J. Astrophys. Astr. (2009) **30,** 79–85

Reconnection in Solar Flares: Outstanding Questions

Hiroaki Isobe[1,*] & Kazunari Shibata[2]
[1]*Department of Earth and Planetary Science, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. e-mail: isobe@eps.s.u-tokyo.ac.jp*
[2]*Kwasan and Hida Observatories, Kyoto University, Yamashina, Kyoto 607-8471, Japan. e-mail: shibata@kwasan.kyoto-u.ac.jp*

Received 2007 April 9; accepted 2009 April 10

Abstract. Space observations of solar flares such as those from Yohkoh, SOHO, TRACE, and RHESSI have revealed a lot of observational evidence of magnetic reconnection in solar flares: cusp-shaped arcades, reconnection inflows, plasmoids, etc. Thus it has been established, at least phenomenologically, that magnetic reconnection does occur in solar flares. However, a number of fundamental questions and puzzles still remain in the physics of reconnection in solar flares. In this paper, we discuss the recent progresses and future prospects in the study of magnetic reconnection in solar flares from both theoretical and observational points of view.

Key words. Flares—magnetic reconnection—magnetohydrodynamics.

1. Introduction

Magnetic reconnection is believed to be a fundamental process in various energetic phenomena in space and astrophysical plasmas (Tajima & Shibata 1997; Priest & Forbes 2000). Although the idea of magnetic reconnection for explaining the energy release in solar flares had been proposed many decades ago (Parker 1957; Sweet 1958) it was after *Yohkoh* (Ogawara *et al.* 1991) observations that the reality of magnetic reconnection occurring during solar flares was established. Examples of evidence for reconnection include cusp-shaped post-flare loops (Tsuneta *et al.* 1992) a hard X-ray source above flaring loops (Masuda *et al.* 1994), plasmoid ejections in impulsive flares (Shibata *et al.* 1995), and supra-arcade downflows (McKenzie & Hudson 1999). Recent observations from SOHO, TRACE and RHESSI have been producing further evidence; an outstanding example is the discovery of reconnection inflows (Yokoyama *et al.* 2001; Lin *et al.* 2005; Narukage & Shibata 2006). See Shibata (1999) and Martens (2003) for reviews of observational evidence of reconnection.

The idea of magnetic reconnection has been applied, not only to solar flares, but to various explosive phenomena in the solar atmosphere (e.g., Shibata *et al.* 1992;

[*]Present address: Unit of Synergetic Studies for Space, Kyoto University, Japan. e-mail: isobe@kwasan.kyoto-u.ac.jp

Innes *et al.* 1997; Pariat *et al.* 2004). However, the theories of magnetic reconnection itself still have fundamental difficulties. The authors' list of the remaining outstanding problems in the physics of reconnection is as following:

- How is fast reconnection realized in a highly conducting plasma?
- What is and what determines the rate of reconnection?
- Is reconnection in the solar corona Petschek type, generalized Sweet–Parker type, or other type? Can we find slow and fast shocks?
- What is the nature of coupling between micro and macro scales?
- What is the origin of anomalous resistivity?
- What is the acceleration mechanism of non-thermal particles?
- What is the energy build-up process and the triggering mechanism of reconnection in solar flares ?
- What are the differences of reconnection in different plasma environment?
- What are the three-dimensional topology and dynamics?

We are aware that this is a biased list, perhaps biased towards macroscopic aspects. Also, many of the listed items are not independent but closely related to each other. In the rest of the paper we will review the previous achievements and future prospects on the selected issues from the list.

2. How and why reconnection is fast?

The time scale of energy release in a solar flare is typically 10–100 τ_A ($100 \sim 1000$ s), where $\tau_A = L/v_A$ is Alfvén transit time, L is the characteristic size of the system and $v_A = B/\sqrt{4\pi\rho}$ is the Alfvén velocity. Since the resistivity η is extremely small in the solar corona, the diffusion time $\tau_\eta = L^2/\eta$ is huge (say, 100 years). Therefore, we need a mechanism that can drastically increase the rate of energy release, i.e., magnetic reconnection.

It is well known that Sweet–Parker reconnection is too slow to explain solar flares. In Sweet–Parker reconnection, the non-dimensional reconnection rate is given by $v_{\rm in}/v_A = w/L = \sqrt{S}$, where $v_{\rm in}$ is the inflow velocity, w and L are the thickness and the length of the current sheet, and $S = Lv_A/\eta$ is the Lundquist number (magnetic Reynolds number defined with v_A). If one uses classical Spitzer resistivity in the corona, S is as large as 10^{14}, and thus the reconnection rate is as small as 10^{-7}.

Sweet–Parker reconnection is slow because the aspect ratio w/L of the diffusion region (current sheet) is small and therefore plasma exhausting by reconnection outflow is insufficient. In order to overcome this problem, Petschek (1964) considered that the diffusion region is localized in a small region. Then the plasma is heated and accelerated through two pairs of MHD slow mode shocks that extend from the diffusion region. Petschek showed that for large S the reconnection rate is given by $v_{\rm in}/v_A = \pi/8 \log S \approx$ 0.01–0.1. This is fast enough to energize solar flares. MHD simulations have demonstrated that such Petschek-type (i.e., with slow shocks) fast reconnection is realized when resistivity is spatially localized (e.g., Ugai & Tsuda 1977; Yokoyama & Shibata 1994), though reconnection is usually highly intermittent in non-steady simulations (e.g., Kliem *et al.* 2000; Tanuma *et al.* 2001).

How fast is reconnection in real solar flares? Attempts to measure the reconnection rate in flares have been made by many authors (Dere 1996; Tsuneta 1996; Ohyama & Shibata 1997; Isobe *et al.* 2002, 2005; Saba *et al.* 2006; Nagashima & Yokoyama

2006). It is not straight forward to measure the reconnection rate because measurement of coronal magnetic field $B_{\rm corona}$, and inflow velocity $v_{\rm in}$ are difficult. However, separation of chromospheric flare ribbons provides a good measure of reconnection rate (Forbes & Lin 2000). Assuming that reconnection is steady and two-dimensional, the reconnected magnetic flux per unit time is given by:

$$B_{\rm corona} v_{\rm in} = B_{\rm foot} v_{\rm foot}, \tag{1}$$

where $B_{\rm foot}$ and $v_{\rm foot}$ are the magnetic field strength and separation velocity of chromospheric flare ribbons. Isobe *et al.* (2002, 2005) considered this equation and the energy release rate H given by the Poynting flux of reconnection inflow,

$$H = 2\frac{B_{\rm corona}^2}{4\pi} v_{\rm in} A_r, \tag{2}$$

where A_r is the area of reconnection inflow. Using these two equations, they calculated the non-dimensional reconnection rate $v_{\rm in}/v_A$ for several flares from available observations. The calculated values fell in the range of 0.001–0.1. Other studies cited above found similar values, as summarized in Table 4 of Narukage & Shibata (2006).

Direct evidence of reconnection inflows was first found in EUV images of a limb flare observed by SOHO/EIT (Yokoyama *et al.* 2001). Narukage & Shibata (2006) found further such examples. The estimated reconnection rate was 0.001–0.07. In these studies, the inflow velocity $v_{\rm in}$ was measured from the apparent motion in the images and hence may not be the real plasma velocity (Chen *et al.* 2004). Spectroscopic detection of reconnection inflow is therefore important, but such observations are still rare (Lin *et al.* 2005; Hara *et al.* 2006). It is obviously an important target of EUV imaging spectrometer (EIS) onboard *Hinode* (Solar-B).

In summary, the previous quantitative analyses of reconnection rate have indicated that the reconnection rate is in the range of 0.001–0.1. This is fast enough to explain the energy release rate of flares and roughly consistent with Petschek-type reconnection. The lower values in some cases ($\sim$0.001) are probably the spatial and temporal averages. As discussed further in the next section, the reconnection process is likely to be quite intermittent, both in time and in space. Temporal and spatial variation of reconnection rate should be studied in future using high resolution data (Saba *et al.* 2006).

Another important observational challenge is detection of slow shocks. The cusp-shaped loops and Y-shaped structure found by Soft X-ray Telescope aboard *Yohkoh* may be the reconnection slow shocks (Tsuneta *et al.* 1992; Shiota *et al.* 2003), but further evidence, e.g., jump in plasma density, pressure, and velocity, is obviously needed. *Hinode*/EIS will be a strong tool for this purpose (Brooks *et al.* 2004; Shiota *et al.* 2004).

3. Macro–micro coupling

One of the most fundamental problems of Petschek-type MHD reconnection is the nature and origin of localized diffusion region. A localized resistivity may be realized by an anomalous resistivity caused by wave-particle interactions or kinetic instabilities. Although the microscopic origin of such an anomalous resistivity has not been clarified, magnetospheric observations (e.g., Sergeev *et al.* 1993), particle simulations (e.g., Horiuchi & Sato 1999), and laboratory experiments (e.g., Ono *et al.* 1997) indicate that fast magnetic reconnection is initiated when the thickness of the current sheet becomes as thin as the ion inertia length or the ion Larmour radius, where kinetic effects of the plasma becomes significant.

However, both the ion inertia length and ion Larmour radius are of the order of 10^2 cm, while the characteristic size of solar flares is about 10^9 cm. This is a big difference from the magnetospheric case, where the ratio of global scale to ion scales is of the order of 10–100. See Terasawa *et al.* (2000) for a comparison of solar flares and magnetospheric substorms. How to link this huge gap between different scales is the most challenging and fundamental problem in reconnection physics. Perhaps there are some meso-scale structures that connect the global and microscopic scales?

Observations give us some hints to tackle this problem. As mentioned already, reconnection in solar flares is quite intermittent. This is inferred from fine structures in flare ribbons (e.g., Kitahara & Kurokawa 1990; Fletcher *et al.* 2004) and fast temporal variation of hard X-ray and radio lightcurves (e.g., Aschwanden *et al.* 1996; Karlický *et al.* 2005). Such spatial and temporal fine structures suggest the existence of fine structures in the reconnecting current sheet.

Another significant observational fact is the correlation of reconnection and plasmoid ejection. Almost all the explosive events in the solar corona is accompanied by ejection of plasma, from coronal mass ejections to microflares (e.g., Shibata *et al.* 1995; Innes *et al.* 1997; Zhang *et al.* 2001; Sakajiri *et al.* 2004; Asai *et al.* 2004). Careful examination of plasmoid motion and flare lightcurve have revealed that the plasmoid had started to move slowly well before the impulsive phase of the flare, and then suddenly accelerated and ejected during the impulsive phase (Ohyama & Shibata 1997; Chifor *et al.* 2006). From such observations, Shibata & Tanuma (2001) suggested ‘plasmoid-induced’ reconnection model, in which fast reconnection and plasmoid ejection are dynamically coupled.

Karlický *et al.* (2005) examined the Fourier power spectra of pulsating structure observed in 500–1500 MHz, which is interpreted as the result of plasmoid ejection from reconnection site. They found power law spectra in the short period (0.06–0.2 s) range. This indicates that there is no characteristic scale in reconnection and hence the reconnecting current may have a turbulent, possibly fractal structure as suggested by Tajima & Shibata (1997). Similar picture of a reconnecting current sheet, i.e., full of many small plasmoid, has been given by Aschwanden (2002). Such turbulent structure may give a way to link the microscopic and macroscopic scales in reconnection.

What can be the origin of such turbulent structures in a current sheet? Shibata & Taunua (2001) suggested multiple tearing instability. This is a ‘top-down’ process, approaching from macro-scale to micro-scale by an MHD instability. For magnetospheric reconnection, Hoshino *et al.* (1994) proposed an opposite approach, i.e., formation of large-scale plasmoid by bottom-up process from microscopic scales. Presumably both happen at the same time in the solar case.

A three-dimensional MHD simulation carried out by the authors provides an interesting result that may be related to this problem (Isobe *et al.* 2005, 2006). Figure 1 shows three-dimensional visualizations of the MHD simulation of magnetic reconnection between an emerging flux and pre-existing coronal field. It was shown that the top of the emerging flux becomes unstable to the magnetic Rayleigh–Taylor instability in the corona. As the Rayleigh–Taylor instability grows, an interchanging, filamentary structure is created in the emerging flux, which is similar to an arch filament

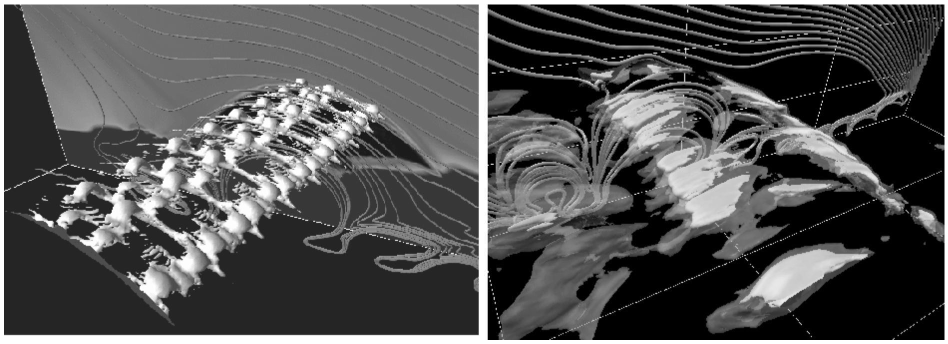

Figure 1. Three-dimensional visualization of the result of MHD simulation of magnetic reconnection between an emerging flux and a pre-existing coronal field. Left: Isosurface of plasma pressure and a selected magnetic field lines. Right: Isosurfaces of the magnitude of velocity, corresponding 60 km s^{-1} (transparent) and 120 km s^{-1}.

system observed in Hα. See Isobe *et al.* (2006) for details of the simulation. Consequently, the current sheet between the emerging flux and coronal field also undergoes interchanging. Tearing instability locally occurs in the current sheet, creating many small plasmoid as shown in the left panel of Fig. 1. This is remarkably similar to the cartoon by Aschwanden (2002, Fig. 47) in which many plasmoids exist in a reconnecting current sheet. After the ejection of these plasmoids, fast reconnection occurs in temporally and spatially intermittent way. The right panel shows the structure of the reconnection outflows. Many narrow jets are ejected from the localized diffusion regions.

Thus, the MHD simulation has demonstrated the turbulence excitation and associated reconnection in a self-consistent way. In this case, the origin of turbulence is an ideal MHD instability, namely the magnetic Rayleigh–Taylor instability. From this simulation result, we conjecture that a possible scenario to link the micro and macro scales is as follows. First, small scale structure is created by ideal MHD instabilities such as Rayleigh–Taylor instability or Kelvin–Helmholtz instability (top-down process). When the turbulence cascades down to the ion scale, tearing and reconnection are initiated at such small scale. Then the small scale islands become bigger by coalescence (bottom-up process).

Of course, this is still a rough conjecture. Direct numerical simulation of such processes requires multi-scales and multi-physics. It is a big challenge of the theoretical and numerical studies in the next decades.

4. Reconnection in the lower atmosphere

In this section we briefly mention the magnetic reconnection in the lower atmosphere of the Sun. Reconnection is likely to be occurring in the photosphere and chromosphere. Canceling magnetic features (Litvinenko & Martin 1999) and Ellerman bombs (Pariat *et al.* 2004; Isobe *et al.* 2007) are believed to be the manifestations of such lower level reconnection. Chromospheric reconnection may play a significant role in the coronal heating (Sturrock 1999).

Although the photosphere and the chromosphere are weakly ionized regions and therefore the resistivity is relatively large, the Lundquist number is still larger than 10^4.

Reconnection in such plasma environment is also of interest in some astrophysical systems such as protoplanetary disks (Inutsuka & Sano 2005), but it is still poorly understood (Litvinenko 1999; Chen *et al.* 2001; Chae *et al.* 2002). Theoretical and observational studies on this subject are therefore desired. The Solar Optical Telescope on *Hinode* will provide further detailed observations of the lower atmospheric reconnection.

5. Conclusion

In this paper we have discussed a selected issue on the outstanding questions of the physics of magnetic reconnection. Due to the space restriction we did not discuss some very important issues such as particle acceleration (Aschwanden 2002) and three-dimensionality (Priest & Forbes 1992; Isobe *et al.* 2002; Tripathi *et al.* 2006).

The solar atmosphere provides an excellent laboratory to study the basic plasma physics. Since magnetic reconnection is of great interest not only for solar physics but also for much larger fields of plasma physics and astrophysics, it is desirable to utilize the solar observation to study reconnection, not only to utilize reconnection to interpret the solar phenomena. Recently launched *Hinode* satellite and other upcoming projects will provide us further advanced data, from which we may get deeper insight of the basic physics of reconnection.

References

Asai, A., Yokoyama, T., Shimojo, M. *et al.* 2004, *Astrophys. J.*, **611**, 557.

Aschwanden, M. J. 2002, *Space Sci. Rev.*, **101**, 1.

Aschwanden, M. J., Wills, M. J., Hudson, H. S. *et al.* 1996, *Astrophys. J.*, **468**, 398.

Brooks, D. H., Isobe, H., Shibata, K., Chen, P. F., Lanzafame, A. C. 2004, In: *The Solar-B Mission and the Forefront of Solar Physics, ASP Conference Series* (eds) Sakurai, T., Sekii, T. **325**, 367.

Chae, J., Choi, B.-K., Park, M. 2002, *J. Korean Astron. Soc.*, **35**, 59.

Chen, P. F., Fang, C., Ding, M. D. 2001, *Chinese J. Astron. Astrophys.*, **1**, 176.

Chen, P. F., Shibata, K., Brooks, D. H., Isobe, H. 2004, *Astrophys. J.*, **602**, L61.

Chifor, C., Mason, H. E., Tripathi, D., Isobe, H., Asai, A., 2006, *Astron. Astrophys.*, **458**, 965.

Dere, K. P. 1996, *Astrophys. J.*, **472**, 864.

Fletcher, L., Pollock, J., Potts, H. E. 2004, *Solar Phys.*, **222**, 279.

Forbes, T. G., Lin, J. 2000, *Atmos. Sol.-Terr. Phys.*, **62**, 1499.

Hara, H., Nishino, Y., Ichimoto, K., Delaboudinière, J.-P. 2006, *Astrophys. J.*, **648**, 712.

Horiuchi, R., Sato, T. 1999, *Phys. Plasmas*, **6**, 4565.

Hoshino, M., Nishida, A., Yamamoto, T., Kokubun, S. 1994, *Geophys. Res. Lett.*, **21**, 2935.

Innes, D. E., Inhester, B., Axford, W. I., Willhelm, K. 1997, *Nature*, **386**, 811.

Inutsuka, S., Sano, T. 2005, *Astrophys. J.*, **628**, L155.

Isobe, H., Miyagoshi, T., Shibata, K., Yokoyama, T. 2005, *Nature*, **434**, 478.

Isobe, H., Miyagoshi, T., Shibata, K., Yokoyama, T. 2006, *Publ. Astron. Soc. Japan*, **58**, 423.

Isobe, H., Shibata, K., Machida, S. 2002, *Geophys. Res. Lett.*, **29(21)**, 2014.

Isobe, H., Takasaki, H., Shibata, K. 2005, *Astrophys. J.*, **632**, 1184.

Isobe, H., Tripathi, D., Archontis, V. 2007, *Astrophys. J.*, **657**, L53.

Isobe, H., Yokoyama, T., Shimojo, M. *et al.* 2002, *Astrophys. J.*, **566**, 528.

Karlický, M., Bárta, M., Mészárosová, H., Zlobec, P. 2005, *Astron. Astrophys.*, **432**, 705.

Kitahara, T., Kurokawa, H. 1990, *Solar Phys.*, **125**, 321.

Kliem, B., Karlický, M., Benz, A. O. 2000, *Astron. Astrophys.*, **360**, 715.

Lin, J., Ko, Y.-K., Sui, L. *et al.* 2005, *Astrophys. J.*, **622**, 1251.

Litvinenko, Y. E. 1999, *Astrophys. J.*, **515**, 435.

Litvinenko, Y. E., Martin, S. F. 1999, *Solar Phys.*, **190**, 45.
Martens, P. C. H. 2003, *Adv. Space Res.*, **32**, 905.
Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., Ogawara, Y. 1994, *Nature*, **371**, 495.
Nagashima, K., Yokoyama, T. 2006, *Astrophys. J.*, **647**, 654.
Narukage, N., Shibata, K. 2006, *Astrophys. J.*, **637**, 1122.
Ogawara, Y. *et al.* 1991, *Solar Phys.*, **136**, 17.
Ohyama, M., Shibata, K. 1997, *Publ. Astron. Soc. Japan*, **49**, 249.
Ono, Y., Inomoto, M., Okazaki, T. *et al.* 1997, *Phys. Plasmas*, **4**, 1953.
Pariat, E., Aulanier, G., Schmieder, B. *et al.* 2004, *Astrophys. J.*, **614**, 1099.
Parker, E. N. 1957, *J. Geophys. Res.*, **62**, 509.
Petschek, H. E. 1964, In: *AAS-NASA Symp. on Solar Flares* (ed.) Hess, W. N. (NASA SP-50), 425.
Priest, E. R., Forbes, T. G. 2000, *Magnetic reconnection: MHD theory and applications*, Cambridge University Press, New York.
Priest, E. R., Forbes, T. G. 1992, *J. Geophys. Res.*, **97**, 1521.
Saba, J. L. R., Gaeng, T., Tarbell, T. D. 2006, *Astrophys. J.*, **641**, 1197.
Sakajiri, T., Brooks, D. H., Yamamoto, T. *et al.* 2004, *Astrophys. J.*, **616**, 578.
Sergeev, V. A., Mitchell, D. G., Russell, C. T. *et al.* 1993, *J. Geophys. Res.*, **98**, 17,345.
Shibata, K. 1999, *Astrophys. Space Sci.*, **264**, 129.
Shibata, K. *et al.* 1992, *Publ. Astron. Soc. Japan*, **44**, L173.
Shibata, K., Masuda, S., Shimojo, M. *et al.* 1995, *Astrophys. J.*, **451**, L83.
Shibata, K., Tanuma, S. 2001, *Earth, Planets Sci.*, **53**, 473.
Shiota, D., Isobe, H., Brooks, D. H., Shibata, K., Chen, P. F. 2004, In: *The Solar-B Mission and the Forefront of Solar Physics*, (eds) Sakurai, T., Sekii, T., *ASP Conference Series* **325**, 373.
Shiota, D., Yamamoto, T. T., Sakajiri, T. *et al.* 2003, *Publ. Astron. Soc. Japan*, **55**, L35.
Sturrock, P. A. 1999, *Astrophys. J.*, **521**, 451.
Sweet, P. A. 1958, In: *IAU Symp. No.6, Electromagnetic Phenomena in Cosmical Physics* (ed.) Lehnert, B., 123.
Tajima, T., Shibata, K. 1997, *Plasma Astrophysics* (Massachusetts: Addison-Wesley).
Tanuma, S., Yokoyama, T., Kudoh, T., Shibata, K. 2001, *Astrophys. J.*, **551**, 312.
Terasawa, T., Shibata, K., Scholer, M. 2000, *Adv. Space Res.*, **26**, 573.
Tripathi, D., Isobe, H., Mason, H. E. 2006, *Astron. Astrophys.*, **453**, 1111.
Tsuneta, S. 1996, *Astrophys. J.*, **456**, 840.
Tsuneta, S. *et al.* 1992, *Publ. Astron. Soc. Japan*, **44**, L63.
Ugai, M., Tsuda, T. 1977, *J. Plasma Phys.*, **17**, 337.
Yokoyama, T., Akita, K., Morimoto, T., Inoue, K., Newmark, J. 2001, *Astrophys. J.*, **546**, L69.
Yokoyama, T., Shibata, K. 1994, *Astrophys. J.*, **436**, L197.
Zhang, J., Dere, K. P., Howard, R. A., Kundu, M. R., White, S. M. 2001, *Astrophys. J.*, **559**, 452.