"Sweeping Pinch" Mechanism and the Acceleration of Jets in Astrophysics

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Abstract : A magnetodynamic mechanism of jet formation, in which a packet of the toroidal component of the magnetic field B_φ plays a role, is proposed. Such a packet of toroidal field, produced by the rotational motion in the $\beta = p_g/p_m >> 1$ region, relaxes itself in the $\beta << 1$ region when brought up into such a region, for example, by the process of flux emergence due to magnetic buoyancy. In the $\beta << 1$ region, a progressive pinch is caused by this relaxation and the mass is swept out by the pinch near the axis and also by the j x B force in the twisted field region surrounding the axis.

1. Introduction

Acceleration of jets is pretty common in cosmical objects, ranging from solar flare-surges to the bipolar jets in radio galaxies and quasars. It is getting clearer that the origin of these highly directional flows may be related to the magnetic field combined with the rotational motion in the objects. For example, jets in the solar atmosphere (surges, Brueckner's jets (1980), and so on) are known to originate from magnetic patches and it is suggested that the emergence of the twist of the magnetic field produced in the $\beta >> 1$ region down in the photosphere by convective motions may play an important role in the formation of these jets along the external field lines (Uchida and Shibata 1983). Also it is likely that the part of the large scale intergalactic magnetic field lines, entangled in the accretion disk of the galaxy or quasar and twisted up by the rotation of the disk, may play a similar role in causing jets along the large scale fields when the magnetic twist is released from the accretion disk.

2. Numerical Simulations

In the following we demonstrate that the jet can actually be accelerated when toroidal component of the magnetic field emerges from the $\beta >> 1$ region to the $\beta << 1$ region. We solve the standard equations of

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conservations of mass, momentum, and energy together with the induction equation in the MHD approximation in a cyclindrical coordinate $(r,\ \varphi,\ z)$ where z is taken to be antiparallel to the gravity under which the parts of the atmosphere of widely different β-values stratify. In solving the equations, we adopt modified Lax-Wendroff scheme (e.g. Rubin, and Burstein 1967, Shibata 1983) in pseudo three dimension (axisymmetry but allowing v_φ and B_φ) with artificial viscosity. As an example, the unperturbed condition was taken to be that of the solar case, in which the corona (β<<1) and the chromosphere (β<1) with temperatures 10^6 K and 10^4 K, respectively, stratify under gravity in hydrostatic equilibrium with the transition layer at around z_t=2000 km above the photosphere. Magnetic field is assumed to be an axisymmetric potential field which diverges moderately with height (these are seen in Figure 1 at t=0). We assume the initial distribution of $B_\varphi(r,z)$ in the chromosphere with the radius of the peak, r_0=300 km as seen in Figure 2 at t=0. This corresponds either to the twisted part of the flux tube floated up as the emerging flux appearing in active regions, or the twist of compact loop transferred to a large scale open flux tube through magnetic reconnection (Uchida and Shibata 1983).

The boundary conditions are those of free boundary on the surface of the cylinder (right-hand-side of the rectangular region in the Figures) and the top and bottom surfaces. On the axis (left-hand side of Figures) the symmetry condition with vanishing v_r, v_φ, B_r and B_φ are imposed.

3. Results and Physical Interpretation

Figures 1 and 2 show the behavior of $\mathbf{B}_{/\!/}$ and B_φ in an example in which $\alpha=(B_\varphi/B_z)_{z=0}=1$ and $\beta=(p_g/p_m)_{z=0}=1$, respectively, and Figures 3 and 4 show the corresponding velocity components v_φ and $\mathbf{v}_{/\!/}$ induced in this process respectively. Figures 5 and 6 are corresponding changes in log ρ and log T. It is clearly shown that a directed flow or a jet is accelerated as B_φ relaxes itself into the transition zone and into the corona. The magnetic field pattern in Figures 1 and 2 shows that the bunch of B_φ, which was passively produced in the β>>1 region by the rotational motion of the convection and could not relax by itself, now relaxes itself to a new equilibrium with $\mathbf{B}_{/\!/}$ as it is brought up by the flux emergence process into the β<<1 region where the gas pressure can no longer confine the magnetic field. A pinching toward the axis at around the height of the transition layer occurs when B_φ starts relaxing in the upper chromosphere to the transition region (whereas B_φ at larger r expands), and as the front of this twist proceeds into the corona, the pinching sweeps up the material along $\mathbf{B}_{/\!/}$. In the region surrounding the axis, the front drives plasma also through $\mathbf{j} \times \mathbf{B}$ force (cf. Hollweg *et al.* 1982) as the originally untwisted field lines are pulled into the helical pattern, or the twist proceeds into the region. The pinching can be understood as the process of relaxation of the field to a new equilibrium in which force-free field is to be established after the twist wave front comes into the region and bounces on the borders if the region concerned is a closed finite region. In our present situation of open flux tube, the twist wave escapes out of the region.

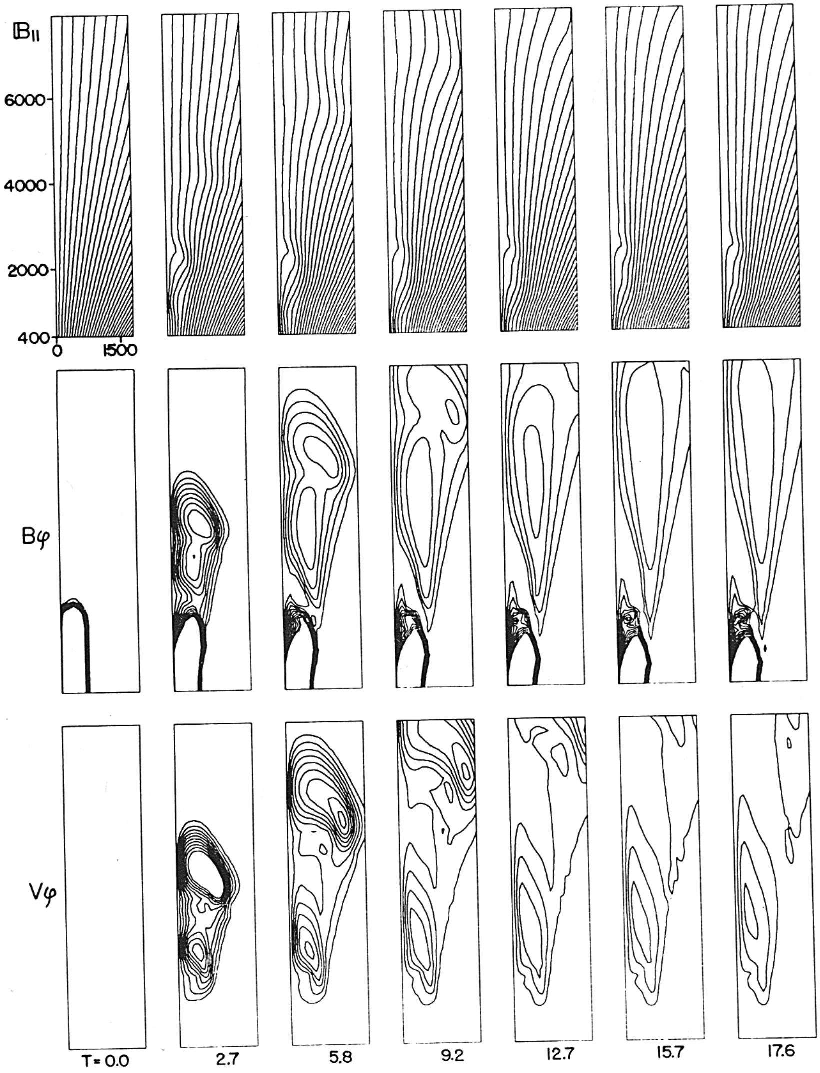

Figure 1, 2 and 3 (from the top to the bottom) : Time variation of the poloidal field $\mathbf{B}_{\parallel}$ (Fig.1) in response to the relaxation of the toroidal component B_{φ} into the $\beta \ll 1$ region (Fig.2 in B_{φ}/B_0). Figure 3 shows the induced v_{φ} (in v_{φ}/v_0). Numbers on the abscissa and ordinate are r and z in km.

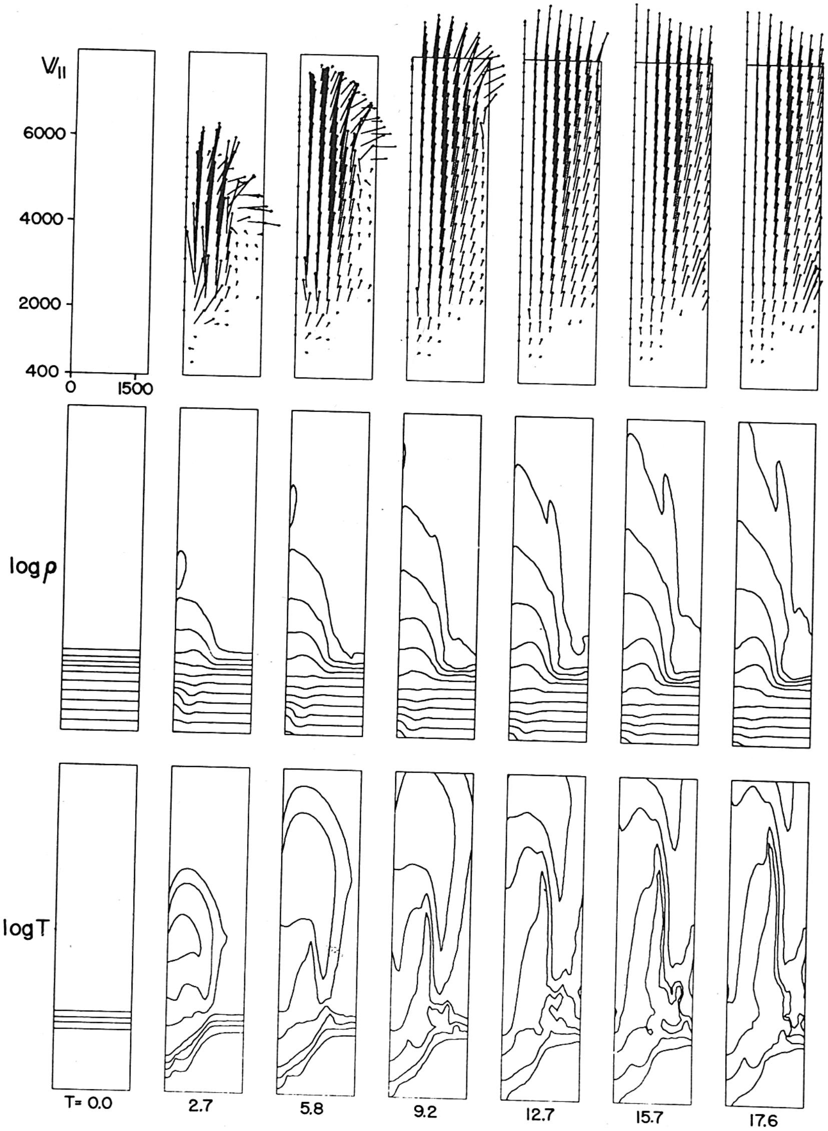

Figure 4, 5, and 6 (from the top to the bottom) : Corresponding evolution of $\mathbf{v}_{\parallel}$ (Fig. 4), log ρ (Fig. 5), and log T (Fig. 6). These show the formation of a jet with a high temperature($>10^7$ K) part at the head progresses roughly with the Alfven velocity, and a sheath of the spinning material with the transition zone temperature follows it.

It is to be noticed that the temperature rises markedly due to strong pinching at the incidence of the twist wave front into the transition region, and this high temperature blob progresses along the field lines as seen in Figure 6. After some time the high temperature part of the jet caused by the sweeping pinch is followed by a spinning sheath with the transition zone temperature. The velocity of the front of the sweeping pinch is of the order of the Alfven velocity, and that of the material of the spinning sheath in this case reaches a good fraction of it, or about 50 % of the Alfven velocity. The velocity of the latter may be brought up to the Alfven velocity if multiple twist wave fronts repeatedly outrun it.

4. Discussion and Prospect for Applications

There seem to be a number of applications of this mechanism in astrophysics. It is readily seen from the above example that the observed properties of jetting phenomena in the sun seem to favor the present mechanism. Often they clearly show helical motions, which is a clear characteristic of our mechanism. Another application on the sun is the dynamical theory of formation of simple-loop flares (Uchida and Shibata 1983). As shown in that paper, the appearances of the superhot region as well as the acceleration of non-thermal particles (Tanaka *et al.* 1983, Tsuneta *et al.* 1983) in the solar simple-loop flares may be explained in a natural way in our mechanism.

Other cosmic jets, like quasar's jets with radio lobes, may also be explained by the present mechanism. For example, the rotation of the accretion disk may twist up the part of the large scale intergalactic magnetic field lines, and when the mass is freed from the field line by magnetic reconnection and falls into the central blackhole, the liberated twist wave front sweeps out along the large scale field and accelerates the plasma and particles. In such a picture, the energy comes from the gravitational energy, and the magnetic field plays the role of a converter of this gravitational energy with high efficiency.

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