MHD SIMULATIONS OF MAGNETIC RECONNECTION AND SOLAR FLARES

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Abstract: Recent development of numerical simulations of magnetic reconnection and solar flares is reviewed with emphasis on the numerical modeling of various evidence of reconnection in flares that are discovered by Yohkoh X-ray observations.

1. Introduction

Solar flares are explosions occurring in the solar atmosphere, releasing a huge amount of magnetic energy $10^{29} - 10^{32}$ erg in a relatively short time scale $10^2 - 10^3$ sec. Flares have spatial scales $10^4 - 10^5$ km, and emit almost all electromagnetic spectrum from radio waves to gamma rays. The energy release mechanism of solar flares has been one of the most challenging subjects in solar physics and plasma astrophysics in the latter half of this century.

What is the basic difficulty to understand solar flares? This is easily understood if we calculate the magnetic diffusion time (or Ohmic dissipation time) of the solar coronal magnetic loop with a spatial scale L and temperature T on the basis of the classical Spitzer conductivity;

$$t_D = \frac{L^2}{\eta_{\rm spitzer}} \simeq 10^{14}\Big(\frac{L}{10^9{\rm cm}}\Big)^2\Big(\frac{T}{10^6{\rm K}}\Big)^{3/2} \ \ {\rm sec.}$$

This is nearly 3 million years (!), much longer than the observed time scale of solar flares. Hence the simple current dissipation mechanism cannot work for solar flares. Another way to see the difficulty is to calculate magnetic

S. M. Miyama et al. (eds.), Numerical Astrophysics, 303–310.

Reynolds number R_m;

$$R_m = \frac{t_D}{t_A} = \frac{V_A L}{\eta_{\rm spitzer}} \simeq 10^{13} \gg 1,$$

where t_A is the Alfven time

$$t_A = \frac{L}{V_A} \simeq 10\Big(\frac{L}{10^9 {\rm cm}}\Big)\Big(\frac{B}{10{\rm G}}\Big)^{-1}\Big(\frac{n}{10^9 {\rm cm}^{-3}}\Big)^{1/2} \quad {\rm sec.}$$

In general, $R_m \gg 1$ in astrophysical plasmas so that it is very difficult to dissipate magnetic energy in a short time scale ($\sim t_A$). Nevertheless, explosive energy release similar to solar flares often occur in astrophysical objects in a time scale comparable to Alfven time ($10 - 100t_A$).

In order to overcome this difficulty, the theory of magnetic reconnection connecting microscopic physics (resistivity) and macroscopic dynamics (flow) has been proposed (Giovanelli 1947) and developed by Sweet (1958), Parker (1957), Petschek (1964) and others. Magnetic reconnection mechanism has been applied also to geomagnetic aurora-substorms by Dungey (1961) and disruption of magnetically confined fusion plasma (e.g., see Biskamp 1993). From late-70's, new era of reconnection study has begun; i.e., numerical simulations of reconnection have started, which greatly contributed to the development of not only reconnection theory but also realistic modeling of solar flares, geomagnetic substorms, and disruption of confined fusion plasma. In spite of the progress of both analytical and numerical studies (e.g., Forbes and Priest 1987, Biskamp 1993, Tajima and Shibata 1997), the magnetic reconnection theory has still not yet been established. The enormous gap between t_D and t_A is still a big obstacle for numerical simulations, laboratory experiment, and analytic theories.

In this article, we review basic reconnection theory, recent development of numerical simulations of reconnection, and new observations and numerical modeling of solar flares based on the reconnection model.

2. Basic Reconnection Theory

Sweet (1958) and Parker (1957) developed a simple theory of magnetic reconnection, taking into account of the effect of *flow*. This is now called *Sweet-Parker model*. In this model, the plasma inflow with a speed of V_i drives the reconnection in the current sheet with a length L. Since the magnetic energy is converted to plasma outflow, the speed of outflow (*reconnection jet*) becomes comparable to Alfven speed V_A just outside the current sheet. The time scale of reconnection (and energy release) is $t_{SP} \simeq L/V_i \simeq {R_m}^{1/2} t_A \sim 10^6 t_A$ when applied to solar flares, which is much faster than simple magnetic diffusion ($t_D \simeq R_m t_A$) but still much slower than the observed time scale of solar flares ($10 - 100 t_A$).

Petschek (1964) proposed a remarkable idea that if the effect of *slow mode MHD shock (or wave)* is considered, it is possible to construct *fast reconnection* model. Namely, the slow shock enables the conversion of magnetic energy to plasma kinetic and internal energies, and the magnetic reconnection occurs only in a very small localized region (called *diffusion region*) where the *Sweet-Parker model* holds locally. The speed of outflow (reconnection jet) is again V_A, while the inflow speed becomes $V_i/V_A \sim (\pi/8)/\ln R_m \sim 0.01 - 0.1$, nearly independent of R_m. The time scale of reconnection (and energy release) is $10 - 100 t_A$ which is exactly the observed time scale of solar flares. Although this model (called *Petschek model*) is very successful and has been considered to be the most promising model for solar flares, there are still some basic questions: (1) The Petschek model is not based on an exact solution of the resistive MHD equation, but on an approximate solution. Is the Petschek model a real solution of the resistive MHD equation? (2) If the origin of resistivity is Coulomb collisions (i.e., Spitzer resistivity), the length of diffusion region must be less than 1 cm to explain solar flares! (Note that the typical flare size is 10^9 cm.) Is it really true that such a small single diffusion region controls the entire flare process? In order to answer the first question, people had to await the development of computers.

3. Numerical Simulations of Magnetic Reconnection

Ugai and Tsuda (1977) first numerically solved the time dependent resistive MHD equation in 2D space. They assumed a *locally enhanced resistivity* (which is spatially and temporally fixed in a current sheet), and followed the subsequent evolution of magnetic field and plasma dynamics caused by the locally enhanced resistivity. They found that the solution is very similar to the Petschek model, i.e., they found appearance of reconnection jet with Alfven speed, a pair of slow shocks, and logarithmic dependence of reconnection rate on R_m.

Sato and Hayashi (1979) studied similar problem with different assumption; they assumed strong inflow from the side boundaries which drives the reconnection. They also assumed non-fixed resistivity that depends on current density such that $\eta = \eta_0 (j - j_c)^2$ (for $j > j_c$), and $\eta = 0$ (for $j < j_c$), mimicing the *anomalous resistivity* caused by plasma turbulence. They again found that the resulting solution is similar to the Petschek model, and proposed that *external driving* is essential to induce (Petschek type) fast reconnection. At this stage, it is clear that the Petschek model is a real solution of the resistive MHD equation under some special condition.

However, a fundamental question is remained; *what is the condition of the (Petschek type) fast reconnection?* Is it *external driving* or *locally enhanced resistivity such as anomalous resistivity*?

There were some controversies about this question. Biskamp (1986) studied the same problem but assuming *uniform resistivity*, and found that the external driving does *not* lead to the Petschek type fast reconnection. Instead, he found only the Sweet-Parker solution in his numerical simulations. On the basis of these simulation results, he criticized the Petschek model (Biskamp 1993). Priest and Forbes (1992), on the other hand, constructed a unified reconnection theory using analytical but approximate method, and demonstrated that the external boundary condition for inflow is essential for determining whether reconnection is fast or slow.

However, many self-consistent resistive MHD numerical simulations (Ugai 1986, Scholer 1989, Yan et al. 1992, Yokoyama and Shibata 1994) have shown that the fast reconnection (Petschek type reconnection) is realized only when the *locally enhanced resistivity* such as anomalous resistivity is assumed. Namely, if *uniform resistivity* is assumed, only the slow reconnection (Sweet-Parker reconnection) is realized irrespective of any external driving at the inflow boundary condition. [1]

This notion is important especially when the reconnection model is applied to actual solar flares and magnetospheric substorms using numerical simulations. If one assumes uniform resistivity, one would not find (global) slow shocks inherent to Petschek type reconnection. If such simulation results are applied to flares and substorms, one might predict that no slow shocks would be found in flares and substorms. But actually slow shocks have been found in the geotail current sheet during substorms (Saito et al. 1995).

It should be also mentioned that *ideal MHD numerical simulations* often lead to violent fast reconnection due to *numerical resistivity.* For example, according to our own experience, the "ideal MHD simulation" of reconnection using modified Lax-Wendroff scheme lead to (nonsteady) Petschek type reconnection. In this scheme, the numerical resistivity is spatially nonuniform and is similar to anomalous resistivity. It is interesting to note that the ideal MHD case (or the least resistive case in an exact sense) leads to the most violent magnetic reconnection (Yokoyama and Shibata 1994). Of course, the type of numerical resistivity strongly depends on the numerical scheme. Karpen et al. (1998) numerically simulated solar flares with FCT

[1] Of course, these are results of numerical simulations at the present stage, whose numerical magnetic Reynolds number is at most $10^3 - 10^4$ in a uniform grid. Biskamp (1998, private communication) conjectures that even a uniform resistivity case may generate effective turbulent anomalous resistivity leading to fast reconnection. However, this is only a conjecture at the present stage. No one knows at what numerical magnetic Reynolds number we can get such fast reconnection under a uniform resistivity.

scheme assuming ideal MHD equation, and obtained the results very similar to those found for uniform resistivity case. This is probably because of nearly uniform numerical resistivity in a dicontinuous layer (current sheet) in FCT scheme. MOCCT scheme often lead to explosive reconnection in a current sheet in ideal MHD numerical simulations (e.g., Hawley and Stone 1995, Kudoh et al. 1998). In such explosive case, however, the total energy is not conserved, so that numerical results cannot be applied to any physical problems. In summary, to use ideal MHD numerical simulations for reconnection problems is somewhat dangerous unless we should be well aware of the properties of numerical scheme. We recommend people to use resistive MHD equations with physical resistivity term (larger than numerical resistivity) if their MHD problems include reconnecting current sheets.

4. Numerical Modelings of Solar Flares and Their Role in Interpretating New Observations of Flares

Before launch of Yohkoh in 1991, solar physicists have sometimes doubted the reconnection model since there were not enough observational evidence of reconnection. Now the situation has dramatically changed because a wealth of observational evidence of reconnection has been discovered through Yohkoh X-ray observations (see the review by e.g. Shibata 1996). It must be stressed that during the course of analysis and interpretation of Yohkoh data, the numerical simulations of magnetic reconnection played a very important role as listed in the following examples of observational evidence of reconnection discovered by Yohkoh.

(1) **Cusp-shaped flare loops**: Although the cusp-shaped magnetic field configuration was predicted by *CSHKP model* (Carmichael-Sturrock-Hirayama-Kopp-Pneuman), the numerical simulations by Ugai (1987), Forbes and Malherbe (1991), Magara et al. (1996) were extremely useful to understand physics of reconnection. Tsuneta et al. (1992, 1996) discovered that outer regions of cusp-loops have systematically higher temperature, which have been predicted by the reconnection model. More recently, Yokoyama and Shibata (1998) succeeded to develop a model of flares including reconnection, heat conduction, and chromospheric evaporation, and reproduced observed temperature distribution in cusp-shaped loops.

(2) **Loop top hard X-ray sources**: Masuda et al. (1994) discovered a hard X-ray source well above the top of the soft X-ray flare loop, which indicated that energy release occurred outside of the soft X-ray flare loop. In interpreting this observation, numerical simulations of Ugai (1987) played a leading role, since the simulation clearly showed the appearance of the fast shock above the reconnected loop. Hence Masuda et al. (1994) interpreted that the loop top hard X-ray source may correspond to the very hot region

just behind the fast shock, and they indeed found that the observed temperature is consistent with the theoretically predicted temperature behind the fast shock.

(3) **X-ray plasmoid ejections**: On the basis of numerical simulations of reconnection, Shibata et al. (1995) conjectured that if the impuslive flares are caused by the reconnection, the plasmoid ejections would be found high above the main flare loop (reconnected loop). They indeed discovered plasmoid ejections in many compact impulsive flares. Magara et al. (1997) developed a numerical simulation model explaining the observed motion of X-ray plasmoids analyzed by Ohyama and Shibata (1997).

(4) **X-ray jets**: Yohkoh discovered many jet-like mass ejections in the solar corona (Shibata et al. 1992b, Shimojo et al. 1996). Shibata et al. (1992b) proposed the magnetic reconnection model for these X-ray jets, and Yokoyama and Shibata (1995, 1996) carried out extensive numerical simulations of reconnection occurring between emerging flux and coronal field to construct a model of X-ray jets (Fig. 1 and CD-ROM for movies). They successfully reproduced observed properties of X-ray jets, and predicted the coexistence of hot X-ray jets and cool Hα jets (surges). The latter has been confirmed observationally by Canfield et al. (1996).

5. Summary

MHD reconnection model successfully explained Yohkoh observations, such as cusp-shaped flares, loop top hard X-ray sources, X-ray plasmoid ejections, and X-ray jets. On the basis of these solar studies, the reconnection model has been applied also to protostellar flares (Hayashi et al. 1996) and "galactic flares" (Tanuma et al. 1998).

There remains some fundamental questions, i.e., origin of resistivity and particle acceleration mechanism, both of which are closely related microscopic physics of reconnection such as non-MHD effects (e.g., Hoshino 1998). The former is related also to macroscopic turbulence (e.g., Biskamp 1994, Nordlund 1998). Another important remaining question is the preflare energy build-up; how the magnetic energy is accumulated in the solar atmosphere? Is it due to photospheric shear flow (e.g., Kusano 1998) or emergence of twisted flux tubes (e.g., Matsumoto et al. 1998)?

Consequently, future subjects for numerical astrophysicists are: (1) 3D MHD modeling of flares (e.g., emergence of twisted flux tubes and resulting 3D reconnection). (2) To develop adaptive mesh MHD code. This is necessary to resolve thin current sheet in high R_m plasma which has probably a fractal structure (Tajima and Shibata 1997). Note again that $L_{flare} \simeq 10^9$ cm $\gg r_{ion,Larmor} \simeq 100$ cm, the latter being the typical scale of anomalous resistivity. (3) To develop numerical code including both MHD and non-

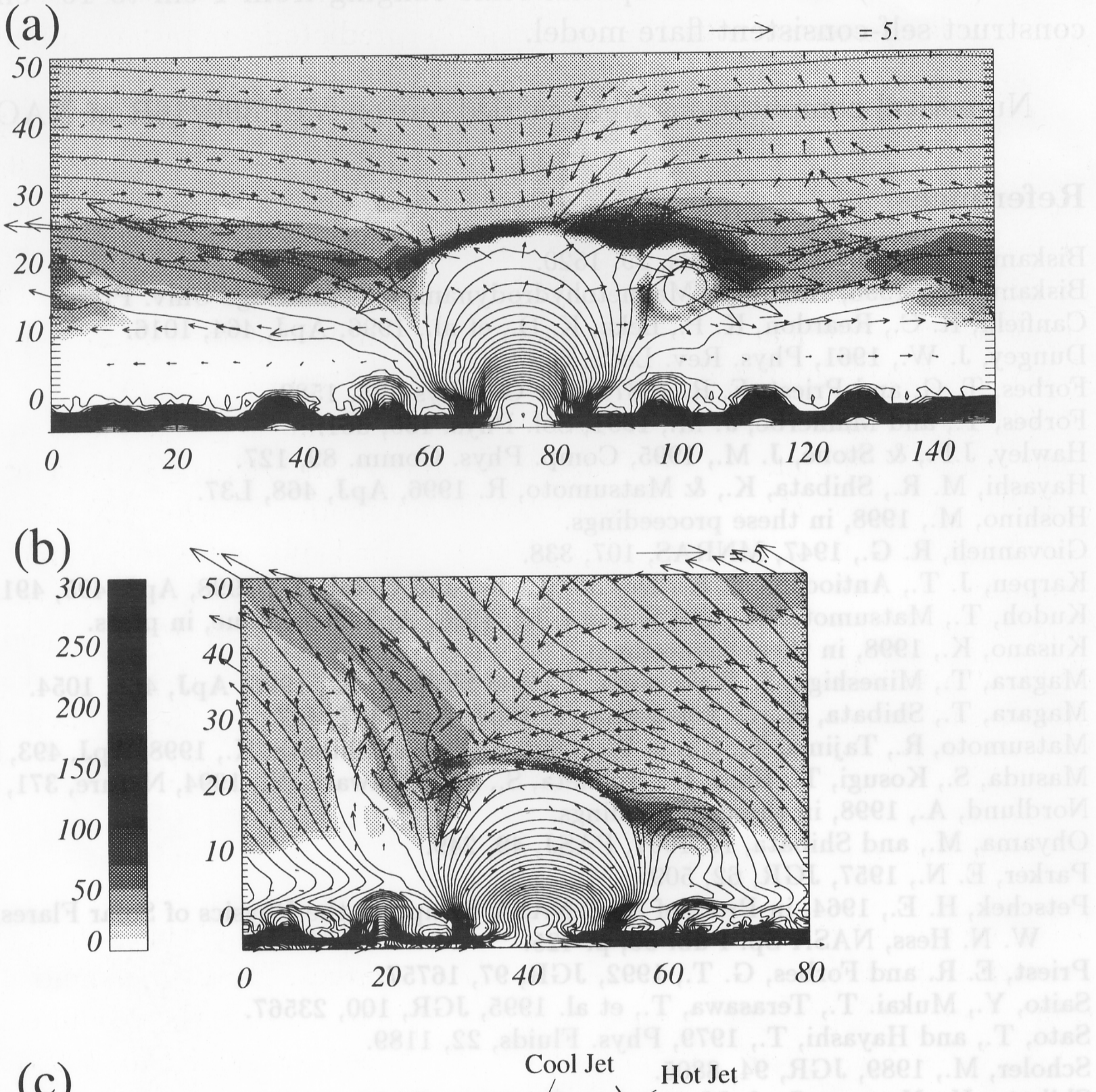

Figure 1. MHD numerical simulation of magnetic reconnection model for X-ray jets (from Yokoyama and Shibata 1995, 1996). This is an extension of the simulation by Shibata et al. (1992a). (a) *Two-sided-loop type*, in which the initial coronal field is horizontal. (b) *Anemone-jet type*, in which the initial coronal field is oblique. Both figures show temperature distribution (grey scale; darker region is hotter), magnetic field lines (lines), and velocity vectors. The unit of length is ~ 200 km. The velocity of the hot jet is about 0.3 – 1.0 in unit of coronal Alfven speed $V_{A,cor}$ (~ 1000 km/s). (c) Schematic illustration of physical processes found from numerical simulations.

MHD (kinetic) effects for a spatial scale ranging from 1 cm to 10^9 cm to construct self-consistent flare model.

Numerical computations were carried out on VPP300/16R at NAOJ.

References

Biskamp, D., 1986, Phys. Fluids, 29, 1520.
Biskamp, D., 1993, Nonlinear Magnetohydrodynamics, Cambridge Univ. Press.
Canfield, R. C., Reardon, K. P., Leka, K. D., et al., 1996, ApJ, 464, 1016.
Dungey, J. W., 1961, Phys. Rev. Lett., 6, 47.
Forbes, T. G. and Priest, E. R. 1987, Rev. Geophys., 25, 1583.
Forbes, T., and Malherbe, J. M., 1991, Sol. Phys. 135, 361.
Hawley, J.F., & Stone, J. M., 1995, Comp. Phys. Comm. 89, 127.
Hayashi, M. R., Shibata, K., & Matsumoto, R. 1996, ApJ, 468, L37.
Hoshino, M., 1998, in these proceedings.
Giovanneli, R. G., 1947, MNRAS, 107, 338.
Karpen, J. T., Antiochos, S. K., DeVore, C. R., and Golub, L., 1998, ApJ, 495, 491.
Kudoh, T., Matsumoto, R., and Shibata, K., 1998, ApJ, Nov. issue, in press.
Kusano, K., 1998, in these proceedings.
Magara, T., Mineshige, S., Yokoyama, T., and Shibata, K., 1996, ApJ, 466, 1054.
Magara, T., Shibata, K., & Yokoyama, T. 1997, ApJ, 487, 437.
Matsumoto, R., Tajima, T., Chou, W., Okubo, A., and Shibata, K., 1998, ApJ, 493, L43.
Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., and Ogawara, Y., 1994, Nature, 371, 495.
Nordlund, A., 1998, in these proceedings.
Ohyama, M., and Shibata, K. 1997, PASJ, 49, 249.
Parker, E. N., 1957, JGR, 62, 509.
Petschek, H. E., 1964, in Proc. of AAS-NASA Symp. on the Physics of Solar Flares, ed. W. N. Hess, NASA Sp. Pub. 50, p. 425.
Priest, E. R. and Forbes, G. T., 1992, JGR, 97, 16757.
Saito, Y., Mukai. T., Terasawa, T., et al. 1995, JGR, 100, 23567.
Sato, T., and Hayashi, T., 1979, Phys. Fluids, 22, 1189.
Scholer, M., 1989, JGR, 94, 8805.
Shibata, K., Nozawa, S., & Matsumoto, R. 1992a, PASJ, 44, 265.
Shibata, K., Ishido, Y., Acton, L., et al., 1992b, PASJ, 44, L173.
Shibata, K., Masuda, S., Shimojo, M., et al., 1995, ApJ, 451, L83.
Shibata, K., 1996, Adv. Space Res., 17, (4/5)9.
Shimojo, M., Hashimoto, S., Shibata, K., et al. 1996, PASJ, 48, 123.
Sweet, P. A., 1958, in *Electromagnetic Phenomena in Cosmic Physics, IAU Symp. No. 6*, ed. Lehnert, B. (Cambridge Univ. Press), p. 123.
Tajima, T., & Shibata, K. 1997, *Plasma Astrophysics*, Addison Wesley, Massachusetts.
Tanuma, T., Yokoyama, T., Kudoh, T., and Shibata, K., 1998, in these proceedings.
Tsuneta, S., et al., 1992, PASJ, 44, L211.
Tsuneta, S., 1996, ApJ, 456, 840.
Ugai, M. and Tsuda, T., 1977, J. Plasma Phys. 17, 337.
Ugai, M., 1986, Phys. Fluids, 29, 3659.
Ugai, M., 1987, Geophys. Res. Lett., 14, 103.
Yan, M., Lee, L. C., and Priest, E. R., 1992, JGR, 97, 8277.
Yokoyama, T., & Shibata, K. 1994, ApJ, 436, L197
Yokoyama, T., & Shibata, K. 1995, Nature, 375, 42.
Yokoyama, T., & Shibata, K. 1996, PASJ, 48, 353.
Yokoyama, T., & Shibata, K. 1997, ApJ, 474, L61.
Yokoyama, T., & Shibata, K. 1998, ApJ, 494, L113.