

Session 1: Plasma and Fresh Nucleosynthesis Phenomena

1-1. Sun and Stars

THEORY OF FLARES AND MHD JETS

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Abstract: Recent development on the theory and numerical modeling of solar flares and jets is reviewed with emphasis on the magnetic reconnection model. Application to protostellar flares and jets is also discussed.

1. Introduction: Why do we need magnetic reconnection ?

Hot plasmas have very high electrical conductivity so that their magnetic Reynolds number R_m is very large; for example, we find

$$R_m = \frac{t_D}{t_A} = \frac{V_A L}{\eta_{\text{Spitzer}}} \sim 10^{13} \left(\frac{B}{10\text{G}} \right) \left(\frac{L}{10^9\text{cm}} \right) \left(\frac{n}{10^9\text{cm}^{-3}} \right) \left(\frac{T}{10^6\text{K}} \right) \gg 1,$$

for solar coronal plasma, where the diffusion time is $t_D \sim 3 \times 10^6$ years (!), and the Alfvén time $t_A = L/V_A \sim 10 - 100$ sec. Since the observed time scale of solar flares is a few min – a few hours and thus $10 - 100t_A$, the simple Ohmic dissipation cannot explain solar flares. This is a universal property of various hot plasmas in our universe from magnetically confined fusion plasmas to intergalactic plasmas, and gives us fundamental difficulty in understanding explosive energy release such as solar flares.

If we consider very small scale (e.g., 0.01 cm), R_m becomes small (~ 100) so that we can explain time scale. However, in this case, we cannot explain total flare energy ($\sim 10^{29} - 10^{32}$ erg) since we need a large volume to explain total energy of flares whose size is $\sim 10^9 - 10^{10}$ cm. Hence we need coupling between micro-scale physics (resistivity) and macro-scale physics (flow dynamics), which is an essential element of magnetic reconnection.

Recently, Yokohkō discovered a number of evidence of magnetic reconnection in solar flares (e.g., Tsuneta 1998), such as cusps, X-ray plasmoids, X-ray jets, and so on. Although the origin of resistivity has not yet been

fully understood at present, it has been established that the non-uniform resistivity (such as anomalous resistivity) can lead to fast reconnection at time scale of $10 - 100t_A$ (e.g., Ugai 1989, Yokoyama and Shibata 1994) and hence the numerical modeling of solar flares and related mass ejections (jets and plasmoids) based on the reconnection model has greatly been advanced, which will be reviewed in this article.

2. Magnetic Reconnection Model for Solar Flares and Jets

Cusp-Shaped Flares: Yokoyama and Shibata (1998) succeeded to construct a fully self-consistent reconnection model of cusp-shaped flares discovered by Yokoh (Tsuneta et al. 1992, Tsuneta 1998 for a review), taking into account the effect of heat conduction (Yokoyama and Shibata 1997) and evaporation. According to their results (see Fig. 1 of Yokoyama and Shibata 1998), the adiabatic slow shock dissociates into *isothermal slow shock* and *conduction front* (Forbes et al. 1989), and the fast shock becomes nearly isothermal and post-fast-shock plasmas become much denser than in the adiabatic case. This fast shock structure explains the loop top hard X-ray source discovered by Masuda et al. (1994). Yokoyama and Shibata (1998) further found that the temperature of flare loops scales with the field strength B as

$$T_{flare} \simeq 2 \times 10^7 \left(\frac{B}{30G} \right)^{6/7} \left(\frac{L}{10^9 \text{cm}} \right)^{2/7} \left(\frac{n}{10^9 \text{cm}^{-3}} \right)^{-1/7} \text{ K},$$

where L is the half length of the loop, n is the electron number density. This formula is applicable not only to solar flares but also to stellar flares (and even to galactic flares) as far as the Spitzer conductivity is applicable.

X-ray Plasmoid Ejections: Magara et al. (1997) developed a reconnection model of X-ray plasmoid ejections discovered by Yokoh (Shibata et al. 1995, Tsuneta 1998), assuming initially a sheared force free arcade (see Kusano et al. 1995 and Choe and Lee 1996 for the formation and evolution of such a sheared arcade), and succeeded to explain the observation (Ohyama and Shibata 1997) that acceleration of a plasmoid (to a few 100 km/s) precedes a hard X-ray impulsive peak (if the latter is a measure of electric field strength at the neutral point).

X-ray Jets: X-ray jets are also discovered by Yokoh (Shibata et al. 1992, Shimojo et al. 1996). These jets occur in association with microflares or subflares and their apparent velocity is $10 - 1000$ km/s. Yokoyama and Shibata (1995,1996) developed 2D numerical simulation model of X-ray jets, in which magnetic reconnection occurs in the current sheet between emerging flux and pre-existing coronal field (Fig. 1). They found; (1) reconnection proceeds with formation of magnetic islands (plasmoids) by tearing instability, coalescence of islands, and their ejections, (2) reconnection jets

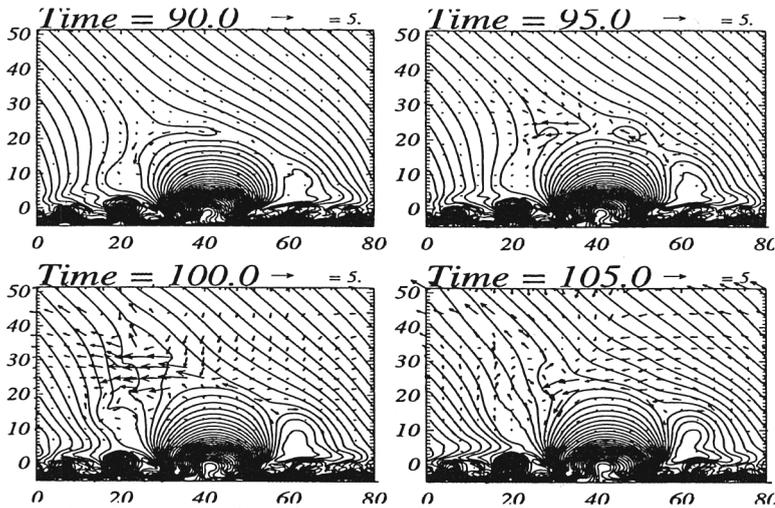


Figure 1. Numerical simulation of X-ray jets based on emerging flux reconnection model (Yokoyama and Shibata 1995, 1996). Note that plasmoids (magnetic islands) are repeatedly created and ejected from the current sheet, and disappear due to secondary reconnection.

collide with the ambient field to form fast shock at the colliding point, (3) both hot and cool jets are formed simultaneously, which were actually observed by Canfield et al. (1996) as X-ray jets and $H\alpha$ surges.

Unified Model: Yokohya has revealed that various (apparently different) flares show common properties such as ejection of plasma. Numerical simulations of reconnection show also ejection of plasmoids (or flux rope in 3D space). Hence Shibata (1996) proposed a unified model, *plasmoid-induced-reconnection model*, to explain various flares. In this model, if the current sheet is long, ejected plasmoids (helical loop) are directly observed, while if it is short, plasmoids collide with ambient field to disappear as a result of secondary reconnection (Fig. 1), though the helical field and mass are released into open flux tubes to accelerate spinning jets along them. The physics of the spinning jet is basically the same as that of magnetically driven jets from accretion disks (e.g., Uchida and Shibata 1985, Shibata and Uchida 1986).

3. Astrophysical Application: Protostellar Flares and Jets

Hayashi et al. (1996) studied the interaction between a protostellar magnetosphere and an accretion disk surrounding it, using 2D axi-symmetric numerical simulations. They found that once the accretion disk plasma is coupled with stellar field, the stellar field is enormously sheared by the rotation of the disk to expand outward, like solar coronal mass ejections. The

expanding loop finally detaches from the stellar field due to reconnection to form a plasmoid or a helically twisted toroid. During this stage, a very hot plasma ($\sim 10^8$ K with total energy $\sim 10^{36}$ erg) is created, which explains protostellar flares observed by ASCA and ROSAT (Koyama et al. 1996, Tsuboi et al. 1998, Monmerle 1998). The velocity of the ejected plasmoid is 200 – 400 km/s, which corresponds to optical jets. This model also shows the ejection of the cold gas from the disk (e.g., Uchida and Shibata 1985, Shibata and Uchida 1986), which corresponds to high velocity neutral winds.

Finally it should be stressed that the processes discussed in this article could occur in various astrophysical situations (Makishima 1997), not only in solar and stellar magnetosphere but also in our Galaxy (Tanuma et al. 1998), and even in cluster of galaxies (Makishima 1997, Matsumoto et al. 1998, Hirashita et al. 1998).

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