

MHD Jets, Flares, and Gamma Ray Bursts

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Abstract

Recent numerical simulations of MHD jets from accretion disks are briefly reviewed with emphasis on the scaling law for jet speed and the role of magnetic reconnection in relation to time variability in accretion disks, jets, and flares. On the basis of these studies, possible interpretation is given on why statistical properties of peak intensity, peak interval, and peak duration of gamma ray bursts (log-normal distribution) are different from those in solar flares and black hole accretion disks (power-law distribution). From these considerations, a new model, “magnetized plasmoid model”, is proposed for a central engine of gamma ray bursts.

1 Introduction

Recent development of astronomical observations has revealed that our universe is full of enigmatic explosive phenomena, such as jets, bursts, and flares. Jets ejected from active galactic nuclei (AGN) are probably among the biggest in size and the most energetic in total energy. Similar jets on much smaller scale have been found in young stellar objects (YSO) as well as in close binary system. These active objects show vigorous time variability, often called bursts or flares, in optical, radio waves, X-rays, etc., in almost all electromagnetic spectrum. Though the central objects and jets in AGNs, YSOs, and binary system are quite different in mass and size, there are many similar properties in them, such as time variability, morphology of jets, and existence of accretion disks.

Gamma ray bursts (GRBs) were discovered nearly 30 years ago. Since then, they have remained the most enigmatic object in our universe. Recent rapid development of observations, however, is uncovering a part of enigma of GRBs (e.g., Fishman and Meegan 1995, Piran 1999, Meszaros 2002); (1) they occur in cosmological distance (i.e., most luminous in our universe, $\sim 10^{51-53}$ erg/s, but different from AGNs), (2) there is evidence that they are emitted from relativistic jets via synchrotron emission, and (3) some GRBs (long bursts) seem to be associated with supernovae. Some

properties are similar to those of AGN jets (blazars), suggesting common physics in blazars and GRBs.

On the other hand, recent space observations of our Sun, the nearest star, have revealed that the solar corona is full of jets and flares. Though the total energy of the solar jets and flares is much smaller than those in cosmic jets and flares, the spectrum and time variability of electromagnetic waves emitted from solar flares are quite similar to those of cosmic flares, suggesting common physical origin. In the case of the solar flares, it has been established that magnetic field is the source of energy, so that the knowledge of solar jets and flares will be useful for understanding the role of magnetic field in cosmic jets and flares in distant stars and galaxies.

In this article, we first briefly review recent understanding of magnetically driven jets from accretion disks (as a model of AGN jets). We then discuss flares and magnetic reconnection associated with production of jets, especially in the case of protostars. Finally, we discuss similarity and differences in time variability of GRBs, black hole accretion disks, and solar flares, and on the basis of these observations, we propose a new model for central engine of GRBs.

2 MHD Jets

Magnetically driven jets from accretion disks (Fig. 1) were first proposed to explain jets from active galactic nuclei (Blandford 1976, Lovelace 1976, Blandford and Payne 1982). After the discovery of CO molecular bipolar flows in star forming regions (Snell et al. 1980), the MHD jet model started to be applied to bipolar flows and jets from young stars (Uchida and Shibata 1985, Pudritz and Norman 1986). 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).

The MHD jet model (e.g., Tajima and Shibata 1997, Ferrari 1998, 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.

Shibata and Uchida (1986) and subsequent many 2.5D MHD numerical simulations (Stone and Norman 1994, Matsumoto et al. 1996, Hirose et al. 1997, Ouyed and Pudritz 1997, Kudoh et al. 1998, 2002, Kuwabara et al. 1999, Ustyugova et al. 1999, Kato et al. 2002) and 3D MHD simulations (Matsumoto and Shibata 1997, Ouyed et al. 2003) have revealed that *the velocity of MHD jets is of order of Keplerian velocity at the footpoint of MHD jets*. Kudoh et al. (1998) and Kato et al. (2002) have shown that the jet velocity has a weak dependence on B (Fig. 2);

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

Fig.4

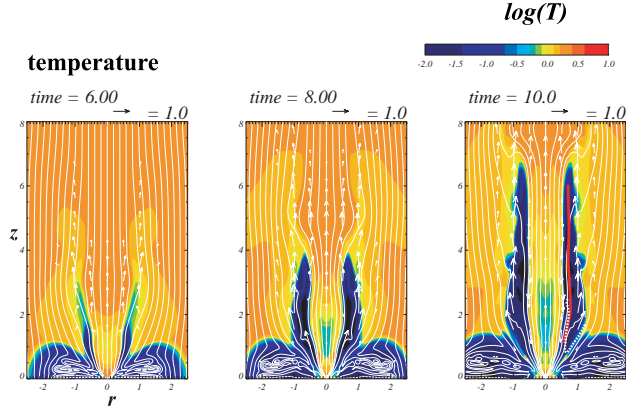


Figure 1: Typical example of 2.5D MHD numerical simulations MHD jets from a thick disk (Kudoh et al. 2002). Note that the disk becomes turbulent because of magneto-rotational instability.

Here, $E_{mg} = (V_A/V_k)^2 \propto B_p^2$, and B_p is the initial poloidal magnetic field strength.

This is consistent with the results of one-dimensional steady jet theory (Kudoh and Shibata 1995, 1997), and also can be derived semi-analytically using the Michel (1969)'s relation;

$$V_\infty \simeq \left(\frac{\Omega^2 B_p^2 r^4}{\dot{M}} \right)^{1/3}. \quad (2)$$

Here, Ω is the angular speed of the disk at the footpoint of the jet, r is the radial distance from the central object, and \dot{M} is the mass flux of the jet.

It is very important to note that the terminal velocity strongly depends on the mass flux \dot{M} . In our problem, the mass flux is given by

$$\dot{M} \simeq 4\pi \rho_{slow} V_{slow} r^2 \simeq 4\pi \rho_{slow} C_s \frac{B_p}{B} r^2, \quad (3)$$

where ρ_{slow} is the mass density at the *slow magnetosonic point*, V_{slow} is the slow magnetosonic speed, C_s is the sound speed, and $B = (B_p^2 + B_\varphi^2)^{1/2}$. In a cold disk, the slow magnetosonic point corresponds to the local maximum of the effective gravitational (Blandford-Payne) potential, and is located near the disk plane ($\rho_{slow}/\rho_0 \sim 0.1$ in our case). For stronger fields ($E_{mg} > 10^{-2}$), the magnetic field lines become straight $B \sim B_p \gg B_\varphi$ so that the mass flux does not depend on B_p , but for weaker fields ($E_{mg} < 10^{-2}$), field lines are highly twisted and the azimuthal component becomes

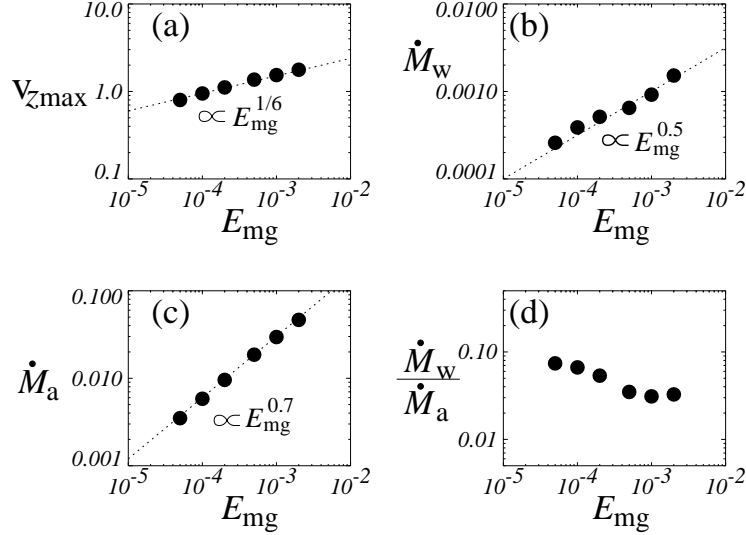


Figure 2: (a) Maximum velocity of jets in unit of Keplerian velocity at the footpoint of jets. (b) Mass flux of jets. (c) Mass accretion rate. (d) Ratio of mass flux of jets to mass accretion rate. All data are based on 2.5D nonsteady MHD simulations in the case of thick disks (Kudoh et al. 1998)

dominant $B \sim B_\varphi \gg B_p$ near the disk so that the mass flux is in proportion to B_p (Kudoh and Shibata 1995, 1997). Considering these effects, the terminal speed of the MHD jet becomes

$$\frac{V_\infty}{V_k} \simeq \left(\frac{\rho_{slow}}{\rho_0} \right)^{-1/6} E_{th}^{-1/6} E_{mg}^{1/6}, \quad (4)$$

where $E_{th} = (C_s/V_k)^2 = (\text{thermal energy}) / (\text{gravitational energy})$, $E_{mg} = (V_A/V_k)^2 = (\text{magnetic energy}) / (\text{gravitational energy})$. Since $\rho_{slow}/\rho_0 \sim 0.1$ and $E_{th}/E_{mg} \simeq \beta = \text{gas pressure} / \text{magnetic pressure} \sim 1 - 10$ in the disk, we find that *the terminal speed of the jet is comparable to the Keplerian velocity* for wide range of poloidal magnetic field strength, and $V_\infty \propto B_p^{1/3}$. This explains the results (eq. 1) of the previous 2.5D MHD numerical simulations very well.

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* ($V_{jet} \sim 0.1 - 1.0 V_k$ for $E_{mg} \sim 10^{-8} - 10^{-2}$). The physical reason is that magnetic field lines are highly twisted by the differential rotation of the disk until the local magnetic energy density ($B_\varphi^2/8\pi$) becomes comparable to the rotational energy ($\rho V_k^2/2 \sim \rho GM/r$ gravitational energy) at the surface of the disk. Since the kinetic energy of the jet ($\rho V_{jet}^2/2$) comes from the magnetic energy, it eventually becomes comparable to the gravitational energy ($\rho V_k^2/2$) at the disk surface (i.e., at the slow magnetosonic point).

This process is similar to the magneto-rotational instability (Balbus and Hawley 1991) in the sense that the magnetic effect becomes eventually important even if the initial magnetic field is very weak.

Recently, Koide et al. (1998, 2000, 2002) have succeeded to extend these newtonian MHD simulations of jets to general relativistic MHD versions. They have shown that the accretion (and the jet ejection) become more violent near black hole than in the newtonian case. They confirmed the extraction of rotational energy from a Kerr hole by the effect of magnetic field. The maximum Lorentz factor of jets in these simulations is still of order of 2, much smaller than those observed for AGN jets (Lorentz factor 10-100) and GRBs (Lorentz factor 100-1000). We do not know yet whether this result (small maximum Lorentz factor) is simply a result of numerical limitations, or a result of physics.

It is important to note that the jet ejection has never reached steady state, even if the velocity and mass flux of the jet is well explained by steady theory (Kudoh et al. 1998). Recently, Sato et al. (2003) have succeeded to run the MHD simulation of jets including accretion disk self-consistently for many orbital periods (up to 15-20 orbits), and revealed that the jet ejection is intermittent and often associated with transient accretion events. They found that accretion disk is fully turbulent (due to magneto-rotational instability), and full of reconnection event. Often the jets are ejected in association with such reconnection events. The time variability of mass accretion rate in a simulated accretion disk show power law in the power density spectrum as first noted by Kawaguchi et al. (2000).

3 Flares : Magnetic Reconnection

Recent space solar observations such as Yohkoh, SOHO, TRACE have revealed that *solar corona is much more dynamic than had been thought, and is full of flares, microflares, nanoflares, jets, and various mass ejections*. Among them, the largest mass ejections are called coronal mass ejections (CMEs). It has also been revealed that the reconnection plays essential role not only in large scale flares and CMEs, but also small scale flares and jets, leading to unified model (e.g., Shibata 1999).

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 dipole magnetic field. Figure 3 shows one of their simulation results. They assumed that an accretion disk is penetrated by stellar dipole field at $t = 0$, and examined the subsequent 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 magnetic field is twisted by the rotating disk, and the $\mathbf{J} \times \mathbf{B}$ force associated with the twist accelerates the plasma in the

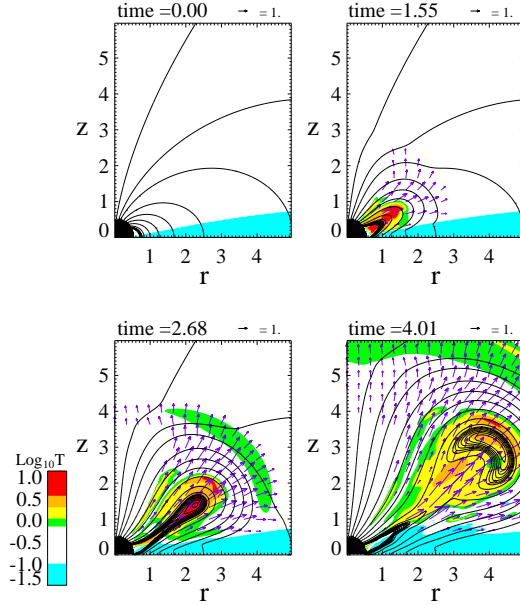


Figure 3: A magnetic reconnection model of protostellar flares (Hayashi et al. 1996). It is assumed that at $t = 0$ a stellar dipole magnetic field penetrates an accretion disk. The parameters in the initial disk (at $r = 1$) are $E_{th} = 2 \times 10^{-3}$, $E_{mg} = 2 \times 10^{-4}$. The color shows the temperature, and solid curves denote magnetic field lines. The arrows depict velocity vectors in r - z plane.

surface layer of the disk to form an MHD jet in bipolar directions. 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 orbit. 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 1999, Yokoyama and Shibata 2001). The reconnection releases huge amount of magnetic energy of order of 10^{36} erg (about 10^4 times more energetic than solar flares) stored in a sheared loop with a size of $L \sim 10^{11}$ cm.

The temperature of super hot plasma created by reconnection amounts to

$$T \sim 10^8 \left(\frac{B}{100\text{G}} \right)^{6/7} \left(\frac{n_0}{10^9\text{cm}^{-3}} \right)^{-1/7} \left(\frac{L}{10^{11.5}\text{cm}} \right)^{2/7} \text{ K}, \quad (5)$$

which is based on the balance between reconnection heating and conduction cooling (Yokoyama and Shibata 2001, Shibata and Yokoyama 2002). Here n_0 is the pre-flare coronal density. These results explain characteristics of protostellar flares observed by ASCA and ROSAT (e.g., Koyama et al. 1996, Shibata and Yokoyama 2002).

4 Gamma Ray Bursts

It is well known that the gamma ray burst light curves are very similar to those of solar flare gamma rays and hard X-rays. Hence, it was often considered that there may be some physical similarity between gamma ray bursts and solar flares. Recently, it has in fact been revealed that there is evidence that gamma ray bursts are emitted from collimated jets, which might be similar to relativistic jets from active galactic nuclei. If this is so, MHD jet models developed for AGN jets can be applied to gamma ray bursts. There is also evidence that some neutron stars have very strong magnetic fields up to 10^{15} G, called magnetars (Duncan and Thompson 1992, Kouveliotou et al. 1999). Hence, the GRB model including strong magnetic field has been proposed (e.g., Kluzniak and Ruderman 1998). On the other hand, recent theory of accretion disks showed that magnetic field is essential for generating viscosity through the occurrence of magneto-rotational instability (Balbus and Hawley 1991). Altogether, the role of magnetic field in gamma ray bursts is considered to be more and more important than had been thought.

Here we shall discuss analogy between solar flares/coronal mass ejections (CME) and gamma ray bursts, emphasizing the basic MHD physics of solar flares/CMEs.

As we discussed above, the time variability of gamma ray burst light curve is similar to those of solar flares. The power spectrum analysis of time variability of gamma ray bursts (Beloborodov et al. 2000) and solar X-ray emission (Ueno et al. 1997) show that both show power-law distribution with index $\alpha \sim 1.5 - 1.8$. Interestingly, the X-ray light curve of Cygnus X-1 (black hole candidate) also show similar time variability with power law spectrum (Miyamoto et al. 1992, Negoro 1992).

However, there is a fundamental difference in statistical properties between gamma ray bursts and solar flares. That is, many physical quantities in solar flares, such as duration, peak intensity, peak interval, show power-law frequency distributions, while these quantities in gamma ray bursts do not show power-law distribution but show log-normal distribution (Li and Fenimore 1996; see Fig. 4). In other words, there is no characteristic time and intensity in solar flares, whereas there is characteristic time and intensity in gamma ray bursts. What does this mean? In spite of apparent similarity between solar flares and gamma ray bursts, does this suggest that basic physics of gamma ray bursts is different from that of solar flares?

In relation to this, Negoro and Mineshige (2002) recently found interesting fact on statistical properties of X-ray shots (sub-bursts) emitted from black hole accretion disks: If only large shots are picked up from the time variability of X-ray emission of accretion disk, the distribution of shot peak become log-normal. They argued that the X-ray shots are occurring at the surface of accretion disks, and hence may be similar to solar flares and do not have characteristic time scale (Ueno et al. 1997, Kawaguchi et al. 2000). On the other hand, according to internal shock model of

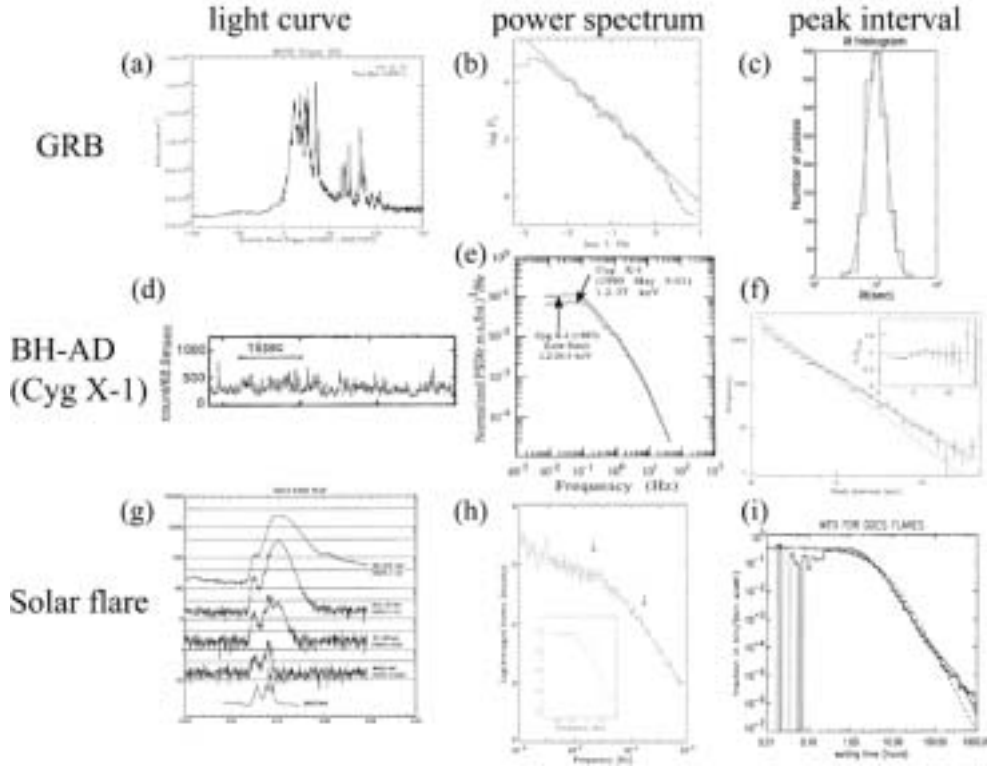


Figure 4: Light curves of (a) GRBs (<http://www.batse.msfc.nasa.gov/batse/grb/lightcurve>), (d) black hole accretion disks (BH-ADs, Miyamoto et al. 1992), (g) solar flares (Zirin et al. 1971), power density spectra of (b) GRBs (Belobodorov et al. 2002), (e) BH-ADs (Miyamoto et al. 1992), (h) solar flares (Ueno et al. 1997), and histograms of time intervals of (c) GRBs (Nakar and Piran 2002), (f) BH-ADs (Negoro et al. 1995), and (i) solar flares (Wheatland 2000).

gamma ray bursts (e.g., Meszaros 2002), the burst emissions are from internal shocks in the jet ejected from central engines. If the jets are ejected in association with X-ray shots, only large shots can eject enough mass to generate internal shock. This explains log-normal distribution in the duration and peak intensity of GRB.

Similar discussion may be applied to solar flares. In the case of solar flares, there is a tendency that larger flares produce larger mass ejections, called coronal mass ejections (CMEs). It is difficult for small flares to eject much mass from solar surface, because they do not have enough energy to escape from magnetically confined solar active regions. Aoki et al. (2003) examined this property by using actual data. Figure 5 shows number of CMEs associated with solar flares versus peak X-ray flux of those flares, indicating that log-normal distribution roughly holds. The number of CMEs versus CME speeds also show similar log-normal distribution.

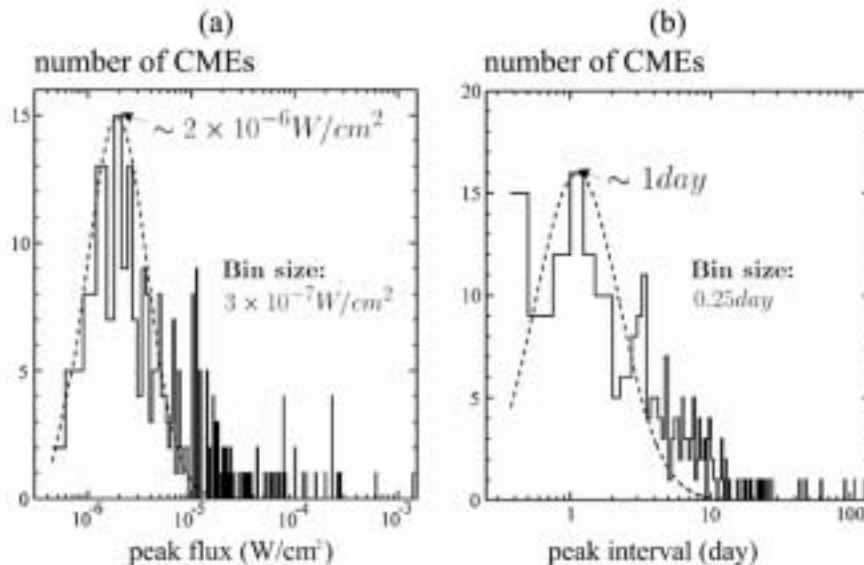


Figure 5: (a) Number of CMEs associated with solar flares vs. peak X-ray intensity of these flares, (b) number of CMEs associated with solar flares vs. peak interval of these flares (from Aoki et al. 2003).

Hence we propose a new model for gamma ray bursts (see Figure 6), which is basically in the same line of thought as that of Negoro and Mineshige (2002): magnetic reconnection (flares) occurs everywhere in the surface of accretion disks, whose spatial distribution is fractal, and time variability is power-law, both of which are quite similar to those of solar flares. Only ejecta from energetically and spatially large reconnection events (flares or shots) can escape from magnetosphere of accretion disks to form jets. In fact, nonsteady MHD simulations of magnetically driven jets from accretion disks (Kudoh et al. 2002, Kuwabara et al. 2002, Sato et al. 2003) show that the ejection of jets is highly time variable, intermittent, and base of jets is full of reconnection events; when large reconnection events occur, large plasmoid ejection occurs, like the protostellar flare model (Hayashi et al. 1996, Miller and Stone 1997, Goodson et al. 1999). Jets have non-uniform density distribution, consisting of intermittently ejected plasmoid (confined in magnetic island or helical field in 3D space) like solar coronal mass ejections. It is natural that these intermittently ejected magnetized plasmoid produce lots of internal shocks, which are site of gamma ray emission as modeled in internal shock model of gamma ray bursts.

There is another merit in this “magnetized plasmoid model” (or “flare/CME model”). Ejected plasmoid has a structure similar to spheromak. It is well known that spheromak is unstable to tilting instability (e.g., Hayashi and Sato 1984), so that ejected spheromak-like plasmoids would have various angles to the direction of the

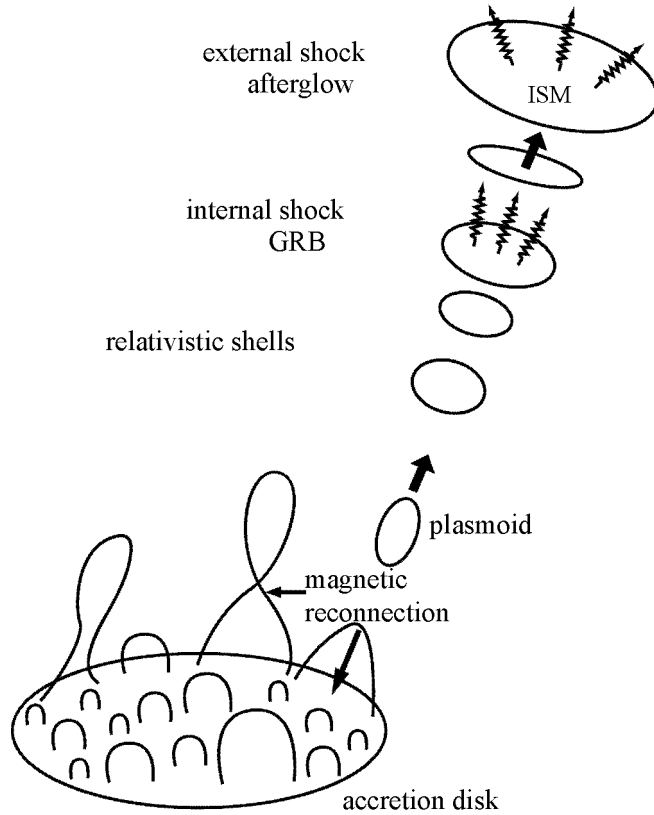


Figure 6: Schematic illustration of “magnetized plasmoid model” (or flare/CME model) of gamma ray bursts (Aoki et al. 2003).

ejection as they propagate. Hence they collide with each other, and there is a high possibility that tangent magnetic field has an opposite component, thus leading to magnetic reconnection. This means that even if the initial energy conversion from magnetic energy to plasma energy (kinetic and internal) is not efficient, it is possible that all magnetic energy (Poynting flux) contained in magnetized plasmoids would eventually be converted to plasma energy through magnetic reconnection. It should also be noted that magnetic reconnection generate lots of MHD shocks: Petschek slow shocks are formed just sides of reconnection jets, and fast shocks are created when reconnection jets collide with ambient medium (e.g., Yokoyama and Shibata 2001). These situations, containing lots of shocks as well as X-type and O-type neutral points, are similar to fractal MHD turbulence, and very suitable for high energy particle acceleration. Such fractal structure or fractal reconnection (Shibata and Tanuma 2001, Tanuma et al. 2001) may be the origin of power-law time variability spectrum of solar flares, black hole accretion disks, and GRBs.

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Discussion

J. Rhoads: How do you generalize the relation $V_{jet} = v_{escape} = v_{Kepler}$ to the highly relativistic case? Here $V_{jet} = v_{escape} = c$ is obvious, but it is not clear if $\Gamma_{jet} = \Gamma_{escape}$. For the Newtonian case, I assume that V_{escape} is measured in the region where the jet is launched. Trying to apply the same idea to the $\Gamma = 100$ flow in a GRB would imply the jet is launched barely outside the event horizon. This seems improbable. How do we explain this?

K. Shibata: You are right. In the Newtonian case, our theory explains observed speeds of various jets very well, such as protostellar jets, SS433 jets, jets from cataclysmic variables, and so on. However, in the relativistic case, we have not yet succeeded to explain observed large Lorentz factor of AGN jets and gamma ray bursts.

M. Lyutikov: In case of a rotating BH the flow is generated on field lines that do not cross BH horizon, but thread the ergosphere.

K. Shibata: Koide et al. (2002) successfully simulated such case.

A. Beloborodov: Keplerian timescale is very short (ms) to explain the main variability in GRBs (0.1-10 s). Should the accretion timescale appear as a characteristic time in the model variability spectra?

K. Shibata: MHD numerical simulations of accretion disks and jets revealed that the time variability of accretion rate show temporal $1/f^\alpha$ fluctuation (Kawaguchi et al. 2000, Sato et al. 2003), i.e., there are continuous distribution on time scales, which includes the one much longer than Keplerian time scale. The longest time scale of variability is probably related to duration of main accretion and/or dynamo in our magnetized accretion disks.

S. Woosley: Getting 10% of the accreted mass into the jet is too much in the context of GRBs. Γ of 2 may be OK initially but very important is the energy loading of that matter. Do you follow energy generation or are your jets all "cold" ? Do you see the energy loading might be increased ?

K. Shibata: The jet with 10% of the accreted mass is a cold, dense jet directly ejected from cold part of the disk. We found another component of a jet ejected from hot corona with less material. Since our mechanism can produce enough poynting flux to explain total energy of GRBs, we suggest magnetic reconnection in the corona and jet might explain the energy loading. Such simulations of jets including reconnection in general relativistic regime should be done in future.

A. Hujerit: The Blandford & Payne 1982 and my calculations predict the existence of a super-Keplerian transition layer between the disk and the corona. Why do your calculation don't predict such a layer ?

K. Shibata: Our calculations also show such super-Keplerian layer just above the disk (see e.g., Shibata and Uchida 1986, Kudoh and Shibata 1997).

A. Brandenburg: Why does the magnetic field not penetrate the black hole horizon? This seems to be quite a general phenomena in relativistic electrodynamics. What is the force preventing this ?

K. Shibata: In our simulations, we adopt the coordinate system such that the time proceeds slowly near the event horizon, so that accreting plasmas and magnetic field lines have not yet penetrated into the event horizon in our results.

C. Fendt: Your statement about the highly intermittant jet formation was derived from ideal MHD simulations of the disk. What happens if you include turbulence or diffusion ? Will it stabilize the jet formation?

K. Shibata: Kuwabara et al. (2002) studied the effect of resistivity on jet formation. According to them, if the resistivity is large ($R_m = rV_k/\eta < 100$), the jet formation is suppressed. In the intermediate regime ($100 < R_m < 1000$), the quasi-steady jet is formed. In the case of weak resistivity ($R_m > 1000$), the results show formation of jets with high time variability and intermittency.