Pergamon

Adv. Space Res. Vol. 17, No. 4/5, pp. (4/5)9–(4/5)18, 1996

0273–1177/96 $9.50 + 0.00

0273–1177(95)00534–X

NEW OBSERVATIONAL FACTS ABOUT SOLAR FLARES FROM YOHKOH STUDIES – EVIDENCE OF MAGNETIC RECONNECTION AND A UNIFIED MODEL OF FLARES

K. Shibata

National Astronomical Observatory, Mitaka, Tokyo 181, Japan

ABSTRACT

Recent discoveries on flares and related phenomena with the soft X-ray telescope aboard *Yohkoh* are discussed with emphasis on evidence of magnetic reconnection. These include also the big discovery of a hard X-ray loop top source by Masuda et al. (1994) using the hard X-ray telescope. It is emphasized that *LDE (long duration events) flares*, *large scale arcade formation*, and (*simple loop) impulsive flares* show many common features, such as plasmoid/filament ejection, in *Yohkoh* images. I will discuss that many of them are interpreted as due to magnetic reconnection, or to be related to reconnection, and present a unified model to explain LDE flares and impulsive flares with a single physical mechanism, in which a plasmoid ejection plays a key role to induce fast reconnection. It is further discussed that the same physical mechanism may be applied to smaller "flares", such as *microflares* and *X-ray jets*, in a grand unified scheme.

INTRODUCTION

The solar X-ray satellite, *Yohkoh*, was launched on Aug. 30, 1991, by the Institute of Space and Astronautical Science (ISAS) in Japan, as international collaboration project between Japan, US, and UK /1/. *Yohkoh* carries 4 instruments /1/, Hard X-ray Telescope (HXT), Soft X-ray Telescope (SXT), Bragg Crystal Spectrometer (BCS), and Wide Band Spectrometer (WBS), and has observed already more than a few 100 flares, and has taken more than a few million soft X-ray images. *Yohkoh*/SXT has revealed that *the solar corona is much more dynamic than had been thought*, i.e., the corona is full of transient loop brightenings, jets, global restructuring of magnetic fields, magnetic loop expansion, etc. (see reviews by /2-6/), suggesting that the solar corona is full of *magnetic reconnection*. In this article, I would like to summarize recent discoveries by *Yohkoh*/SXT (with some HXT results also), which show various evidence of magnetic reconnection associated with mass ejection in flares. (As for other new findings on flares by *Yohkoh*, see other review papers in this issue, such as by Kosugi for HXT observations, and by Culhane for BCS observations.)

LDE FLARES

One of the biggest discoveries by *Yohkoh*/SXT is the discovery of cusp-shaped loop structures in LDE (Long Duration Events) flares /7,8/. Fig. 1(a) shows one beautiful example of this kind of flare, which occurred on Feb. 21, 1992, at the west limb (Tsuneta et al. /7/). This flare occurred a few hours after a large scale coronal eruption (possibly, CME), which created a helmet-streamer-like configuration, suggesting that a current sheet is formed as a result of global MHD instability. The apparent height of the loop and the distance between two footpoints of the loop increase gradually with time at a few km/s. This is nicely explained as the result of the succesive reconnection in the current sheet above the loop, as described by the classical flare model for two-ribbon flares, which was developed by Carmichael, Sturrock, Hirayama, and Kopp and Pneuman. This kind of model is hearafter called *CSHKP model* /9/. Modern version of this model has been developed by Forbes and Malherbe /10/ and others.

Tsuneta et al. /7/ further found the following characteristics. (1) The temperature distribution is somewhat chaotic in early phase (during and just after rise phase; < 30 min), while it is systematically higher at the outer edge of the loop (or it is lower at the inner part of the loop) in a later phase (> 1 hour). (2) The gas pressure is highest at the top of the loop, where the temperature is rather low. Both seem to be consistent with modern version of CSHKP model, because the low temperature at the inner region can be explained by the radiative cooling /10/, and the high pressure at the same region may be explained by the slow shock /10,11/.

More recently, from close examination of the SXT movie of this flare /12/, it is found that a small magnetic island (or plasmoid) with a size of a few 10^4 km is ejected at a few 100 km/s along the current sheet during the rise phase of the flare. It is likely that the ejection of the plasmoid triggered the flare. In fact, SXR images in the preflare phase seem to show filamentary structures perpendicular to the current sheet, suggesting that the perpendicular magnetic field lines penetrate the current sheet, preventing the magnetic reconnection in the current sheet. The flare (possibly, reconnection) suddenly occurred after the plasmoid ejection.

LARGE SCALE ARCADE FORMATION

Cusp-shaped loops or arcades which show similar evolutional feature to that of LDE flares have also been found in much larger spatial scale /13-18/. These *large scale arcade formation* usually occur in association with disappearance of a dark filament. Tsuneta et al. /14/ described an event associated with a disapperance of a polar crown filament on Nov. 12, 1991. This event has gradually increased its size for more than 20 hours to a size of 1.5 solar radius times 0.5 solar radius at maximum. Similar events occurred on Apr. 14, 1994, which was luckily reported by KSC *toban* (that means "duty operator" in Japanese) using Email to the world, and the NOAA/SEL people then predicted the large geomagnetic storm successfully.

A large helmet streamer appearing after a filament eruption and CME is possibly a side view of this kind of large scale arcade formation. A beautiful example of such large helmet streamer formation occurred on Jan. 24, 1992, which was reported by Hiei et al. /18/ It is interesting to note that temperature is higher at outer edge of the cusp-shaped loops, similar to LDE flares. Note also that the X-ray intensity of these events is usually very low so that often these cannot be noticed from GOES X-ray light curve. For this reason, previously these events were not considered to be flares. However, *Yohkoh*/SXT has revealed that these large scale arcade formation are very similar to LDE flares from various points of view (morphology, evolution such as apparent rise motion of arcade-loops, emission measure and temperature distribution pattern, etc.). Only difference may be the size and magnetic field strength, which can explain other differences, such as time scale, total released energy, emission measure, etc., using scaling law based on magnetic reconnection theory as discussed later. Consequently, we can now say that these events are one class of flares.

IMPULSIVE FLARES

Though LDE flares and large scale arcade formation events show clear cusp-shaped loop structure suggesting magnetic reconnection, there is no such cusp-shaped structure in *impusive flares* whose occurrence frequency is much more than LDE flares. The impulsive flares are bright in hard X-rays and show impulsive phase whose duration is short (< a few minutes), whereas the LDE flares are usually week in hard X-rays and do not necessarily show impulsive phase. The apparent shape of the impulsive flares in SXT images is *a simple loop*, as already found by Skylab. Are such impulsive, loop flares fundamentally different from LDE flares ? This led some theoreticians to consider the loop flare models which assume energy release occurring inside the loop /19,20/. The apparent lack of cusp-shaped structure of these impulsive flares in SXT images has been thought to be a negative evidence of reconnection model such as the CSHKP model.

Recently, Masuda et al. /21,22/ (see also his paper in this issue) discovered with HXT that *in some of impulsive limb flares, a loop top hard X-ray (HXR) source appeared well above a soft X-ray (SXR) bright loop during the impulsive phase.* Figure 1(b) shows one typical example of such impulsive limb flare showing HXR loop top source. We can see that the HXR source is well above ($5'' - 10''$) the SXR loop. Although this loop top source is somewhat less bright than the two bright

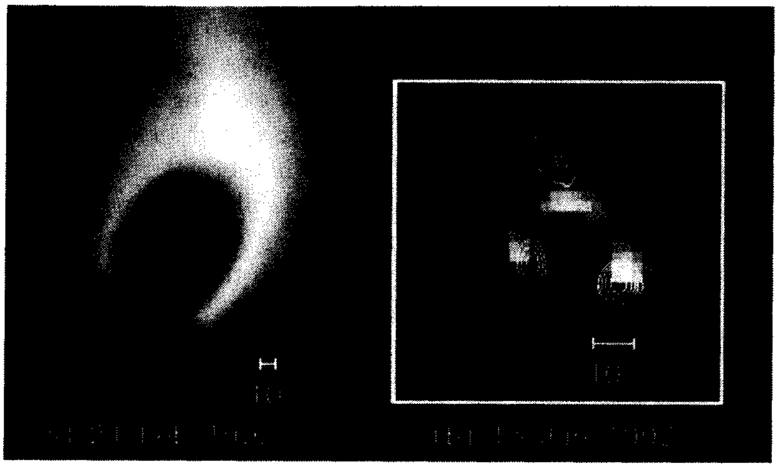

Figure 1: (a) LDE Flare on Feb. 21, 1992 observed with SXT (Tsuneta et al. 1992). (B) Impulisve flare on Jan. 13, 1992 (at 17:26:52 – 17:27:40 UT) which shows a loop top hard X-ray source above soft X-ray loop (Masuda et al. 1994). Contours of hard X-ray (33 – 53 KeV) intensity distribution are overlaid on the soft X-ray (~ 1 KeV) image.

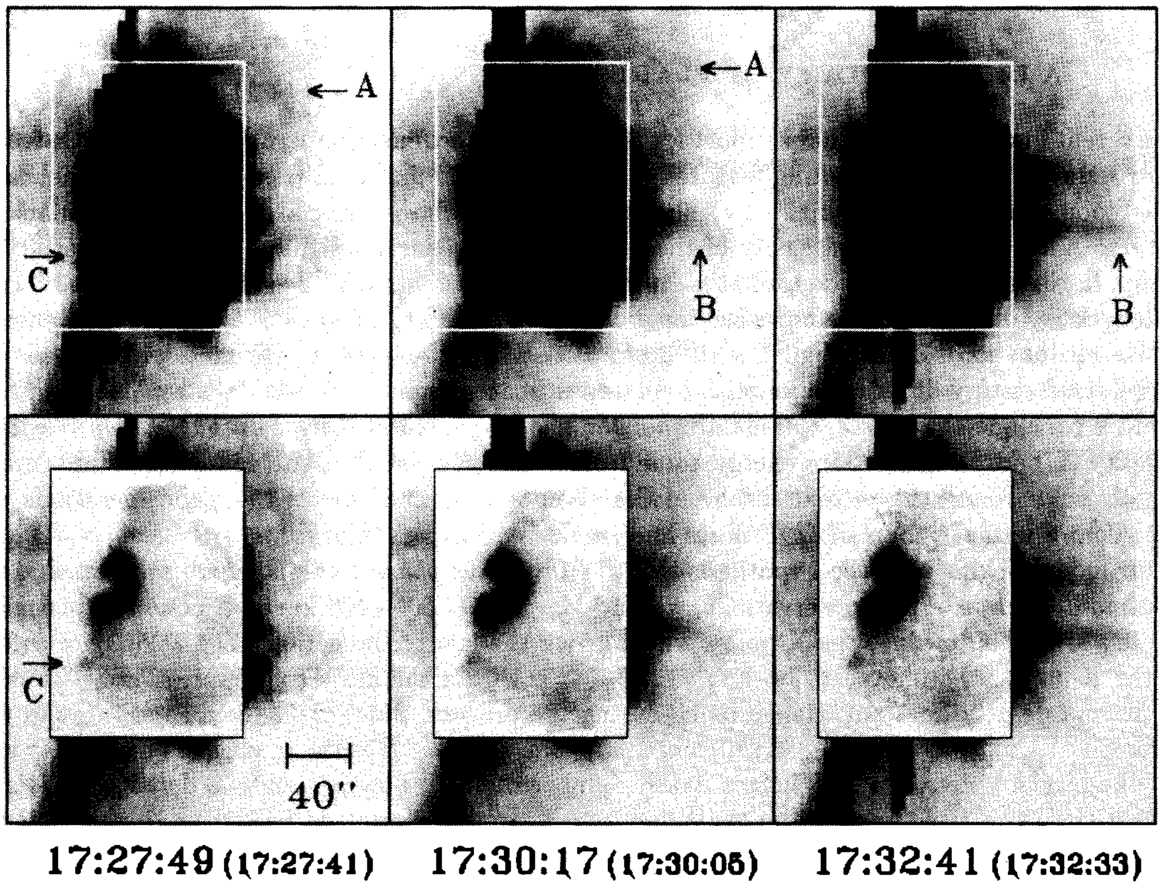

Figure 2: X-ray plasmoid/filament eruption associated with impulsive flare on January 13 1992 which is shown in Fig. 1 (Shibata et al. 1994). The upper three images display long exposure time images, and the bottom displays short exposure time images composited on the long exposure time images. Arrows A and B show the faint X-ray erupting features. The HXR (33 – 53 KeV) impulsive phase is 17:27:30 – 17:29:00 UT.

footpoint HXR sources, the time history of HXR intensity of loop top source is similar to those of footpoint sources /21/. This indicates that an impulsive energy release did not occur within the soft X-ray loop but occurred above the loop. This is a quite exciting discovery because bright soft X-ray loops were often considered to be an evidence of "loop flares" in which energy release occurs within the loop, as discussed above. (If the loop top source is thermal, its temperature is estimated to be as high as a few 100 million K /21,22/.) One possible physical mechanism to produce such loop top hard X-ray source is *magnetic reconnection* occurring above the loop; i.e., a high speed jet is created through the reconnection and collides with the loop top, producing fast shock, superhot plasma and/or high energy electrons emitting hard X-rays. In this sense, the discovery of the loop top HXR source may open a possiblitiy to unify two distinct classes of flares, *LDE flare* and *impulsive flare*, by the single mechanism, the magnetic reconnection.

If the reconnection hypothesis is correct, a plasmoid or a filament (loop) ejection is expected to occur associated with these impulsive flares, as suggested by the CSHKP model. Shibata et al. /23/ searched for such plasmoid or filament (loop) ejections in 8 impulsive limb flares which are selected in an unbiased manner by Masuda /21/, and found that *all these flares were associated with X-ray filament/plasmoid ejections* (see Figure 2). The following characteristics are found /23/: (1) The velocity of the ejections is 50 – 400 km/s. (2) The size of the ejections is 4 – 10 $\times 10^4$ km. (3) The SXR intensity of the ejections is 10^{-4} – 10^{-2} of the peak flare SXR intensity in the main bright SXR loop. A very weak SXR intensity of these ejections is the reason why these ejections have not *always* been seen on the *disk impulsive flares* /24,25/ around which the background SXR intensity is usually high. (4) The onset of the ejections is nearly simultaneous with the impulsive phase. This holds also for multiple ejections. In the case of the 4-Oct-92 flare, the first and second eruptions are nearly coincident with the first and second impulsive peaks. (5) A small SXR bright point appeared during the impulsive phase about a few 10^4 km distant from the SXR loop. The bright point seems to be the footpoint of the large scale erupting loop.

A UNIFIED MODEL OF FLARES

These recent findings give further support for the magnetic reconnection hypothesis as illustrated in Figure 3. In our view, the erupting features correspond to the plasmoid (i.e., a large scale helically twisted loop, in three dimensional view), similar to the LDE flares associated with the Hα filament eruption. A very faint SXR intensity of the erupting features implies that the electron density is not high in these features, of order of $10^9 - 10^{10}$ cm^{-3}. If the volume of these features is $\sim 10^{29}$ cm^3 (the length is 10^{10} cm and the cross-sectional area is $(3 \times 10^9\text{cm})^2$), then the total kinetic energy of the eruptions is of order of 10^{28} – 10^{29} erg. This is an order of magnitude smaller than the total released energy during the impulsive phase, estimated from the HXR data by Masuda /21/. Hence we conclude that *the eruptions are not the energy source of the flares, but simply triggered the flares.* Where does the flare energy come from ? We suggest that the energy is stored in the magnetic field around the current sheet and the plasmoid. On the basis of these considerations, we will present a unified model of LDE flares and impulsive flares as follows.

Our model begins with the hypothesis that *the impulsive phase corresponds to the initial phase of plasmoid ejection.* From observations, we find $V_{plasmoid} \sim 50 - 400$ km/s. Ejection of plasmoid induces a strong inflow into the X-point, which drives the fast reconnection. The velocity of *inflow* into the X-point is estimated to be $V_{inflow} \sim V_{plasmoid}$, from the mass conservation law assuming that plasma density does not change much during the process. Since the Alfven speed around the plasmoid is $V_A \simeq 3000(B/100\text{G})(n_e/10^{10}\text{cm}^{-3})^{-1/2}$km/s, where B is the magnetic flux density and n_e is the electron density. The Alfven Mach number of the inflow becomes $M_A = V_{inflow}/V_A \sim 0.02 - 0.1 V_A$. This is comparable to the inflow speed expected from the Petscheck theory.

The magnetic reconnection theory predicts two oppositely directed high speed jets from the reconnection point at Alfven speed, $V_{jet} \sim V_A$. The downward jet collides with the top of the SXR loop, producing MHD fast shock, superhot plasmas and/or high energy electrons at the loop top, as observed in the HXR images. The temperature just behind the fast shock becomes $T_{loop-top} \sim m_i {V_{jet}}^2/(6k) \sim 2 \times 10^8$ K $(B/100\text{G})^2(n_e/10^{10}\text{cm}^{-3})^{-1}$, where m_i is the hydrogen ion mass and k is the Boltzmann constant. This explains the observationally estimated temperature of the loop top HXR source /21/. We would expect similar physical process for the upward directed

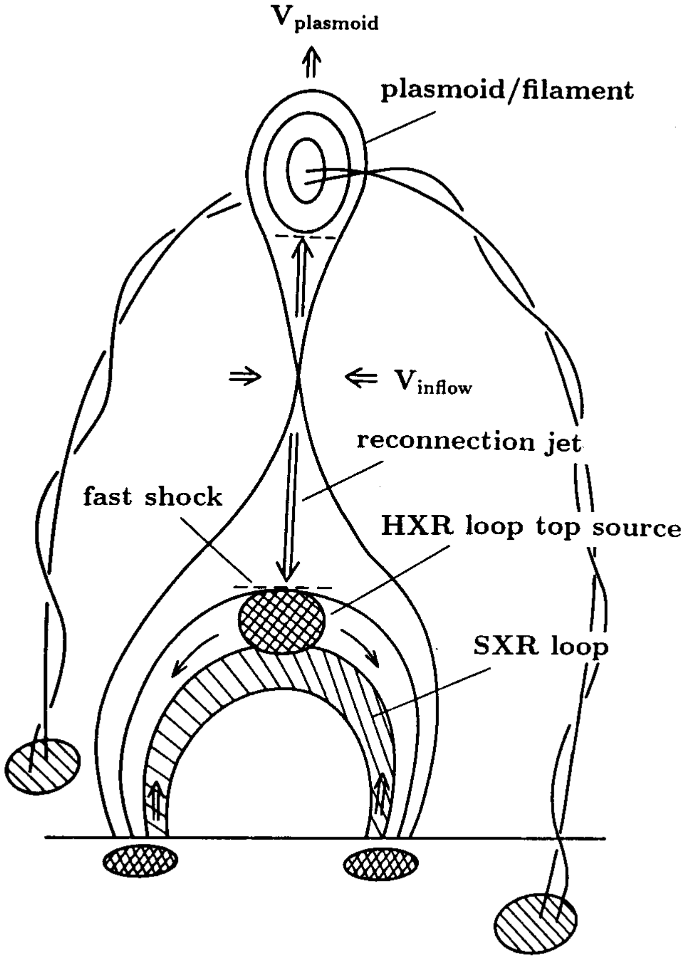

Figure 3: A unified model of flares: plasmoid-driven reconnection model (Shibata et al. 1994).

jet (see Fig. 3). Indeed we find a SXR bright point during the impulsive phase somewhat far from the SXR loop. This bright point seems to be located at the footpoint of the erupting loop.

The magnetic energy stored around the current sheet and the plasmoid is suddenly released through reconnection into kinetic and thermal/nonthermal energies after the plasmoid is ejected. The magnetic energy release rate at the current sheet (with the length of $L_{cs} \sim L_{plamoid} \simeq 2 \times 10^4$ km) is estimated to be $dW/dt = 2 \times L^2_{plasmoid} B^2 V_{inflow}/4\pi \sim 4 \times 10^{28}$ erg/s $(V_{inflow}/100$ km/s) $(B/100$ G$)^2(L_{plasmoid}/2 \times 10^9$ cm$)^2$. This is comparable with the energy release rate during the impulisve phase, $4 - 100 \times 10^{27}$ erg/s, estimated from the HXR data /21/, assuming the lower cutoff energy as 20 keV.

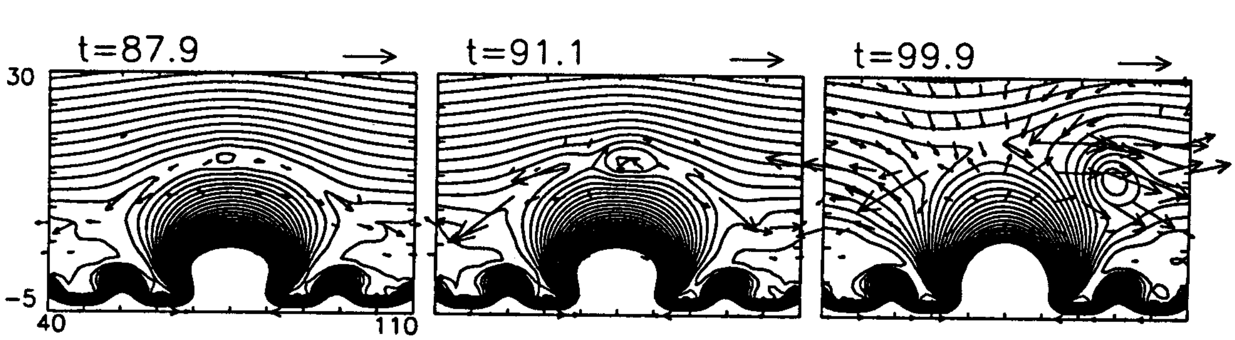

Figure 4: Numerical simulation of reconnection between emerging flux and coronal field (Yokoyama and Shibata 1994). Note that magnetic islands (plasmoids) are formed and ejected even in this small scale reconnection.

The reason why the HXR loop top source is not bright in SXR is that the evaporation flow has not yet reached the colliding point and hence the electron density (and so the emission measure) is low. The key physical parameter discriminating impulsive flares and LDE flares (or impulsive phase and gradual phase) is the velocity of the inflow, V_{inflow}. If V_{inflow} is large, the reconnection is fast, so that the reconnected field lines accumulate very fast and hence the MHD fast shock (i.e., HXR loop top source) is created well above SXR loop which is filled with evaporated plasmas. On the other hand, if V_{inflow} is small, the reconnection is slow and hence the fast shock is produced at the SXR loop. In that case, the density at the shocked region is high because of evaporation, and so the temperature behind the fast shock becomes, $T_{gradual-loop-top} \sim (n_{e,jet}/n_{e,loop})\ m_i V_{jet}{}^2/6k \sim 2 \times 10^7$ K $(B/100\mathrm{G})^2(n_{e,loop}/10^{11}\mathrm{cm}^{-3})^{-1}$, which roughly agrees with temperatures found at the loop top in gradual phase of impulsive flares /21,26-28/ and in LDE flares /7/. The bright knots at the tops of SXR loops /26-28/ also seem to be explained by this model, though more detaild MHD numerical simulations are necessary for modeling the bright knots.

TRANSIENT BRIGHTENINGS (MICROFLARES) AND X-RAY JETS

As mentioned in the Introduction, *Yohkoh*/SXT found that the corona is full of *transient brightenings* /29/ and *X-ray jets* /30,31/, both of which are new discoveries by *Yohkoh*. Shimizu et al. /29,32/ studied the transient brightenings in "active" active regions in detail, and found that *active region transient brightenings* (ARTBs) usually show a single or multiple loops, the total thermal energy content in one transient brightening is $10^{25} - 10^{29}$ erg, time scale is $1 - 10$ min, and the loop length is $0.5 - 4 \times 10^4$ km. They further found that ARTBs correlate well with GOES C-class or sub-C class flares so that ARTBs are considered to be a spatially resolved soft X-ray counterpart of hard X-ray microflares /33/. Using BCS data, Watanabe /34/ found that these sub-C class flares show maximum temperatures of order of 10^7 K, which are not so different from those of larger flares. Morphology of ARTBs, such as multiple loop structures, is suggestive of magnetic reconnection due to *loop-loop interaction* /35,36/, though clear evidence of interaction between two loops has not yet been found until now (though see /37-39/). Although the observational evidence of reconnection in ARTBs are not enough at present, Shimizu et al. /40/ found an interesting statistical property of ARTBs. That is, the number of ARTBs, N, as a function of their total thermal energy content, W, scales as a single power law; $dN/dW \propto W^{-1.5\sim-1.6}$, where W ranges from 10^{27} to 10^{29} erg. Since this relation is essentially the same as that of larger flares and HXR microflares /41/, it is likely that the same physical mechanism causes ARTBs as in larger flares. This is also consistent with the finding by Watanabe /34/ that temperature of microflares is not so different from those of larger flares.

In contrast to ARTBs, there are many observational evidence of reconnection for *X-ray jets*. X-ray jets are defined as transitory X-ray enhancements with an apparent collimated motion /30/ (see figures in /46/ of this issue), and occur in association with small flares (microflares to subflares) which occur in active regions (ARs), emerging flux regions (EFRs), or X-ray bright points (XBPs). The occurrence frequency is more than 20 per month between November 1991 and May 1992. Shimojo et al. /55/ compiled 136 jets during this period, and studied statistical property of jets. They found that average length and (apparent) velocity of jets are $\simeq 1.7 \times 10^5$ km and $\simeq 200$ km/s. Shibata et al. /30,43-46/ found several cases in which the footpoint AR changed their shape or morphology during a jet, which can be an indirect evidence of reconnection in the AR. Shibata et al. /43/ noted that jets are often ejected from EFRs as a result of interaction between emerging flux and coronal magnetic field (some of which are clearly seen in SXT full Sun movie), and that there are basically two types of interaction of emerging flux with coronal fields; (1) *Anemone-Jet* type: When an emerging flux appears in coronal holes, a vertical jet is ejected from an EFR. During the jet, a small loop flare occurs in the EFR. An EFR (or an AR) looks like a sea-anemone and hence is called an anemone-AR. (2) *Two-Sided-Loop (or Jet)* type: When an emerging flux appears in quiet region, two horizontal jets (or loops) are produced both sides of an EFR. These features are explained very well by magnetic reconnection model developed by Yokoyama and Shibata /47,48/ (Fig. 4) and Shibata et al. /49/ .

TOWARD A GRAND UNIFIED MODEL OF "FLARES"

Recent MHD numerical simulations of reconnection between emerging flux and coronal field /47-49/ have shown that magnetic islands (plasmoids) are formed and ejected out of current sheet. This plasmoid ejection is somewhat similar to plamoid ejection seen in larger flares. In this sense, physical processes occuring in small scale reconnection in small flares (microflares and subflares) may be similar to those in large scale reconnection in larger flares (LDE flares and impulsive flares). In both cases, if the current sheet is long enough, the coupling between anomalous resistivity and nonlinear tearing instability leads to the formation of magnetic islands (plasmoids with helically twisted field lines), and the ejection of plasmoids triggers the rapid collapse of the current sheet, leading to very fast reconnection /48/. New observations by *Yohkoh* have shown that the mass ejection (plasmoids or jets) in association with flares is much more universal than had been thought, which seems to support our hypothesis.

Consequently, we may now be able to develop a *grand unified model* explaining both larger and smaller flares in fundamentally the same phsyics. In this model, the start of a story is the global MHD instability (or loss of equilibrium) which creates a current sheet. In largest flares, this corresponds to CME, while it could be emerging flux driven by magnetic buoyancy instability in smaller flares. Any other instability can be a candidate if it creates a current sheet. The point is that the fast reconnection does not necessarily begin immediately after the instability. As shown by Yokoyama and Shibata /48/, the fast reconnection can delay depending on the local plasma condition (such as the presence of perpendicular field penetrating the current sheet and the condition for occurrence of anomalous resistivity) even if the current sheet is compressed by the global instability. *Yohkoh* observations also have shown such examples (e.g., LDE flare on Feb. 21, 1992 /7/, see also recent work by Nitta /50/ who showed some observational evidence of time delay between flux emergence and flares). Observations show that the impulsive phase or the rise phase is nearly simulaneous with rapid ejection of plasmoids (X-ray/Hα filament eruption). Hα surge (and/or X-ray jets) often observed in subflares may correspond to such plasmoid ejection.

SUMMARY AND REMAINING QUESTIONS

In this article, I have summarized various new observational findings by *Yohkoh*, with emphasis upon observational evidence of magnetic reconnection. Some of key observational findings are summarized in Table I. The point is that various flare-like event ranging from very small microflars

Table I Comparison of Various "Flares"

"flare"	size (L) (10^4 km)	time scale (t) (sec)	energy (erg)	mass ejection
microflares (ARTBs)	0.5 – 4	60 – 600	$10^{26} - 10^{29}$	jet/surge
impulsive flares	1 – 10	$60 - 3 \times 10^3$	$10^{29} - 10^{32}$	X-ray/Hα filament eruption
LDE flares	10 – 40	$3 \times 10^3 - 10^5$	$10^{30} - 10^{32}$	X-ray/Hα filament eruption
large scale arcade formation	30 – 100	$10^4 - 2 \times 10^5$	$10^{29} - 10^{32}$	X-ray/Hα filament eruption

Table I Comparison of Various "Flares" (continued)

"flare"	B (G)	n_e (cm^{-3})	V_A (km/s)	$t_A = L/V_A$ (sec)	t/t_A
microflares	100	10^{10}	3000	5	12 – 120
impulsive flares	100	10^{10}	3000	10	6 – 300
LDE flares	30	2×10^9	2000	90	$30 - 10^3$
large scale arcade formation	10	3×10^8	1500	400	25 – 500

to very large arcade formation events can be understood by the same physical process, *magnetic reconnection*. The wide range of total flare energy, from 10^{26} erg to 10^{32}, is simply explained by the available magnetic energy contained in the relevant volume, $W_{flare} \sim L^3B^2/(8\pi) \sim 4 \times 10^{32}\mathrm{erg}(B/100\mathrm{G})^2(L/10^{10}\mathrm{cm})^3$. On the other hand, the time scale of the flare ranges from 1 min to 1 day. If we normalized it by the Alfven time, it becomes $t_{flare} \sim 10 - 100\ t_A$. This is similar to time scale observed in magnetospheric substorm and in explosive phenomena in laboratory fusion plasma, and is also similar to that expected from fast reconnection theory.

On the basis of these new observations, I tried to construct a *unified model* of LDE flares and impusive flares, and even a *grand unified model* explaining both larger flares (LDE and impulsive flares) and smaller flares (microfalres, subflares, and X-ray jets), which include fast reconnection driven by plasmoid ejection as a key process. But of course, this is only a first trial to understand the complex "flares" as simple as possible, and we need more detailed observations such as high spatial resolution observations ranging from X-ray to optical regime, especially on smaller flares (microflares and X-ray jets). In fact, there are still not enough observational evidence of reconnection in microflares because of lack of high spatial resolution in *Yohkoh*. No one knows "true" vecocity of X-ray jets at present due to lack of Doppler-shift measurement. Even in large flares, high speed reconnection jet (> 2000 km/s) have not yet been found by *Yohkoh*. All these remaining puzzles and questions would be an important subject in the next Japanese solar mission /51/.

REFERENCES

1. Y. Ogawara et al. 1991, *Solar Phys.*, **136**, 1.
2. L. Acton et al. 1992, *Science*, **258**, 618.
3. Y. Uchida, 1993, in *Proc. "Physics of Solar and Stellar Coronae"*, J. F. Linsky and S. Serio (eds.), Kluwer Academic Pub., pp. 97.
4. S. Tsuneta and J. R. Lemen, 1993, in *Proc. "Physics of Solar and Stellar Coronae"*, J. F. Linsky and S. Serio (eds.), Kluwer Academic Pub., pp. 113.
5. K. Shibata, 1994, in *Proc. "The Sun as a Variable Star"*, J. M. Pap et al. (eds.), Cambridge Univ. Press, in press.
6. H. S. Hudson, 1994, in *Proc. of Kofu Sympo.*, S. Enome and T. Hirayama (eds.), Nobeyama Radio Observatory Report No. 360, pp. 11.
7. S. Tsuneta et al., 1992, *Publ. Astr. Soc. Japan*, **44**, L63.
8. K. Ichimoto et al., 1994, in *X-ray Solar Physics from Yohkoh*, Y. Uchida et al. (eds.), Univ. Academy Sci., Tokyo, p. 259.
9. P. A. Sturrock, 1992, in *Eruptive Solar Flares*, Z. Svestka et al. (ed.), Springer-Verlag, pp. 397.
10. T. G. Forbes and J. M. Malherbe, 1991, *Solar Phys.*, **135**, 361.
11. M. Ugai, 1987, *Geophys. Res. Lett.*, **14**, 103.
12. H. S. Hudson and J. Lemen, 1994, private communication.
13. S. Tsuneta, 1993, in *Magnetic and Velocity Fields of Solar Active Regions, Proc. IAU Colloq. No. 141*, H. Zirin et al. (eds.), Astr. Sco. Pacific, p. 239.
14. S. Tsuneta et al., 1992, *Publ. Astr. Soc. Japan*, **44**, L211.
15. A. McAllister et al., 1992, *Publ. Astr. Soc. Japan*, **44**, L205.
16. R. Kano, 1994, in *X-ray Solar Physics from Yohkoh*, Y. Uchida et al. (eds.), Univ. Academy Sci., Tokyo, p. 273.

17. Y. Hanaoka et al., 1994, *Publ. Astr. Soc. Japan*, **46**, 205.

18. E. Hiei et al., 1993, *Geophys. Res. Let.*, **20**, 2785.

19. D. Spicer, 1977, *Solar Phys.*, **53**, 305.

20. Y. Uchida, and K. Shibata, 1988, *Solar Phys.*, **116**, 291.

21. S. Masuda, 1994, Ph. D. Thesis, Univ. of Tokyo.

22. S. Masuda et al., 1994, *Nature*, in press.

23. K. Shibata et al., 1994, submitted to *Nature*.

24 R. Kitai et al., 1994, in *Proc. of Kofu Sympo.*, S. Enome and T. Hirayama (eds.), Nobeyama Radio Observatory Report No. 360, p. 150.

25 K. Shibata et al., 1993, in *Proc. China-Japan workshop on Solar Physics*, T. Sakurai et al. (eds.), p. 220.

26 L. Acton et al., 1992, *Publ. Astr. Soc. Japan*, **44**, L71.

27 U. Feldman et al., 1994, *Astrophys. J.* , **424**, 444.

28 G. A. Doschek, K. T. Strong, and S. Tsuneta, 1994, *Astrophys. J.* , submitted.

29. T. Shimizu et al., 1992, *Publ. Astr. Soc. Japan*, **44**, L147.

30. K. Shibata et al., 1992, *Publ. Astr. Soc. Japan*, **44**, L173.

31. K. T. Strong et al., 1992, *Publ. Astr. Soc. Japan*, **44**, L161.

32. T. Shimizu et al., 1994, *Astrophys. J.* , **422**, 906.

33. R. P. Lin et al., 1984, *Astrophys. J.* , **283**, 421.

34. Te. Watanabe, 1994, in *Proc. of Kofu Sympo.*, S. Enome and T. Hirayama (eds.), Nobeyama Radio Observatory Report No. 360, p. 99.

35. T. Tajima et al., 1987, *Astrophys. J.* , **321**, 1031.

36. J-I. Sakai and S. Koide, 1992, *Solar Phys.*, **142**, 399.

37. Y. Hanaoka, 1993, *Astrophys. J. Let.*, **420**, L37.

38. C. C. Chen and L. Acton, 1994, in *X-ray Solar Physics from Yohkoh*, Y. Uchida et al. (eds), Universal Academy Pub., p. 83.

39. M. Akioka, L. Acton, H. Hudson, 1994, in *X-ray Solar Physics from Yohkoh*, Y. Uchida et al. (eds), Universal Academy Pub., p. 241.

40. T. Shimizu et al. 1994, in *Proc. of Kofu Sympo.*, S. Enome and T. Hirayama (eds.), Nobeyama Radio Observatory Report No. 360, p. 61.

41. H. S. Hudson, 1991, *Solar Phys.*, **133**, 357.

42. M. Shimojo et al. 1994, in preparation.

43. K. Shibata et al. 1994, *X-ray Solar Physics from Yohkoh*, Y. Uchida et al. (eds), Universal Academy Pub., p. 29.

44. K. Shibata et al. 1994, *Astrophys. J. Let.*, **431**, L51.

45. K. Shibata, T. Yokoyama, and M. Shimojo, 1994, in *Proc. of Kofu Sympo.*, S. Enome and T. Hirayama (eds.), Nobeyama Radio Observatory Report No. 360, p. 75.

46. K. Shibata, T. Yokoyama, and M. Shimojo, 1995, this issue.

47. T. Yokoyama, and K. Shibata, 1994, in *Proc. of Kofu Sympo.*, S. Enome and T. Hirayama (eds.), Nobeyama Radio Observatory Report No. 360, p. 367.

48. T. Yokoyama, and K. Shibata, 1994, *Astrophys. J. Lett.*, in press.

49. K. Shibata, S. Nozawa, and R. Matsumoto, R., 1992, *Publ. Astr. Soc. Japan*, **44**, 265.

50. N. Nitta et al., 1995, this issue.

51. Y. Ogawara, 1995, this issue.