CORONAL DYNAMICS AND FLARES: NEW RESULTS FROM YOHKOH SXT -EVIDENCE OF MAGNETIC RECONNECTION AND A UNIFIED MODEL OF FLARES -

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Abstract

Recent discoveries on coronal dynamics and flares with the soft X-ray telescope aboard *Yohkoh* are discussed with emphasis on evidence of magnetic reconnection. It is emphasized that *LDE (long duration events) flares*, *large scale arcade formation*, and *(simple loop) impulsive flares* show many common features, such as hot plasma ejection. 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 kêy 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.

1 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 (Ogawara *et al.* 1991, 1992). *Yohkoh* carries 4 instruments, Hard X-ray Telescope (HXT) (Kosugi *et al.* 1991), Soft X-ray Telescope (SXT) (Tsuneta *et al.* 1991), Bragg Crystal Spectrometer (BCS) (Culhane *et al.* 1991), and Wide Band Spectrometer (WBS) (Yoshimori *et al.* 1991), and has observed already more than a few 100 flares, and 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 Acton *et al.* 1992, Uchida 1993, Tsuneta and Lemen 1993, Shibata 1994, Hudson 1994), suggesting that the solar corona is full of *magnetic reconnection.*

Here, we would like to summarize recent discoveries by *Yohkoh*/SXT (with some HXT results also), which show various evidences of magnetic reconnection associated with hot plasma ejection in flares.

2 LDE Flares

One of the biggest discoveries by *Yohkoh*/SXT is the discovery of cusp-shaped loop structures in LDE (Long Duration Events) flares. Fig. 1a shows one beautiful example of this kind of flare, which occurred on Feb. 21, 1992, at the west limb (Tsuneta *et al.* 1992a). 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 (1964), Sturrock (1966), Hirayama (1974), and Kopp and Pneuman (1976). This kind of model is hearafter called *CSHKP model* (Sturrock 1992). Modern version of this model has been developed by Forbes and Priest (1983) and others.

Tsuneta *et al.* (1992a) further found the following characters: (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 this class of flare model, because the low temperature at the inner region can be explained by the radiative cooling (Forbes and Malherbe 1991), and the high pressure at the same region may be explained by the slow shock (see also Ugai 1987).

More recently, from close examination of the SXT movie of this flare (Hudson 1994), 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 show that there seem to be 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.

3 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 (Tsuneta 1993, Tsuneta *et al.* 1992b, McAllister *et al.* 1992, Watanabe *et al.* 1992, Hanaoka *et al.* 1994). These *large scale arcade formation* usually occur in association with disappearance of a dark filament. Tsuneta *et al.* (1992b) 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 maxium. Similar events occurred on Apr. 14, 1994, which was luckily reported by KSC *toban* 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.* (1993). 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.

4 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 ? (The term, *compact flares* or *confined flares* are often used to describe this class of loop flares, though these do not necessary correspond to exactly the same phenomena.) This led some theoreticians to consider the loop flare models which assume energy release occurring inside the loop (Spicer 1977, Uchida and Shibata 1988). 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.* (1994) 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 1b shows one typical example of such impulsive limb flare showing HXR loop top source. We can see in this figure 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 footpoint HXR sources, the time history of HXR intensity of loop top source is similar to those of footpoint sources (Masuda 1994). 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.) 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 ejection is expected to occur associated with these impulsive flares, as suggested by the CSHKP model. Shibata *et al.* (1995a,b) searched for such plasmoid or filament (loop) ejections in 8 impulsive limb flares which are selected in an unbiased manner by Masuda (1994), and found that *all these flares were associated with X-ray plasma ejections* (see Figure 2). The following characteristics are found (Shibata *et al.* 1995a,b): (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* 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 neary simultaneous 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.

5 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 (1994). 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 $V_A \simeq 3000(B/100\mathrm{G})(n_e/10^{10}\mathrm{cm}^{-3})^{-1/2}$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 $(B/100\mathrm{G})^2(n_e/10^{10}\mathrm{cm}^{-3})^{-1}$, 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 (Masuda 1994). We would expect similar physical process for the upward directed 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 (Masuda 1994), assuming the lower cutoff energy as 20 keV.

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 and in LDE flares. The bright knots at the tops of SXR loops also seem to be explained by this model, though more detaild MHD numerical simulations are necessary for modeling the bright knots.

6 Transient Brightenings (Microflares) and X-ray Jets

As mentioned in the Introduction, *Yohkoh*/SXT found that the corona is full of *transient brightenings* (Shimizu *et al.* 1992), and *X-ray jets* (Shibata *et al.* 1992b), both of which are new discoveries by *Yohkoh.* Shimizu *et al.* (1992, 1994) 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 (Lin *et al.* 1984). Using BCS data, Watanabe (1994) 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* (Gold and Hoyle 1960, Tajima *et al.* 1987, Sakai and Koide 1992), though clear evidence of interaction between two loops has not yet been found until now. It is possible that the magnetic reconnection similar to that occurring in larger flares produces two neighboring loops as a result of reconnection, which can be seen as "multiple loop brightenings". Although the observational evidence of reconnection in ARTBs are not enough at present, Shimizu *et al.* (1992) 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 (Hudson 1991), it is likely that the same physical mechanism causes ARTBs as in larger flares. This is also consistent with the finding by Watanabe (1994) that temperature of microflares is not so different from those of larger flares.

In contrast to ARTBs, there are many observational evidences of reconnection for *X-ray jets*. X-ray jets are defined as transitory X-ray enhancements with an apparent collimated motion (Shibata *et al.* 1992b, 1994a) (Fig. 5), 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.* (1994) compiled 125 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.* (1992b, 1993, 1994a,b,c) 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.* (1993) 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 (see Fig. 7); (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 (1994a,b). They performed two dimensional MHD numerical simulation of reconnection between emeriging flux and coronal field (Shibata *et al.* 1992a), extending the pioneering work by Heyvaerts *et al.* (1977). Shimojo *et al.* (1994) found also that many smaller jets ejected from XBPs show a converging shape or an upside down Y shape, and that the brightest parts of the small flare associated with jets are not just at the footpoint of jets. These features are very similar to those found for larger jets, *anemone-jet*, and hence could be an indirect observational evidence of magnetic reconnection even if the footpoints of these jets are not spatially resolved well.

7 Toward a Grand Unified Model of "Flares"

Recent MHD numerical simulations of reconnection between emerging flux and coronal field (Shibata *et al.* 1992a, Yokoyama and Shibata 1994a,b) have shown that magnetic islands (plasmoids) are formed and ejected out of current sheet. This plasmoid ejection is somewhat similar to plasma ejection seen in larger flares. In this sense, physical processes occurring 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 (Yokoyama and Shibata 1994b). 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 (see Table II). 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 (1994b), the fast reconnection can delay depending on the local plasma condition (such as the presence of perpendicular field penetrating the current sheet or 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 [Tsuneta *et al.* 1992a]). 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.

8 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 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} erg, 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 (Petschek 1964).

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.

REFERENCES

Acton, L., *et al.* 1992, *Science*, **258**, 618.

Carmichael, H., 1964, in *Proc. of AAS-NASA Symp. on the Physics of Solar Flares,* W. N. Hess (ed.), NASA-SP 50, p. 451.

Culhane, L. *et al.* 1991, *Solar Phys.*, **136**, 89.

Forbes, T. G. and Priest, E. R. 1983, *Solar Phys.*, **84**, 169.

Forbes, T. G., and J. M. Malherbe, 1991, *Solar Phys.*, **135**, 361.

Gold, T. and Hoyle, F., 1960, *Mon. Not. R. Astr. Soc*, **120**, 89.

Hanaoka, Y. *et al.*, 1994, *PASJ*, **46**, 205.

Heyvaerts, J., Priest, E. R., and Rust, D. M., 1977, *Ap. J.*, **216**, 123.

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

Hirayama, T., 1974, *Solar Phys.*, **34**, 323.

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

Hudson, H. S., 1994, in *Proc. of Kofu Sympo.*, S. Enome and T. Hirayama (eds.), Nobeyama Radio Observatory Report No. 360, pp. 11.

Hudson, H. S. and Lemen, J., 1994, private communication.

Kosugi, T. *et al.*, 1991, *Solar Phys.*, **136**, 17.

Kopp, R. A., and G. W. Pneuman, 1976, *Solar Phys.*, **50**, 85.

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

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

Masuda, S. *et al.*, 1994, *Nature*, **371**, 495.

McAllister, A. *et al.*, 1992, *PASJ*, **44**, L205.

Ogawara, Y., *et al.* 1991, *Solar Phys.*, **136**, 1.

Ogawara, Y. *et al.* 1992, *Publ. Astr. Soc. Japan Letter*, **44**, L41.

Petscheck, H. E., 1964, in *Physics of Solar Flares, AAS-NASA Symposium*, NASA SP-50 (ed. W. N. Hess), p. 425.

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

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

Shimizu, T. *et al.*, 1994, *Ap. J.*, **422**, 906.

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

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

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

Shibata, K. *et al.* 1993, *X-ray Solar Physics from Yohkoh*, Y. Uchida *et al.* (eds), Universal Academy Pub., p. 29.

Shibata, K., *et al.* 1994a, *Ap. J. Lett.*, **431**, L51.

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

Shibata, K., 1994c, in *Proc. "The Sun as a Variable Star"*, J. M. Pap *et al.* (eds.), Cambridge Univ. Press, p. 89.

Shibata, K. *et al.*, 1995a, *Proc. COSPAR meeting*, in press.

Shibata, K. *et al.*, 1995b, to be submitted to *Nature*.

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

Tajima, T. *et al.*, 1987, *Ap. J.*, **321**, 1031.

Tsuneta, S. *et al.*, 1991, *Solar Phys.*, **136**, 37.

Tsuneta, S. *et al.*, 1992a, *PASJ*, **44**, L63.

Tsuneta, S. *et al.*, 1992b, *PASJ*, **44**, L211.

Tsuneta, S., 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.

Tsuneta, S. and Lemen, J. R., 1993, *Proc. "Physics of Solar and Stellar Coronae"*, J. F. Linsky and S. Serio (eds.), Kluwer Academic Pub., p. 113.

Uchida, Y. 1993, *Proc. "Physics of Solar and Stellar Coronae"*, J. F. Linsky and S. Serio (eds.), Kluwer Academic Pub., p. 97.

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

Ugai, M., 1987, *Geophys. Res. Lett.*, **14**, 103.

Watanabe, Ta. *et al.*, 1992, *PASJ*, **44**, L199.

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

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

Yokoyama, T. and Shibata, K., 1994b, *Ap. J. Lett.*, Dec. issue, in press.

Yoshimori, M. *et al.* 1991, *Solar Phys.*, **136**, 69.

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}	X-ray jet/Hα surge
impulsive flares	1 – 10	60 –3×10^3	10^{29} – 10^{32}	X-ray plasma/Hα filament eruption
LDE flares	10 – 40	3×10^3 – 10^5	10^{30} – 10^{32}	X-ray plasma/Hα filament eruption
large scale arcade formation	30 – 100	10^4 – 2×10^5	10^{29} – 10^{32}	X-ray plasma/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

Table II Grand Unified Scheme of Solar "Flares"

physical process	large flares (LDE, impulsive)	small flares (sub-, microflares)
global MHD instability (driving force)	ex. CME	ex. emerging flux (magnetic buoyancy)
⇓		
current sheet formation	X- or Y- type configuration	interaction with overlying or ambient field
⇓		
(anomalous resistivity + nonlinear tearing)		
⇓		
plasmoid ejection	Hα filament/ X-ray plasma ejection	Hα surge and/or X-ray jets
⇓		
very fast reconnection ($t \sim 10t_A$)	impulsive or rise phase	(impulsive or) rise phase
⇓		
(particle acceleration)	(HXR/SXR double footpoints, HXR loop top)	(SXR double footpoints)
⇓		
fast reconnection ($t \sim 100t_A$)	gradual or decay phase (SXR loop/arcade, Hα loop)	gradual or decay phase (SXR loop)

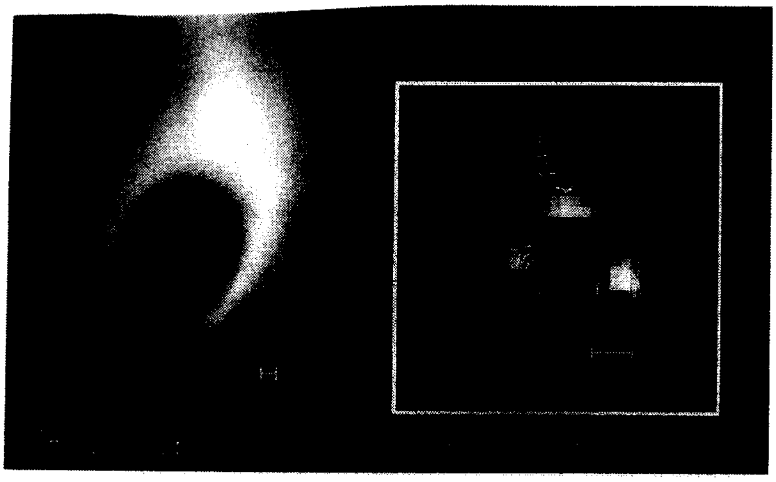

Figure 1: (a) LDE Flare on Feb. 21, 1992 observed with SXT (Tsuneta et al. 1992). (B) Impulisve flare on Jan. 13, 1992 (at 17:26:52 – 17:27:40 UT) which shows a loop top hard X-ray source above soft X-ray loop (Masuda et al. 1994). Contours of hard X-ray (33 – 53 KeV) intensity distribution are overlaid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

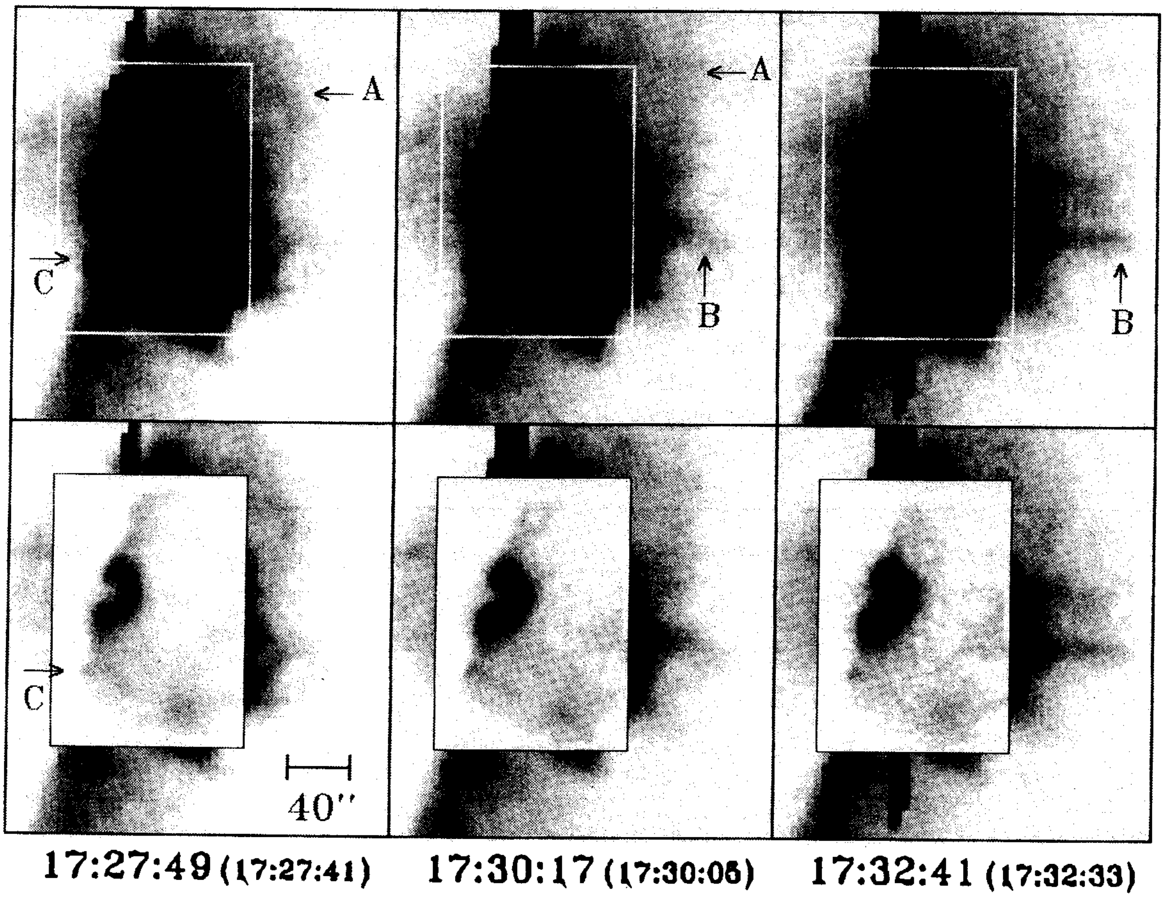

Figure 2: X-ray plasmoid/filament eruption associated with impulsive flare on January 13 1992 which is shown in Fig. 1 (Shibata et al. 1994). The upper three images display long exposure time images, and the bottom displays short exposure time images composited on the long exposure time images. Arrows 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.

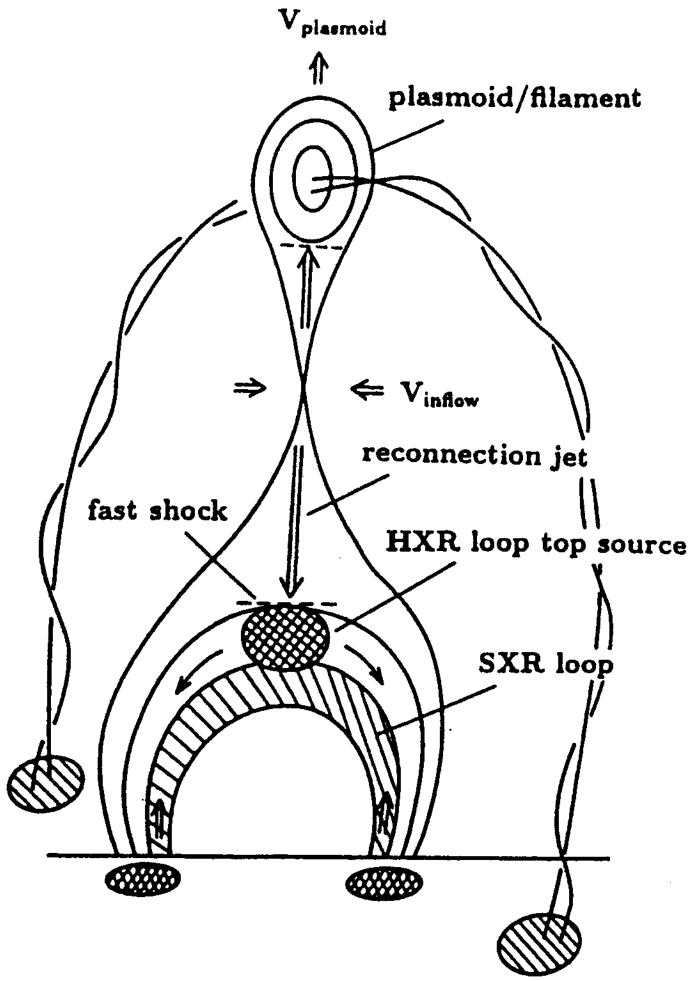

Figure 3: A unified model of flares: plasmoid-driven reconnection model (Shibata et al. 1994).

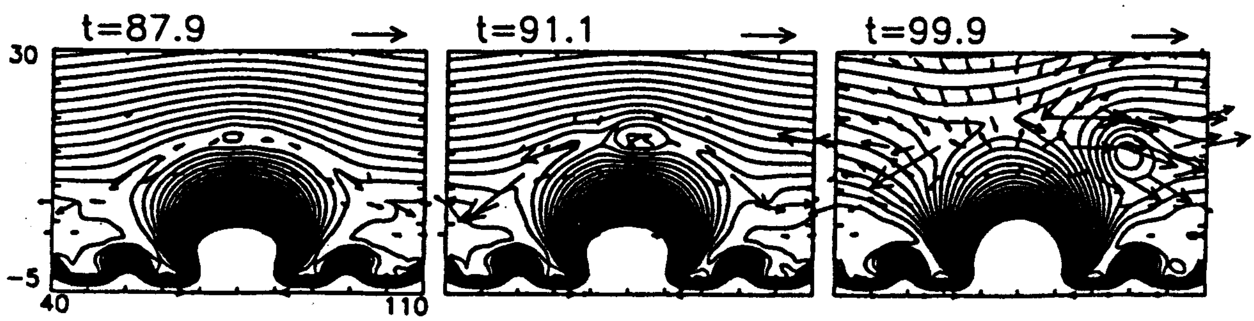

Figure 4: Numerical simulation of reconnection between emerging flux and coronal field (Yokoyama and Shibata 1994). Note that magnetic islands (plasmoids) are formed and ejected even in this small scale reconnection.

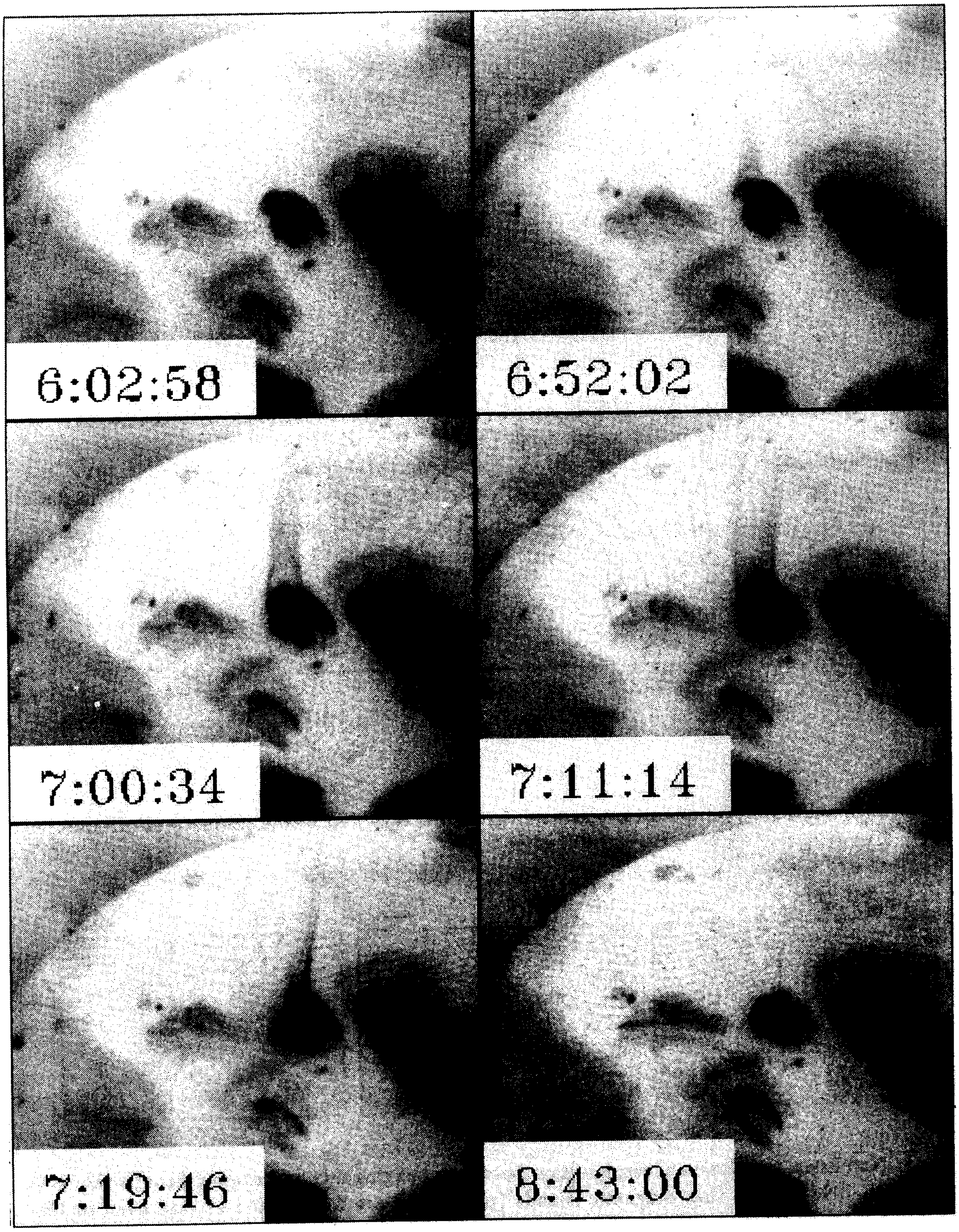

Figure 5: A typical example of X-ray jet (negative image) that occurred on 1992 Jan. 11 (Shibata *et al.* 1994a). The size of each frame is 1200″ x 1040″. The maximum length of the jet is greater than 3 x 10^5 km, and the apparent velocity is within the range of 90 – 240 km/s. This is one of the largest X-ray jets observed so far.