Formation and Collimation of Jets by Magnetic Forces

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Abstract
Recent development of theory and numerical simulations of magnetically driven jets from young stellar objects is reviewed. Topics to be discussed are:
1) Acceleration of jets: Magnetically driven jets are accelerated by both magneto-centrifugal force and magnetic pressure force. The former (latter) becomes important when magnetic field is weak (strong). The basic properties (i.e., terminal velocity and mass flux) of jets accelerated by these two forces is discussed in detail. We also discuss the condition of production of jets, which is applied to answer the following question: When do jets begin to be accelerated in the course of star formation?
2) Collimation of Jets: Magnetically driven jets can in principle be collimated by pinching effect of toroidal magnetic fields. Recently, some controversial arguments have been put forward: Are all field lines (and jets) really collimated by pinching effect? The current status of this issue is discussed.
3) Protostellar flares: Based on theory and numerical simulations, it has recently been recognized that the formation of jets has a close connection with occurrence of flares (possibly due to magnetic reconnection). We discuss how and when magnetic reconnection occurs in relation to jets.

1 Introduction
Magnetically driven jets from accretion disks (Fig. 1) were first proposed to explain jets from active galactic nuclei (Blandford 1976, Lovelace 1976, and Payne 1982). After the discovery of CO molecular bipolar flow in star forming regions (Snell et al. 1976), the MHD jet model began to be applied to bipolar flows and jets from young stars (Pudritz and Norman 1986, Uchida and Shibata 1985). The first time-dependent numerical simulation of MHD jets from accretion disks were carried out by Uchida and Shibata (1985) and Shibata and Uchida (1986, 1990; see Fig. 2).

The MHD jet model (see Tsinganos 1996, Tajima and Shibata 1997 for a review) has the following merits: 1) the magnetic force not only accelerate plasmas from disk surface to form bipolar jets but also extract angular momentum from accretion disks, enabling efficient accretion of plasma onto central objects (stars or black holes), 2) the magnetic force due to toroidal fields collimate jets by pinching effect.

It was first thought that molecular outflows were directly ejected from accretion disks (Uchida and Shibata 1985, Pudritz and Norman 1986), but subsequent observations revealed that there exist high velocity neutral winds between molecular outflows and central regions, suggesting that molecular outflows are accelerated by high velocity neutral winds. Hence it is now better to say that the MHD model of jets should be applied to high velocity neutral winds (and also to optical jets).

There are several indirect observational evidence of MHD jets.
(1) Strong magnetic fields are observed in molecular clouds (e.g., Tamura 1999) and T Tauri stars (e.g., Montmerle 1999); p < B2/r < cGM/r.
(2) Radiation pressure is not sufficient to drive YSO jets; MV > L/ε (e.g., Lada 1985).
(3) Sometimes helical structures are seen in HH jets, which may correspond to helical magnetic fields (e.g., HH47).
(4) The observation of a spinning outflow was reported (Uchida et al. 1987).

At present, the evidence of a spinning jet is not conclusive (Rodriguez 1999). It would be thus particularly important to detect clear evidence of spinning jets, since the spinning motion of jets is a key physical process to observationally distinguish MHD models and other models. Plasma blobs in non-MHD jets undergo only ballistic motion and cannot rotate around a jet axis.

In this article, we review recent theoretical studies of MHD jets especially on basic physics of acceleration and collimation of jets, rather than discussing detailed interpretation of recent observations. We also discuss magnetic reconnection associated with jets, which has recently been recognized as an important physical process associated with jets and is considered to be a promising mechanism to induce protostellar flares.

2 Acceleration of MHD Jets
2.1 When and how a jet is launched?
Recent nonsteady MHD simulations (Kudoh, Matsumoto, Shibata 1998, Kato, Kudoh, Shibata 1999) have revealed that even when a jet is highly transient or nonsteady, the Blandford-Payne mechanism (1989) holds; i.e., a jet is launched by the effect of the centrifugal force when the centrifugal force along a rotating field line becomes larger than the gravitational force along the field line.

Consider the effective gravitational potential
\[ \Psi_{eff} = -\frac{1}{2} \Omega^2 r^2 - \frac{GM}{r} \]

on a rigidly rotating straight magnetic field line with angular velocity Ω whose footpoint is at a distance r0 from the central mass (Fig. 3). Here r is the distance from the rotation axis of the disk, R = (r2 + z2)1/2 is the radial distance from the central mass at the origin, and z is the height from the disk plane. The angle between the field line and the disk plane is θ. Then from the condition \( \frac{\partial \Psi_{eff}}{\partial \theta} < 0 \) (centrifugal force > gravitational force) at \( r_0 = \Delta \theta, \Delta z \) and \( \Delta \theta = (\Omega^2 + \frac{\partial^2}{\partial \theta^2})^{1/2} \), we obtain the following condition
\[ \tan^2 \theta < 3 + \frac{r_0^2}{\Delta \theta^2} \left( \frac{\Omega^2}{\Omega^2_{\Delta z}} - 1 \right) \]

where \( \Omega_{\Delta z} = (GM/r_0^3)^{1/2} \) is the Keplerian angular velocity. This equation means that if a disk is the Keplerian disk, the
critical angle of launching a jet from the (cold) disk is 60° (i.e., Blandford-Payne angle), and that if the disk rotation is sub-Keplerian ($\Omega < \Omega_k$), such as the collapsing disk in the runaway collapsing phase, it is hard to launch a jet from near the disk plane (i.e., small $\delta r = \delta z / \tan \theta$). Hence this equation predicts that a jet is launched after the disk settles into a rotationally supported Keplerian disk (i.e., at the beginning of accretion phase), as shown in a very nice numerical simulation of Tomisaka (1998).

As discussed above, it has been found that the Blandford-Payne mechanism is a universal mechanism for launching jets. However, this does not mean that the centrifugal force is a dominant force to accelerate MHD jets. Kudoh and Shibata (1997a) revealed that for weak magnetic field ($E_{mg} = (V_A / V_c)^2 < 10^{-3}$), the magnetic pressure is a dominant acceleration force, while for strong magnetic field ($E_{mg} > 10^{-3}$), the (magnetocentrifugal) centrifugal force is dominant.

2.2 What is a terminal speed of MHD jets?

The previous 2.5D MHD numerical simulations (Shibata and Uchida 1986, 1990, Stone and Norman 1994, Matsumoto et al. 1996, Hirose et al. 1997, Kudoh et al. 1998, Kato et al. 1999, Kuwabara et al. 1999) and also 3D MHD simulations (Matsumoto and Shibata 1997) have shown that the velocity of MHD jets is of order of Keplerian velocity at the footpoint of MHD jets and has a weak dependence on $B$ (see Fig. 6):

$$V_{jet} \propto E_{mg}^{1/6} \propto B^{1/6}. \quad (3)$$

This is consistent with the results of one-dimensional steady jet theory (Kudoh and Shibata 1995, 1997a; see also Fig. 7), and also can be derived semi-analytically as follows: Since the MHD jet is accelerated by magnetic energy, the kinetic energy of the jet ($\rho V^2 / 2$) is comparable to the magnetic energy of the jet ($B^2 / 8\pi$) at infinity (exactly speaking, at the fast magnetosonic point). Hence the terminal speed is of order of

$$V_{\infty} = B_p / (4\pi \rho)\,^{1/2}. \quad (4)$$

From the condition that the plasma flow must be parallel to the magnetic field line in a co-rotating frame (to maintain steady state), we have

$$V_{\infty} = B_p / \Omega. \quad (5)$$

Since the mass flux is $\dot{M} = 4\pi r^2 \rho V_{\infty}$, we find

$$V_{\infty} = \left( \frac{\Omega B^2 R^4}{M} \right)^{1/3}. \quad (6)$$

This was originally derived by Michel (1969) and hence is called the *Michel velocity.*

It is very important to note that the terminal velocity strongly depends on the mass flux $\dot{M}$. Often people assume...
that the mass flux is a free parameter. Though this assumption is mathematically admissible, it is physically implausible. That is, mass flux is not a given parameter but should be determined by other physical quantities at the boundary. In our problem, the mass flux is approximately given by

$$\dot{M} = 4\pi \rho_{\text{low}} V_{\text{low}} r^2$$

$$= 4\pi \rho_{\text{low}} C_s \frac{B_0}{ B} r^2,$$  \hspace{1cm} (7)

where $\rho_{\text{low}}$ is the mass density at the slow magnetosonic point, $V_{\text{low}}$ is the slow magnetosonic speed, $C_s$ is the sound speed, and $B = (B_0^2 + B_z^2)^{1/2}$. In a cold disk, the slow magnetosonic point corresponds to the local maximum of the effective gravitational (Blandford-Payne) potential (Fig. 5), and is located near the disk plane ($\rho_{\text{low}}/\rho_0 \sim 0.1$ in our case). For stronger fields ($E_{mg} > 10^{-2}$), the magnetic field lines become straight $B \sim B_p > B_\nu$ so that the mass flux does not depend on $B_\nu$, but for weaker fields ($E_{mg} < 10^{-2}$), field lines are highly twisted and the azimuthal component becomes dominant $B \sim B_v > B_\nu$ so that the mass flux is in proportion to $B_\nu$ (Kudoh and Shibata, 1995, 1997a). Considering these effects, the terminal speed of the MHD jet becomes

$$\frac{V_{\infty}}{V_k} \simeq \left( \frac{\rho_{\text{low}}}{\rho_0} \right)^{-1/6} \frac{E_{\text{th}}^{1/6}}{E_{mg}^{1/6}}$$ \hspace{1cm} (8)

where

$$E_{\text{th}} = \left( \frac{C_t}{V_k} \right)^2$$ \hspace{1cm} (9)

$$E_{mg} = \left( \frac{V_k}{V_\nu} \right)^2$$ \hspace{1cm} (10)

Since $\rho_{\text{low}}/\rho_0 \sim 0.1$ and $E_{\text{th}}/E_{mg} \simeq \beta$ = gas pressure/magnetic pressure $\sim 1 - 10$ in the disk, we find from this formula that the terminal speed of the jet is comparable to the Keplerian velocity for wide range of parameters since the dependence on parameters is weak; $V_{\infty} \propto B_\nu^{1/3}$. This explains the results of the previous 2.5D MHD numerical simulations very well.

Figure 7 shows the mass flux and the terminal velocity of jets as a function of $B_p$ in a steady MHD jet (Kudoh and Shibata 1997a):

$$\dot{M} \propto B_p$$ for weak field ($E_{mg} < 10^{-2}$), \hspace{1cm} (11a)

$$\dot{M} \propto \text{const.}$$ for strong field ($E_{mg} > 10^{-2}$). \hspace{1cm} (11b)

We also find that the terminal velocity shows the following dependence

$$V_{\infty} \propto B_p^2/3$$ for weak field ($E_{mg} < 10^{-2}$), \hspace{1cm} (12a)

$$V_{\infty} \propto B_p^{2/3}$$ for strong field ($E_{mg} > 10^{-2}$). \hspace{1cm} (12b)

Note that the former weak field case corresponds to the magnetic pressure driven jet and the latter strong field case corresponds to the centrifugally driven jet. Even in the case of strong magnetic fields, the velocity of jets cannot increase freely, since there is an upper limit for the magnetic field strength $E_{mg} = 1$. (If the field strength becomes larger than this critical value, the rotation of accretion disks is stopped by the magnetic force and even the accretion of plasma is inhibited by the strong magnetic force.) Hence there is an upper limit in the velocity of the jet ejected from accretion disks. This is different from the velocity of the jet ejected from stars (e.g., pulsars). For typical parameters of accretion disks (in the case of Fig. 7), this upper limit of the jet velocity is $\sim V_k$.

Finally, we should emphasize again that even if the magnetic field strength is very weak in accretion disks, the jet velocity is roughly comparable to Keplerian speed ($V_j \sim 0.1 - 1.0 V_k$ for $E_{mg} \sim 10^{-2}$ - $10^{-4}$). The physical reason is that magnetic field lines are highly twisted by the differential rotation of the disk until the local magnetic energy density ($B_j^2/8\pi$) becomes comparable to the rotational energy ($\mu V_j^2/2 \sim GM/r$ gravitational energy) at the surface of the disk. Since the kinetic energy of the jet ($\mu V_j^2/2$) comes from the gravitational energy ($\mu V_j^2/2$) at the disk surface (i.e., at the slow magnetosonic point). This process is similar to the magneto-rotorlational (Balbus-Hawley) instability in the sense that the magnetic effect becomes eventually important even if the initial magnetic field is very weak.

<table>
<thead>
<tr>
<th>Centrifugal Force</th>
<th>Magnetic Pressure</th>
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<tr>
<td>Strong</td>
<td>Weak</td>
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<tr>
<td>Near disk</td>
<td>Straight</td>
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<td>$B_p &lt; B_\nu$</td>
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<td>$B_p \sim B_\nu$</td>
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<td>$B_p &gt; B_\nu$</td>
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Note: $B_p$ and $B_\nu$ are the poloidal and toroidal component of magnetic field, respectively, r is the radial distance from the central mass to the footpoint of a jet, $V_k$ is the rotation velocity (Keplerian velocity), $C_t$ is the sound speed, $V_\nu$ is the poloidal Alven speed, and $\rho$ is the mass density. These are all measured at the slow magnetosonic point. $E_{mg}$ represents the ratio of magnetic energy to gravitational energy at the equatorial plane of the disk, and $E_{mg,c}$ is the critical value separating the magneto-centrifugally driven jet and the magnetic pressure driven jet, and is $E_{mg,c} \approx 0.01$ in the case of the model for Fig. 7.

2.5 What is a mass accretion rate associated with MHD jets?

As we discussed in the Introduction, MHD jets play an important role on angular momentum transport from disk to outside, enabling efficient accretion of disk plasma onto a central object. In the case of strong magnetic field ($E_{mg} > 10^{-2}$), the magnetic field plays a role of a lever arm which transport angular momentum to the Alfvén radius $r_A \sim V_{\infty}/\Omega$. Then the ratio of accretion rate to mass flux of jets (e.g., Rudits and Norman 1986) becomes

$$\frac{M_{\text{acc}}}{M_{\text{jet}}} \sim \left( \frac{r_A}{r_0} \right)^2 \propto B_p^{4/3}. \hspace{1cm} (13)$$

On the other hand, in the case of weak magnetic field ($E_{mg} < 10^{-2}$), the lever arm is short so that the local angular momentum transport by magnetic stress becomes more important which is equivalent to the physics of magneto-rotorlational instability (or Balbus-Hawley 1991 instability). In this case,

$$\frac{M_{\text{acc}}}{M_{\text{jet}}} \propto B_p^4. \hspace{1cm} (14)$$

where $\mu \sim 0.4 - 1.0$ (Kudoh et al. 1998). For very weak field strength ($E_{mg} \sim 10^{-4}$), the ratio $M_{\text{acc}}/M_{\text{jet}} \sim 10$ (Kudoh et al. 1998).
Figure 8: Mass flux of jets as a function of the poloidal magnetic field at the footpoint of the jet. The shaded line shows $M_{\text{acc}}/M \approx 10$. If $10^{-6} M_\odot/\text{yr} < 10^{-7} M_\odot/\text{yr}$, the wind solution should be within the parameter region that is indicated by a hatched area.

2.4 Application to YSO jets
When we apply the MHD jet model to YSO (young stellar object) jets, we should first note that the typical values of the basic parameters $E_{\text{sh}}$ and $E_{\text{mg}}$ for YSO jets are

$$E_{\text{sh}} \approx 6.5 \times 10^{-4} \left( \frac{T}{10^5 \text{K}} \right) \left( \frac{r}{15 R_\odot} \right) \left( \frac{M}{1 M_\odot} \right)^{-1},$$

$$E_{\text{mg}} \approx 3.8 \times 10^{-3} \left( \frac{B}{10^2 \text{G}} \right)^2 \left( \frac{n}{10^{13} \text{cm}^{-3}} \right) \left( \frac{r}{15 R_\odot} \right) \left( \frac{M}{1 M_\odot} \right)^{-1}. \quad (16)$$

Based on these numbers, we find that the jet velocity, mass flux of jets, and mass accretion rate for YSO jets and associated accretion disks (for $a = 1$ in eq. 14) become

$$V_{\text{jet}} \approx 100 \text{ km/s} \left( \frac{B}{10^2 \text{G}} \right)^{1/3} \left( \frac{n}{10^{13} \text{cm}^{-3}} \right)^{-1/6},$$

$$M_{\text{jet}} \approx 10^{-8} M_\odot/\text{yr} \left( \frac{B}{10^2 \text{G}} \right) \left( \frac{n}{10^{13} \text{cm}^{-3}} \right)^{1/2}, \quad (17)$$

$$M_{\text{acc}} \approx 10^{-6} M_\odot/\text{yr} \left( \frac{B}{10^2 \text{G}} \right) \left( \frac{n}{10^{13} \text{cm}^{-3}} \right)^{-1/2}. \quad (19)$$

Using these formulae and observed physical quantities of YSO jets (velocity and mass flux), we can predict the physical quantities of accretion disks at the footpoint of the jet. Since the observed velocity of YSO jets is a few 100 km/s and the MHD jet theory predicts $V_{\text{jet}} \approx V_a$, the footpoint of the jet must be around $r \sim 15 R_\odot$. Figure 8 shows the possible relation between the mass flux of jets, the temperature of the disk, and the magnetic field strength at $r = R_\odot$ for solar mass protostars when $n = 10^{13} \text{cm}^{-3}$. From this, we can predict that the magnetic field strength at the footpoint of YSO jets is about a few - a few 10 G. We can also see from this figure that the actual YSO jets are intermediate between the magnetic pressure driven jet and the centrifugally driven jet.

3 Collimation of MHD Jets
3.1 Can hoop stress collimate jets?
As the jet propagate farther from the disk, the toroidal component of magnetic field becomes dominant compared with the poloidal component ($B_p$) (see eq. (5)),

$$B_p = B_p \frac{r \Omega}{V_\infty} \propto r, \quad (20)$$

since $V_\infty \rightarrow \text{constant}$. Thus the pinching force $(\nabla \times J \times B)$ becomes important as the jet propagates farther, so that it begins to collimate the jet (Blandford and Payne 1982, Pringle and Norman 1986, Uchida and Shibata 1985, Shibata and Uchida 1986, Sakurai 1985, 1987, Kaburaki and Itoh 1987, Heyvaerts and Norman 1989, Lovelace et al. 1991, Saury and Taingano 1994, Ouyed and Prud'homme 1997, Ushiyama et al. 1999, Bogovalov and Taingano 1999). This force is often called the hoop stress.

Sakurai (1985) numerically solved the trans-field equation (Grad-Shafranov equation) for the first time and obtained the solution which show logarithmic collimation of field lines to the polar direction: $B_p \sim R^{-2+2\nu}/\log R$ where $0 \leq \nu \leq 1$ and $R = (r^2 + z^2)^{1/2}$ is the distance from the origin. Heyvaerts and Norman (1989) confirmed the results of Sakurai (1985) using the analytical approach.

While Sakurai (1985)'s results show that the field lines and jet streamlines are actually collimated into the rotation axis of the disk, the collimation is very slow (i.e., it has a logarithmic dependence).

The results of the nonsteady 2.5D MHD numerical simulations of the MHD jets from accretion disk also show slow collimation of jet streamlines (Kudoh et al. 1999).

This slow collimation seems to be in contradiction with actual observations, since many jets show strong collimation from near the disk. Hence, some researchers began to consider alternative ideas to explain the apparently collimated jet structure; Spruit et al. (1997) proposed that the poloidal field is the main collimating agent. On the other hand, Shu et al. (1995) presented a model in which the density distribution show thin jet-like structure, even though actual fluid flows and field lines do not collimate.

3.2 Do all magnetic field lines collimate?
Sakurai (1985)'s numerical calculation showed that all magnetic field lines collimate in the transverse direction, and Heyvaerts and Norman (1989) analytically confirmed this result. Okamoto (1999), however, presented a different view against this "hoop stress paradigm", and claimed that all field lines cannot collimate. He then proposed that the magnetically driven wind consists of two components, a collimated polar wind and an uncollimated equatorial wind. This argument is based on the $J \times B$ force distribution such that it acts to the polar direction near the pole while it acts to the equatorial plane near the equator. In Sakurai (1985)'s calculation, the current $J$ flowing toward $r$-direction near the equator is not included since his calculation assumed split monopole field initially. If we initially assume a dipole (similar to the pulsar wind case), the wind tends to be in the equatorial direction near the equator.

In relation to this, Kudoh et al. (1999) examined the collimation of the MHD wind/jet, by using time dependent 2.5D MHD numerical simulations. They studied the production of MHD jets in the case of initially non-uniform magnetic fields, 1) a paraboloidal field, 2) a dipole field produced by a ring current, to see how diverging magnetic field lines are collim-
mated by the hoop stress. In the former paraboloidal case, they found that the jet and field line tend to be collimated by the pinching effect of toroidal fields as the torsional Alfvén wave front propagates into the static gas layer (see Kudoh et al. 1999). On the other hand, in the latter dipole case, the magnetically driven outflow consists of not only a collimated polar jet but also an uncollimated equatorial wind (see Fig. 10). This seems to be consistent with Okamoto (1999)’s argument.

In summary, the basic theory of collimation of the MHD jet has not yet been established. Current ideas are controversial, and more work (both analytical and numerical) will be necessary to settle this important issue.

4 Magnetic Reconnection Associated with MHD Jets - Protostellar Flares -

What is occurring in between a protostar and a disk? Shu et al. (1994) presented a model in which a disk does not have magnetic field and penetrate into stellar magnetosphere through the “X region” (hence this model is called the X-wind model), trying to explain angular momentum transport between a star, a disk, and a jet, and also the production of the jet from the “X-region.” Though this model has some interesting points, there are a number of uncertainties in this model.

The biggest uncertainty is the presence of the “X-region.” This is the most important point of this model, but unfortunately there is no convincing proof (or quantitative calculation) on the existence of such “X-region.” Even if the X-region is misleading, since it has no relation to X-point magnetic reconnection. Disk plasmas simply go through the X-region by diffusion process, though the physical origin of such diffusion remained puzzling. It seems that this region was artificially introduced to maintain steady state. The actual state of the region between a star and a disk would be much more dynamic and nonsteady than what the X-wind model assumed (e.g., Hirose et al. 1997; Hayashi et al. 1996). In fact, recent observations of protostars with X-ray satellite ASCA and ROSAT have revealed that protostars are frequently producing superhot flares with temperature of 10^6 K (Koyama et al. 1996, Montmerle 1999, Tsuboi et al. 1998). Even the jet itself seems to be very nonsteady; knot structures seen in many optical jets (e.g., Burgarella et al. 1993) could be a result of nonsteady production of jets.

Hayashi, Shibata, Matsumoto (1996) presented a magnetic reconnection model of protostellar flares, by performing 2.5D time dependent MHD numerical simulations of interaction between an accretion disk and stellar magnetosphere (dipole magnetic field). Figure 12 shows one of their simulation models. They assumed that accretion disk plasma enter the stellar magnetosphere (i.e., accretion disk is penetrated by stellar dipole field at t = 0), and then examined the following evolution of the interaction between a rotating disk and a stellar dipole field. The initial process occurring near the disk is basically the same as those in the nonsteady MHD jet model (e.g., Shibata and Uchida 1986); the disk plasma twists magnetic field and thus generated magnetic twist and associated J × B force (magnetic pressure and centrifugal force) accelerates the plasma in the surface layer of the disk to form an MHD jet from the disk. In this case, the magnetic twist is accumulated in a closed loop, increasing the magnetic pressure of the loop, which eventually leads to the ejection of the magnetic loop after about one orbital period of the disk. After the ejection of the loop, a current sheet is created inside the loop, leading to fast reconnection there. This process is similar to that occurring in solar coronal mass ejections, and basic reconnection mechanism is the same as in solar flares (e.g., Tsuneta et al. 1992, Shibata 1996, Yokoyma and Shibata 1998). The reconnection releases huge amount of magnetic energy of order of 10^{36} erg (about 10^{8} times more energetic than solar flares) stored in the sheared loop with a size of L ~ 10^{11} cm. The temperature of super hot plasma created by the reconnection amounts to

\[ T \sim 10^8 \left( \frac{B}{100G} \right)^{6/7} \left( \frac{n_0}{10^3 \text{cm}^{-3}} \right)^{-1/7} \left( \frac{L}{10^{11.5} \text{cm}} \right)^{2/7} \text{K}, \]

which is based on the balance between reconnection heating and conduction cooling (Yokoyma and Shibata 1998, Shibata and Yokoyma 1999). Here n_0 is the pre-flare coronal density. These results explain characteristics of protostellar flares observed by ASCA and ROSAT. Hayashi et al. (1996) suggested
that the cold jet ejected from the disk and the hot plasmodoid
emission may correspond to high speed neutral winds and optical jets, respectively (see Fig. 12).

Similar numerical simulations have been done by Miller and Stone (1997) and Romanova et al. (1998). These simulations revealed that the production of MHD jets are closely related to magnetic reconnection (possibly protostellar flares). Hence it would be interesting to observationally study the relation between protostellar flares and production of jets. (See also Hayashi et al. (1999) on quasi-periodic ejections of plasmodoids and associated reconnection with periodicity of about an orbit of the disk.)

Puruya et al. (1999) recently discovered an evidence of a very tiny jet (with a length of order of a few tens AU) by radio interferometric observations. Since the time scale of this jet is a few tens years, there is a high possibility that we can observe both a big flare and an associated MHD jet within a few -10 years. Hence if big flares occur in such protostars, it would be very interesting to search for jets near such protostars.

5 Summary
1) MHD jets are accelerated by both magnetic pressure and (magnetico-)centrifugal force. The magnetic pressure plays a dominant role for weak field case \( E_m = (V_e/V_f)^2 < 0.01 \), while the centrifugal force is dominant for strong field case \( E_m > 0.01 \).
2) Mass flux of MHD jets is given by
\[
\dot{M} = 4n_{\text{dow}} C_s B p_{\text{p}}^2 \frac{B}{B}
\]
\[\propto B_p \quad \text{for weak field} \quad (E_m < 10^{-2}),\]
\[\text{const.} \quad \text{for strong field} \quad (E_m > 10^{-2}).\]
3) The terminal speed of MHD jets is given by the Michel velocity and is comparable to Keplerian speed
\[
V_{\text{in}} = \left( \frac{\Omega^2 R^4}{M} \right)^{1/3} = \sqrt{\frac{\rho_{\text{dow}}}{\rho_0}}^{1/6} \left( \frac{E_m}{E_{\text{th}}} \right)^{1/6}
\]
\[\propto B_p^{1/3} \quad \text{for weak field} \quad (E_m < 10^{-2}),\]
\[\propto B_p^{1/3} \quad \text{for strong field} \quad (E_m > 10^{-2}).\]
4) The ejection point of MHD jets is determined by the Blandford-Payne potential: a jet begins to be accelerated after the runaway collapse phase is stopped and the accretion phase begins.
5) The hoop stress due to toroidal fields can collimate MHD jets at least around the polar axis.
6) There is a possibility that the entire jet/wind consists of two components: a collimated polar jet and a non-collimated equatorial wind.
7) Magnetic reconnection (possibly, protostellar flares) occurs in close association with production of jets.

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