are all assumed to be free boundaries: i.e., waves and fluid can pass through these boundaries freely. Symmetrical conditions are imposed along the z-axis, and at the equatorial plane $z = 0$.

With an appropriate choice of dimensionless parameters, our problem becomes a scale-free one. The parameters are: β = the ratio of thermal and magnetic energies, ε_d = the ratio of thermal and gravitatinal energies, α = the ratio of rotational and Keplerian rotational velocities, and ρ_d/ρ_c = the ratio of the densities of the disk and corona across the interface. These ratios may be made functions of r, with a coefficient to be fixed, for example, at the inner edge of the disk. We have solved this problem numerically by using a modified Lax–Wendroff scheme with an artificial viscosity.

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3. Results

We will now show a typical example of the numerical results (a full version will appear in Uchida and Shibata, 1985). $\alpha(r, z, t = 0)$, $\beta(r, z, t = 0)$, $\varepsilon_d(r, z, t = 0)$, and $\rho(r, z, t = 0)$ are prescribed by some simple suitable functions, as may be seen from the initial distributions in Figures 1 and 2, and parameters are specified as $\alpha(r, 0, 0) = 0.8$,

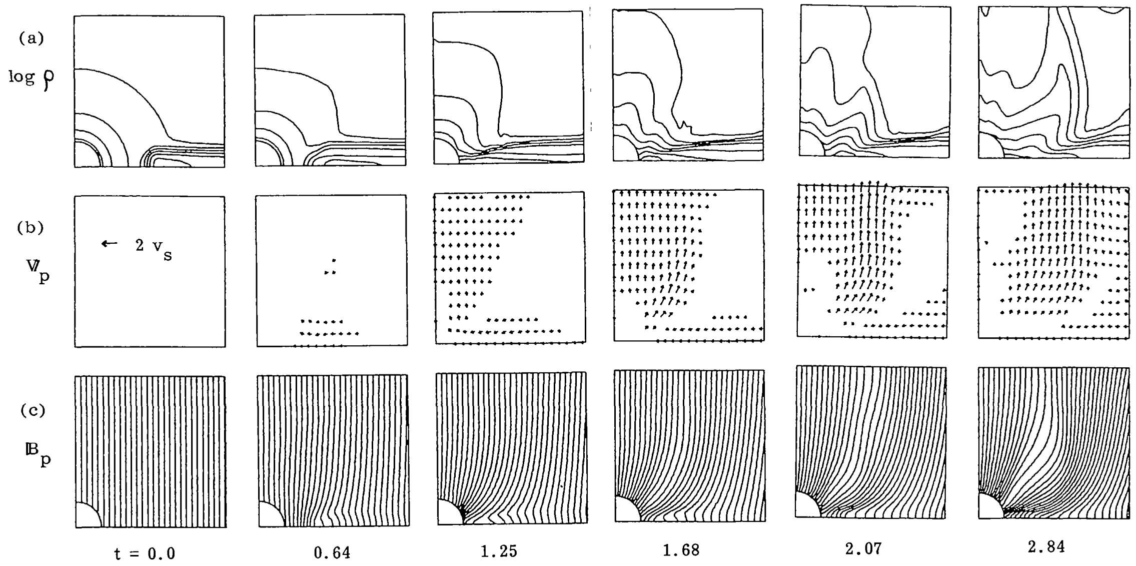

Fig. 1. Time variations of (a) $\log\rho$ (density), (b) the poloidal velocity vector $\mathbf{V}_p$, and (c) the poloidal magnetic field lines. The magnitude of the velocity vector is shown in the $t = 0.0$ figure of $\mathbf{V}_p$, where v_s is the sound velocity in the corona. Note that $\beta = 0.5$ in this case, and so V_A (Alfvén velocity in the corona) $= 1.55\, v_s$. Other initial parameters are: $v_\varphi/v_{\text{Kepler}} = 0.8$, $\varepsilon_d = 3 \times 10^{-3}$, and $\rho_d/\rho_c = 400$. Times are in the unit of the free fall time at the inner edge of the disk.

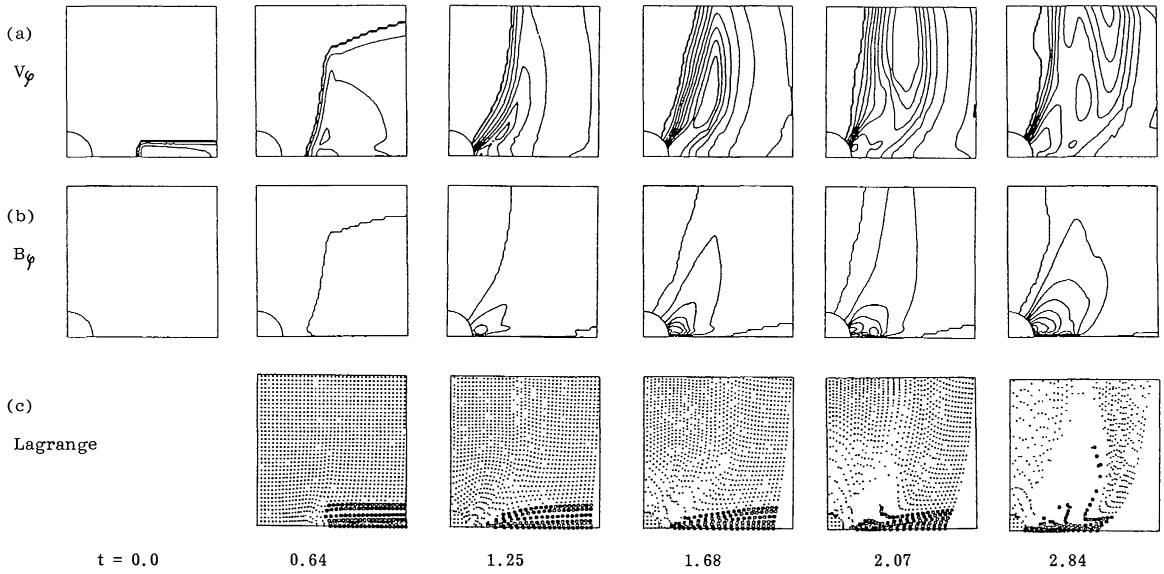

Fig. 2. Time variation of (a) the rotational velocity, v_φ, (b) the azimuthal component of the magnetic field, B_φ, and (c) the Lagrangian description of the motion in the case of Figure 1. Other remarks are the same as in Figure 1.

$\beta(r, 0, 0) = 0.5$, $\varepsilon_d(r, 0, 0) = 3 \times 10^{-3}$ and $\rho_d/\rho_c = 400$, at $r = r_{\mathrm{ie}}$, where r_{ie} is the radius at the innermost part of the initial disk. These values are based on an order-of-magnitude estimate of physical parameters in a typical stellar bipolar flow, L1551, for example.

Figure 1 shows the time variations of density, poloidal velocity vector, and poloidal magnetic field lines. The first one in each row shows the initial distributions of quantities as mentioned above. Times are in the unit of the free-fall time at the inner edge of the initial disk. The rotating disk starts to contract towards the center, because of its sub-Keplerian rotational velocity, and drags magnetic field lines towards the center as well as in the azimuthal direction. After some time of accumulation of the magnetic twist, relaxation of the magnetic twist starts, and a jet with a hollow cylindrical shape appears at around $t = 1.5$. The jet has a velocity which is a large fraction of the Alfvén velocity in the z-direction. Figure 2 shows the azimuthal velocity, the azimuthal component of the magnetic field, and the Lagrangian presentation of the motion for the same case as shown in Figure 1. At $t = 0.6$, we see the propagation of an Alfvén wavefront generated by the interaction between the rotating disk and the vertical field. Angular momentum of the disk is transported to polar directions along the vertical magnetic field. A helical jet is driven out when the gradient of the magnetic twists becomes large. The ejected gas comes from the layer near the surface of the disk.

4. Discussion

The main characteristic features of the jet in our model are (a) helical velocity and (b) hollow cylindrical configuration of the jet. In the galactic scale, the radio lobes observed above the galactic center (Sofue and Handa, 1984) actually seem to show hollow cylindrical jet structure. Although the helical motion has not yet been measured clearly in these lobes themselves, the rotating disk at their footpoints in the galactic plane may suggest the applicability of our model. In the stellar scale, some bipolar flows in the star forming regions, like GL490, also seem to show the hollow cylindrical jet structure (Fukui, private communication, 1984). We predict that helical motion in these structures will also be observationally proven in the near future.

Finally, it is remarked that the seemingly artificial assumption of perpendicular orientation of the plane of the disk relative to the direction of the magnetic field, and thus the parallelism of our jet to the external magnetic field is based on observations of some real cases, including L1551 (cf. Vrba *et al.*, 1976), and this may well have physical reasons. The component of the angular momentum perpendicular to the magnetic field may have been damped in earlier phases of the cloud contraction, due to some larger impediment by the action of the magnetic field on it than on the angular momentum parallel to the field (Mouschovias, 1976).

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