MHD Flares and Jets in the Sun, Stars, and Accretion Disks

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Abstract.
Recent observations of the Sun, stars, and accretion disks (active galactic nuclei, close binary systems, young stellar objects) show that these objects are much more dynamic than it had been thought and are full of flares and jets with many common properties. In this article, we give unified view and model of these flares and jets, in the Sun, stars, protostars, accretion disks, and gamma ray bursts, on the basis of magnetohydrodynamic (MHD) interpretation.

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INTRODUCTION

Recent development of astronomical observations has revealed that the universe is full of flares and bursts. For example, recent space solar observations, such as by Yohkoh, SOHO, TRACE, have revealed that the solar corona is much more dynamic than it had been thought, and the corona is full of flares, microflares, and nanoflares. The X-ray astronomy satellite, such as ASCA, XMM-Newton, Chandra, on the other hand, discovered a lot of flares in young stars, and the gamma ray astronomy satellite, BATSE, Beppo-SAX, HETTI, etc. observed many gamma ray bursts, uncovering the nature of these bursts. Interestingly, the time variation of the X-ray and gamma ray emissions of these cosmic flares and bursts are quite similar to those of solar flares, suggesting common physics.

Indeed these new observations revealed that mass ejections and jets are ubiquitous in our universe and they are often associated with these flares and bursts. Jets ejected from the nucleus of active galaxies or quasars (AGN jets) are one of the oldest examples of jets in the universe. It has also been found that jets and outflows are ejected during the course of star formation, and are also seen in close binary systems. Jets from X-ray binaries are similar to jets from quasars, so they are called microquasars. These jets are often associated with flares in microquasars. Our nearest star, the Sun, also showed that coronal mass ejections (CMEs) and jets are often associated with flares and microflares.

In the case of the solar phenomena, it is well known that active phenomena, such as flares, CMEs, jets, are all consequence of magnetic activity. Magnetic fields are created by dynamo action in the convection zone, and rise up to the surface by magnetic buoyancy. In the atmosphere, plasma beta (p_{gas}/p_{mag}) becomes less than unity, i.e., a magnetically dominated gas layer is created, so that once magnetic energy is released,

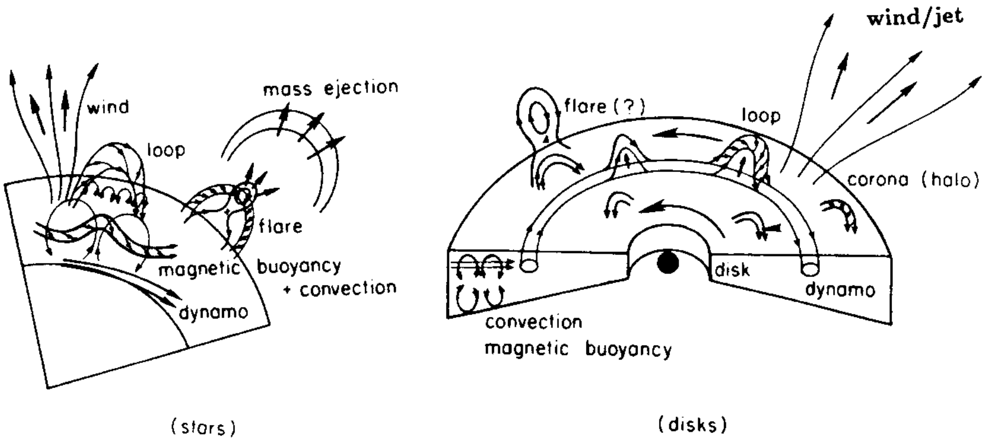

FIGURE 1. Basic magnetohydrodynamic processes in the Sun and stars (a) and in accretion disks (b) (from [60]).

the influence to plasma is huge, and violent heating and mass ejection occur. This is why flares, corona, CMEs, and even solar wind occur. The same physical processes are expected to be occurring in many stars (especially in cool stars). Similar, but more violent activity may be occurring in accretion disks and galactic disks (Fig. 1).

The purpose of this paper is to briefly review recent development of our understanding of flares and jets in the Sun, stars, and accretion disks in a unified fashion on the basis of magnetohydrodynamics.

SOLAR FLARES

Solar flares have been observed with Hα line at ground based observatories, and are known to show two ribbon bright patterns in Hα images. From this, a standard reconnection model, called CSHKP model (after Carmichael [4], Sturrock [59], Hirayama [10], Kopp and Pneuman [19]), has been proposed which predicted the formation of cusp-shaped hot flare loops or arcades. Yohkoh soft X-ray observations indeed discovered cusp-shaped flare loops [61] and as a result, the standard reconnection (CSHKP) model has been finally established.

However, cusp-shaped flares are rather rare, and many flares do not show cusps. Observations revealed that cusps are observed mainly in *long duration event (LDE) flares*, which are long lived (duration more than 1 hours), and large in size, but the occurrence frequency is small. On the other hand, many flares (often called *impulsive flares*) are short lived, small in size, occurrence frequency is large, but show only simple loop structure. Hence, at first some people argued that the observed “simple loop” structure of many flares was anti-evidence of magnetic reconnection.

It was Masuda in 1994 [34] who changed this situation dramatically. He discovered the top loop hard X-ray source high above the simple soft X-ray loop. Since a hard X-ray source is produced by high energy electrons, this is the evidence that the high energy process related to the central engine of flares is NOT occurring in the soft X-ray loop but above the loop. Hence, even non-cusped loop flares may be energized by the magnetic reconnection high above the loop, similarly to the reconnection in cusp-shaped flares [34]. Then, a unified model started to be proposed, which predicted the plasmoid ejection high above the loop top hard X-ray source [48].

Indeed, many plasmoid ejections have been discovered above the Masuda type loop flares [48], [62], [38], [39], [40]. It is interesting to note that strong acceleration of plasmoid ejection occur during the impulsive phase of flares. This may be a hint to understand why and how fast reconnection occur in real flares [52].

About half of coronal mass ejections (CMEs) occurs in association with flares, but other half is not associated with flares. This led some people to argue that CMEs are fundamentally different from flares. However, YOHKOH/SXT revealed the formation of giant arcades at the foot of CMEs. These giant arcades are very similar to cusp-shaped flares in morphology, but very faint in soft X-rays and Hα, and cannot be seen in non-imaging observations of soft X-rays (such as GOES) or hard X-rays. Only imaging soft X-ray observations can reveal the existence of giant arcades. It was found that most of the non-flare CMEs are associated with these giant arcades. Recent MHD modelling of CMEs (Forbes, Antiochos, Chen, Shiota et al.) also show formation of cusps (arcades) and ejection of plasmoid (flux rope in 3D) like in the standard (CSHKP) flare model.

Recent space solar observations revealed that the solar atmosphere is full of small scale flares, called microflares, nanoflares, and even picoflares, and that these small scale flares are often associated with jets. Good examples of such jets are the X-ray jets discovered by YOHKOH/SXT [47], [55]. There are lot of observational evidence that these jets are produced by magnetic reconnection [50]. Yokoyama and Shibata [65], [66] performed MHD simulation of reconnection between emerging flux and overlying coronal field and explained observations of X-ray jets with simulation results. Direct extent of this 2D model to 3D has been carried bout by Isobe et al. [12] using the Earth simulator, which revealed the generation of Rayleigh-Taylor instability in the emerging flux which results in the formation of filamentary structure and associated patchy reconnection, in agreement with the observations.

Table 1 summarizes solar “flare” observations from microflares to giant arcades. The size and time scales range in wide values, from 1000 km and 100 sec for microflares to 1M km and 2 days for giant arcades. However, it is interesting to note that if we normalize the time scale by the Alfven time, then the normalized time scale becomes similar, $100-300t_A$ (Alfven time). So that this is another evidence that these “flares” may be unified with a single mechanism, that is, magnetic reconnection. As we have seen, mass ejections are ubiquitous in these “flares”. However, the morphology is very different between large scale flares and small scale flares. In large scale flares (e.g., giant arcades, LDE flares, impulsive flares), mass ejections (CMEs, filament eruptions) are bubble or flux rope types, while in small scale flares (e.g., microflares, nanoflares), mass ejections are jets or jet-like. What is the reason for this difference? Our answer is as follows. According to our view (Figure 2), the plasmoid ejection is a key process to cause fast reconnection (so we call “plasmoid-induced-reconnection”), since a plamsoid (magnetic island or helical flux rope in 3D) is a natural structure created in the current sheet as a result of tearing instability. In the case of large scale flares, plasmoids (flux ropes) can keep their structure, so that many CMEs look like flux rope, whereas in the

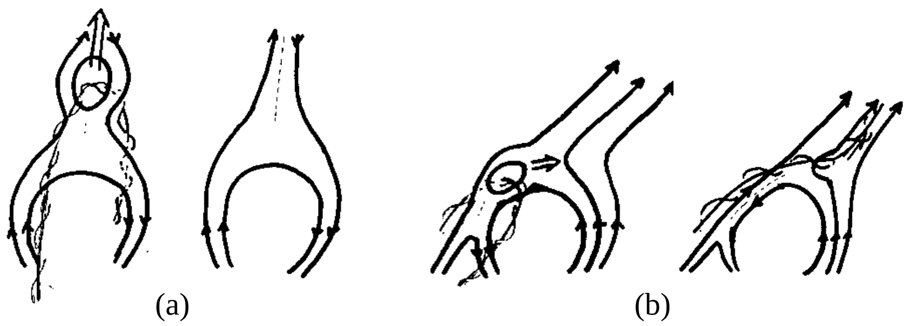

FIGURE 2. Unified model (*plasmoid-induced-reconnection model*) of solar flares and flare-like phenomena (Shibata 1999)[50]: (a) large scale flares (giant arcades, LDE flares, impulsive flares), (b) small scale flares (microflares, nanoflares).

TABLE 1. Summary of Observations of Various "Flares"

"flare"	size (L) (10^4 km)	time scale (t) (sec)	Alfven time (t_A) (sec)	t/t_A	mass ejection
microflares	$0.5-4$	$60 - 600$	$1-10$	~ 100	jet/surge
impulsive flares	$1-10$	$60 - 3\times10^3$	$10-30$	$60-100$	plasmoid/filament eruption
LDE flares	$10-40$	$3\times10^3-10^5$	$30-100$	$100-300$	CME/plasmoid/ filament eruption
giant arcades	$30-100$	$10^4-2\times10^5$	$100-1000$	$100-300$	CME/plasmoid/ filament eruption

case of small scale flares, the plasmoids soon collide and reconnect with the ambient field, and disappear (lose their structure) eventually. The only remnant is the spinning helical jet along the reconnected field line and associated Alfven waves. This explains why jets are usually observed in association with small scale flares. This is still a conjecture and should be tested by future observations. It is interesting to note that some observations [27], [41], [1] have revealed the formation of spinning (helical) jets which may be evidence of the above unified model.

STELLAR AND PROTOSTELLAR FLARES

Stellar flares show X-ray light curves similar to those of solar flares. Time scale and typical properties derived from soft X-rays also show some similarities to solar flares, though the dynamic range of stellar flare parameters are much wider than those of solar flares. Recent X-ray astronomy satellite revealed that flares are frequently occurring in young stars, even in class 1 protostars [20]. One remarkable characteristics of these protostellar flares is that the temperature is generally high, $50-100$MK, much hotter than the temperature of solar flares, $10-20$MK. The total energy estimated is also huge,

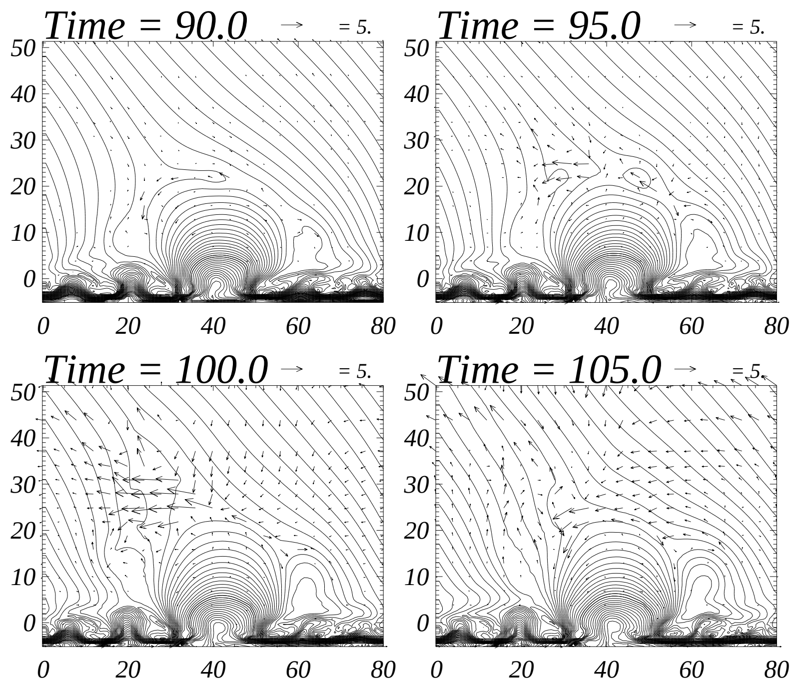

FIGURE 3. 2D MHD simulations of solar X-ray jets on the basis of magnetic reconnection model (Yokoyama and Shibata 1995)[65].

and amounts to 10^{36-37} erg, much greater than that of solar flares, 10^{29-32} erg.

Can we explain these protostellar flares by magnetic reconnection? The answer is, of course, yes. Part of the reason of this answer comes from our finding of an empirical correlation between the emission measure and the temperature of solar, stellar, and protostellar flares. Figure 4 shows the observed relation between the emission measure and the temperature of solar flares, microflares, stellar flares [8], and YSO flares [51]. It is remarkable that these data show the same tendency in a very wide dynamic range. What does this relation mean ?

Our answer is as follows (Shibata and Yokoyama [51],[53]). Yokoyama and Shibata [67], [68] performed a self-consistent MHD simualtion of reconnection with heat conduction and evaporation for the first time. From this simulation, they discovered a simple scaling relation for the flare temperature:

$$T \propto B^{6/7} L^{2/7}. \tag{1}$$

This is simply a result of the energy balance between reconnection heating ($B^2 V_A / 4\pi$) and conduction cooling ($\kappa T^{7/2}/L$). With this equation and definition of emission measure ($EM = n^2 L^3$), and pressure equilibrium ($p = 2nkT = B^2/8\pi$), we finally obtain the following relation:

$$EM \propto B^{-5} T^{17/2}. \tag{2}$$

We plotted this relation for constant field strengths (B = 15, 50, 150 G) in Figure 4. It is remarkable that these B = constant lines nicely explain the empirical correlation. In

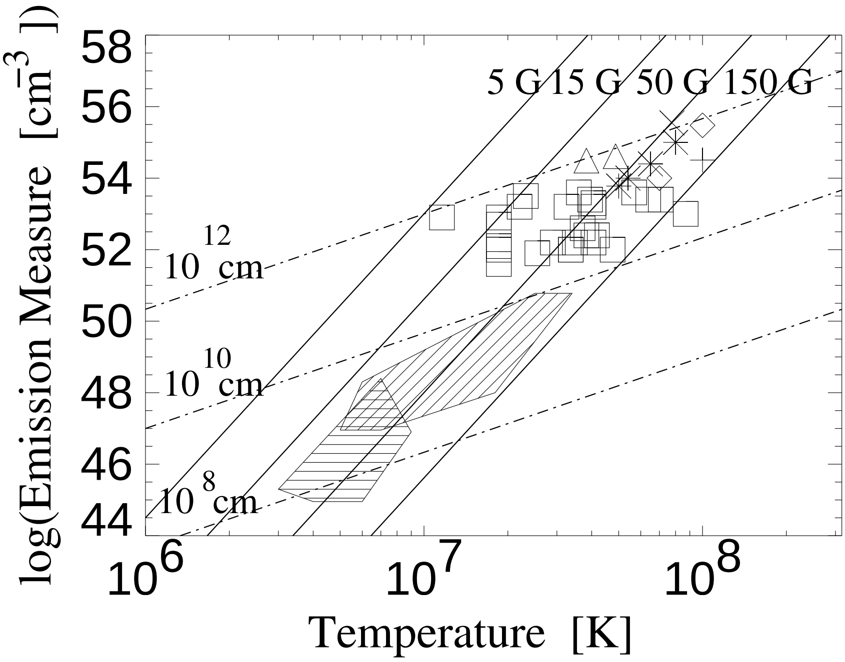

FIGURE 4. The EM (emission measure)$-$T (temperature) diagram for solar and stellar flares and corona (Shibata and Yokoyama 2002)[53]. Hatched area shows solar flares (oblique hatch) and solar microflares (horizontal hatch), whereas other symbols denote stellar/protostellar flares. Solid lines correspond to magnetic field strength = constant, and dash-dotted lines correspond to flare size = constant.

other words, the comparison between observation and our theory tells that the magnetic field strength of solar and stellar flares are not so different, of the order of 50-150 G. In the solar case, this value agrees with the observations (average field strength of active region). In the case of stars, we have only a limited set of observations (T-Tauri star), but these observations show a kG field in the photosphere, suggesting 100 G average field strength in the stellar corona, consistent with our theoretical prediction. We can also plot constant loop length lines in the diagram in Figure 4. The loop length for microflares and flares is $10^8 - 10^{10}$ cm, consistent with observed sizes of microflares and flares, whereas the size of stellar flare loop is huge, even larger than 10^{11} cm, comparable to or even larger than stellar radius. Because of this large size, the total energy of protostellar flares become huge and their temperature becomes hotter than those of solar flares (see eq. 1). Since it is not possible to resolve these stellar flares, these large sizes of stellar flares are simply theoretical predictions at present.

Hayashi, Shibata, and Matsumoto [9] developed a time dependent MHD model of protostellar flares produced by the interaction between a central protostar and a surrounding disk, and nicely explained how the energy is accumulated as a result of the star-disk interaction and how and why gigantic flares occur in protostars with a disk. This model is in some sense similar to Shu et al.[57]'s X-wind model, but the basic difference is that the reconnection and the associated mass ejection are very non-steady and thus are far different from those in the steady X-wind model.

Shibata and Yokoyama [53] noted that the EM-T diagram is similar to HR diagram, and examined basic properties of the EM-T diagram. They found the existence of coronal branch, forbidden regions, and also showed that flare evolution track can be plotted on the EM-T diagram, similarly to the stellar evolution track in the HR diagram.

ASTROPHYSICAL JETS

AGN jets, jets from close binary system, and YSO (young stellar object) jets are often called astrophysical jets. Although the central objects, their sizes, and velocities are very different, their morphologies are impressively similar, showing highly collimated bipolar jet structures with lobes at the head of the jet. Accretion disks are usually found in the central engines of these jets. One of the most interesting common features in these objects is that the velocity of the jet is comparable to the escape velocity of the central objects. Hence the relativity is not the basic mechanism to produce these jets, since YSO jet velocity is only a few hundred km/s. Any theory of astrophysical jets should explain why the velocity of astrophysical jets is comparable to the escape velocity of the central object.

At present, one of the most promising models for astrophysical jets is the MHD model [3],[30], [43], [64], [57]. In this model, the magnetic field is assumed to be penetrating the accretion disk vertically, and then magnetic fields are pulled and twisted by the accretion and rotation of the accretion disk. As a result, the centrifugal force appears on the rotating field lines, and the magnetic pressure force also appears like a pressed spring. With these forces (both originated from the JxB force), the gas in the surface layer of the disk is accelerated to form bipolar outflows or jets.

The first 2.5D time dependent MHD simulations of magnetically driven jets from accretion disks have been performed by Shibata and Uchida [46], and Uchida and Shibata [64] applied the results to CO bipolar flows observed in star forming regions. They initially assumed uniform poloidal field penetrating the accretion disk (Keplerian disk), and followed the subsequent nonlinear evolution of the interaction between the disk and magnetic field with 2.5D MHD code. They have shown that the disk accretion becomes possible because of extraction of angular momentum by the magnetic braking effect of the poloidal field. As the gas falls into the inner region of the disk, the magnetic field gets twisted more and more. When the magnetic twist becomes sufficiently strong, jets start to be accelerated by both centrifugal force and magnetic pressure force in the highly twisted magnetic field just above the accretion disk (see also earlier work on magnetic pressure driven jets by Shibata and Uchida [45], and its modern extension by Kudoh et al. [25] and Kato et al. [14]). The maximum velocity of jets is found to be comparable to the Keplerian velocity of the disk. That is, if our disk is near the central object, the velocity of the jet is comparable to the escape velocity of the central object, since Keplerian velocity is comparable to escape velocity near the central object.

The main findings from many MHD simulations of astrophysical jets from 1986-2002, especially by Kudoh, Matsumoto, Shibata [23], and Kato, Kudoh and Shibata [13] are as follows (see [49] for a review):

1) The velocity of the jets is comparable to the Keplerian speed, and slowly increases with the magnetic field strength

$$V_{jet} \sim V_k (V_A/C_s)^{1/3} \propto {B_p}^{1/3}, \quad (3)$$

where V_k is the Keplerian velocity of the disk, V_A is the initial poloidal Alfven speed $(= B_p/(4\pi\rho)^{1/2})$, C_s is the sound speed in the disk, and B_p is the initial poloidal magnetic field strength.

2) The mass ejection rate is about 0.01 – 0.1 of the mass accretion rate. The mass ejection rate is written as

$$\dot{M} \sim \rho_s C_s (B_p/B_\varphi) r^2 \propto B_p, \quad (4)$$

where ρ_s is the mass density at the slow magnetosonic point and is $\sim 0.1\rho_0$, ρ_0 is the mass density at the equatorial plane of the disk at the foot point of the jet, $B_\varphi \sim (4\pi\rho_s {V_k}^2)^{1/2}$ is the azimuthal component of the magnetic field.

3) Jets and disks never reach steady state, but become very dynamic.

These scaling laws (eqs. (3) and (4)) have also been derived analytically using the steady solution by Kudoh and Shibata [21], [22]. According to Kudoh and Shibata [22], the *magneto-centrifugal force* is a dominant acceleration force to accelerate a jet for the strong field case ($E_{mg} = ((V_A/V_k)^2 > 0.01$), whereas the *magnetic pressure* becomes dominant for the weak field case ($E_{mg} = ((V_A/V_k)^2 < 0.01$). The above scaling laws (eqs. (3) and (4)) correspond to the weak field case. Since the dependence on the magnetic field strength is weak, the equipartition for the jet velocity $V_{jet} \sim V_k$ holds for wide range of magnetic field strengths. It is interesting to note that even for initially very weak magnetic field strengths, the jet velocity becomes comparable to the Keplerian velocity. The basic physics of this is similar to the physics of the magnetorotational instability.

Why do the jet and the disk never reach a steady state? The reason is the magnetorotational instability [2]. Magnetorotational instability is a powerful instability that grows rapidly (in a dynamical (rotational) time scale) until quasi-equipartition values ($\beta \sim 10 - 100$) are reached even if the initial magnetic field is very weak. The saturation is caused by magnetic reconnection [44] and the entire disk and jet become very dynamic and full of reconnection events (e.g., [24], [32]). Many jets or outflows seem to be a result of reconnection events.

Koide, Kudoh and Shibata [16], [17] extended their numerical simulations of MHD jets successfully to the general relativistic MHD regime, and found that the maximum speed of the relativistic jet is 0.2c $-$ 0.9c, which is much smaller than the velocity of some AGN jets (Lorentz factor $10 - 100$) and gamma ray bursts (Lorentz factor $100 - 1000$.) Koide et al. [15], [18] have further extended the simulations to jets ejected from a Kerr black-hole magnetosphere, and again found that the maximum velocity of the jets is of the order of 0.2c $-$ 0.9c. Mizuno et al. [36], [37] applied the same general relativistic MHD code (developed by Koide) to a collapsar model to examine the central engine of gamma ray bursts both for the cases of Schwartzchild and Kerr black-holes. At present, the maximum velocity of jet is still of order of 0.2c to 0.3c.

TABLE 2. Comparison between the magneto-centrifugally driven jet and the magnetic pressure driven jet [49]

	centrifugal force	magnetic pressure
poloidal field (B_p)	strong	weak
field configuration		
near disk	straight	highly twisted
B_p vs B_φ *	$B_p \gg B_\varphi$	$B_p \ll B_\varphi$
mass flux ($\dot{M}$)	$\rho C_s r^2$	$\rho C_s \frac{B_p}{B_\varphi} r^2$
– dependence on B_p	independent of B_p	$\propto B_p$
terminal speed (V_∞)	$V_k(\frac{V_A{}^2}{C_s V_k})^{1/3}$	$V_k(\frac{V_A}{C_s})^{1/3}$
range of application	$E_{mg,c} < E_{mg} < 1$	$E_{mg} < E_{mg,c}$

* Note: B_p and B_φ are the poloidal and toroidal components of the 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_s is the sound speed, V_A is the poloidal Alfven speed, and ρ is the mass density. These are all measured at the *slow magnetosonic point*. E_{mg} represents the ratio of the magnetic energy to the 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 $E_{mg,c} \simeq 0.01$ in the case of the model in [49].

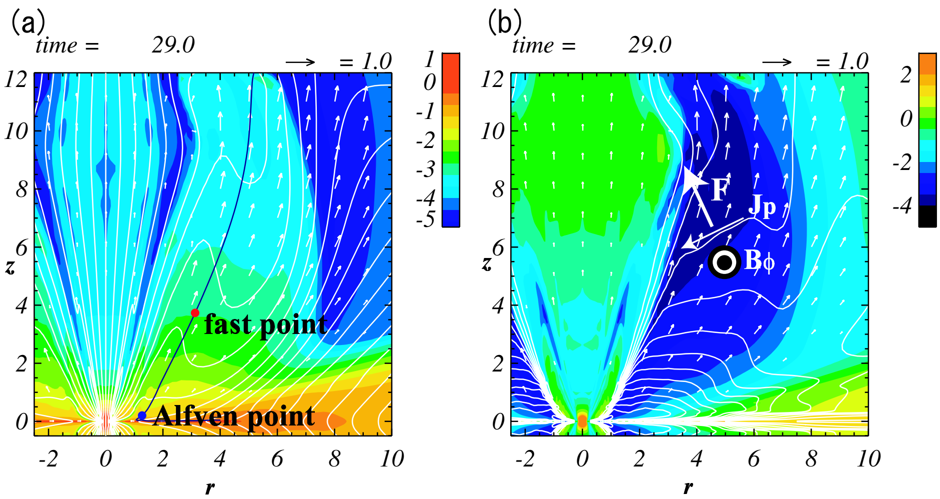

FIGURE 5. Typical example of MHD simulations of jets from accretion disk (Kudoh, Matsumoto, Shibata 2003) [26].

SUMMARY

1) The reconnection model for solar flares (especially, the unified model) has significantly developed in these 10 years, though key puzzles (triggering mechanism, coronal heating, etc) remain. These are the main subjects of the Solar B mission which will be launched in 2006.

2) The reconnection model has been successfully applied to stellar and protostellar flares. EM-T scaling law was found, which corresponds to a unified model of solar and

stellar flares.

3) The MHD model of astrophysical jets has been developed, including general relativistic effects, though ultra relativistic jets (Lorentz factor > 10) have not been well reproduced in MHD simulations.

4) MHD simulations have revealed that jets and disks never reach steady state and are full of reconnection events which would have interesting implications for future theories and observations of jets and disks.

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