SESSION 5

FIELDS IN THE CHROMOSPHERE AND CORONA

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SOLAR FLARES AS AN ONGOING MAGNETIC RECONNECTION PROCESS

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ABSTRACT The soft X-ray images taken by the *Yohkoh* Soft X-ray Telescope (SXT) provide a powerful new tool to solve the mechanism of solar flares. In particular, a limb flare that occurred on 1991, December 2 gives us convincing evidence that magnetic reconnection of a neutral sheet formed at the loop top participates in the flare energy release. The neutral sheet appears to be associated with a destabilized rising loop system (filament) sheared with respect to the flaring loop. Similar formations of X-ray arcades are seen in the quiet Sun associated with filament eruptions on much larger spatial dimension and with a much smaller energy scale.

INTRODUCTION

The *Yohkoh* Soft X-ray Telescope (SXT) allows us for the first time to perform *continuous* soft X-ray observations from before the onset of flares, through their development, and during the recovery of the corona after the end of the flare with high time (2 s) and spatial (2.5 arcsec) resolutions (Tsuneta *et al.* 1991, see Ogawara *et al.* 1991 for details on the *Yohkoh* spacecraft). *Yohkoh* observed more than 250 flares in the first year of operation, and most of the flare observations have good coverage of the pre-flare active regions. We now have ample data to constrain the various flare models, and to address fundamental questions such as the magnetic configuration and the triggering mechanism of solar flares. Indeed, *Yohkoh* SXT data indicates that magnetic reconnection is involved in the flare energy release process for a few examples.

1991 DECEMBER 2 FLARE

In this paper, I will concentrate on a flare that occurred on the east limb, because this flare is suitable for studies of its vertical structure and the surrounding magnetic structure. *Yohkoh* observations of a similar type of flare are described in Tsuneta *et al.* (1992a). Figure 1 shows the time profiles of the flare that occurred on 1991, December 2 from 5 keV to 100 keV. The flare has a very gradual time profile with some fluctuating components even in the decay phase. The X-ray spectrum is very soft, and impulsive spikes can be seen only during 2 minutes of the peak phase.

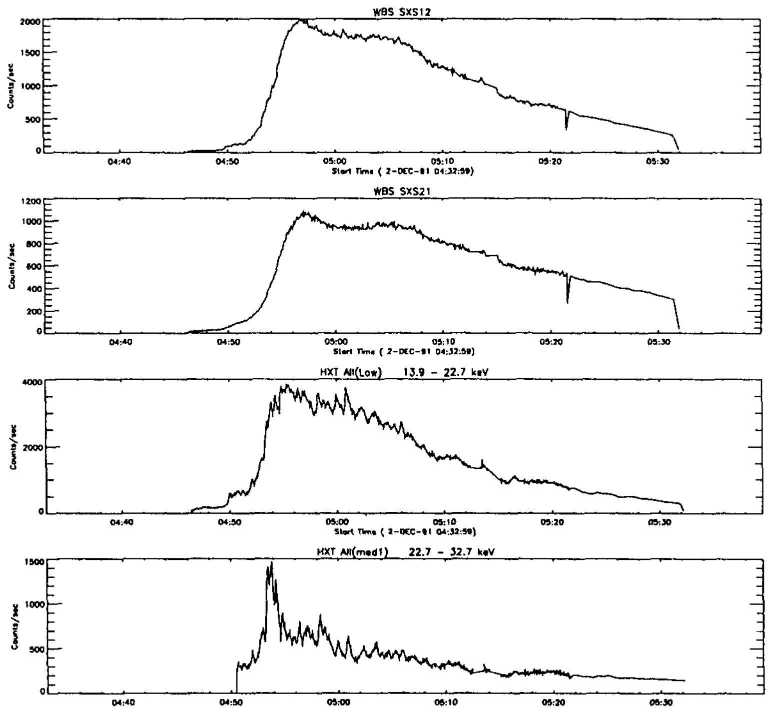

Fig. 1. X-ray time profile of 1991 December 2 flare from 3 to 33 keV. Energy bands are (from above) 3-15 keV, 14-23 keV, 23-33 keV. The first two time profiles are obtained from the *Yohkoh* Soft X-ray Spectrometer, and the others are from the Hard X-ray Telescope.

X-ray morphology

Figure 2 shows the pre-flare images from 2 hours to 3 minutes before the start of the hard X-ray flare. An overlying loop is seen about one hour before the flare (4:35 - 4:46 UT) above the compact bright loop that will flare later. The height of the overlying loop is about 50 arcsec. The compact loop increases its soft X-ray brightness by a factor of 10 between 20 min and 3 min before the start of the hard X-ray flare (4:30 - 4:48 UT). This can be seen by the rapid decrease of the AEC (Automatic Exposure Control)-adjusted exposure time in Figure 2. (The bright loop is seen just on the limb near the center of the field of view.) A small rising loop with a speed of 50-100 km/s appears around 10 minutes prior to the flare (4:44 UT). This expanding loop is located under the steady overlying loop and above the compact bright loop.

The loop that started to expand in the pre-flare phase continues to rise in the impulsive phase of the flare. Figure 3 shows the X-ray images during the flare from the hard X-ray rise phase through the long gradual decay phase over 30 minutes. The flare loop is formed beneath the expanding loop (see 4:52 - 4:56 UT images of Figure 3). The flare loop is about 20 arcsec high in the initial

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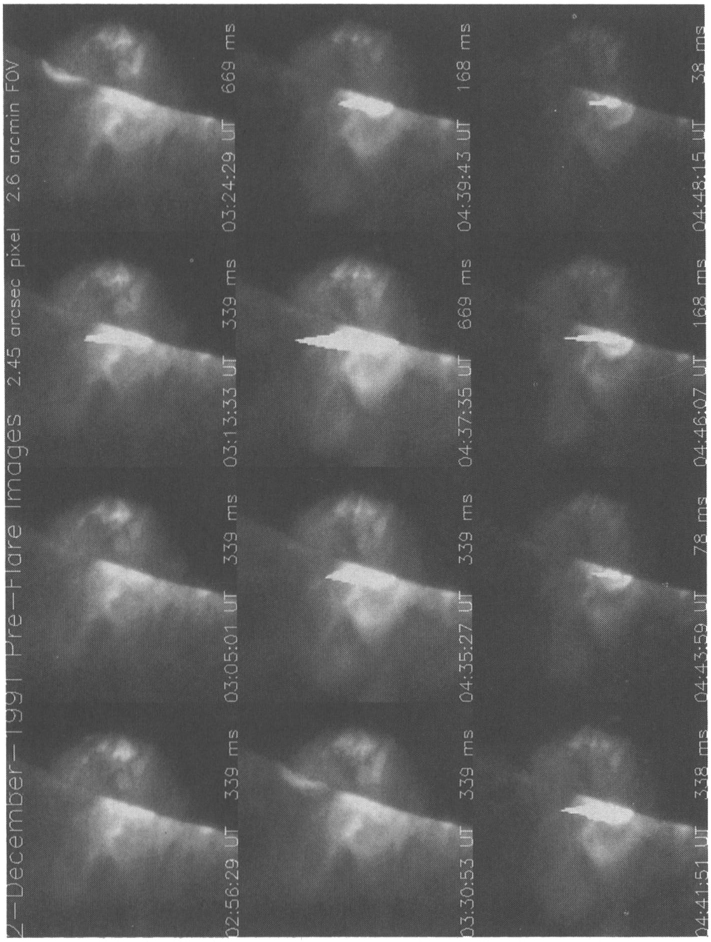

Fig. 2. Pre-flare X-ray images of 1991 December 2 flare. The field of view is 5.2 arcmin, and the pixel size is 2.5 arcsec. The analysis filter is thin aluminum (Tsuneta *et al.* 1991). The observation starts about 2 hours before the onset of the flare in hard X-rays. North is up, and East is left. The bright core is saturated in some of the images, and has a streak along North-South direction. Note the rapid change of the exposure times.

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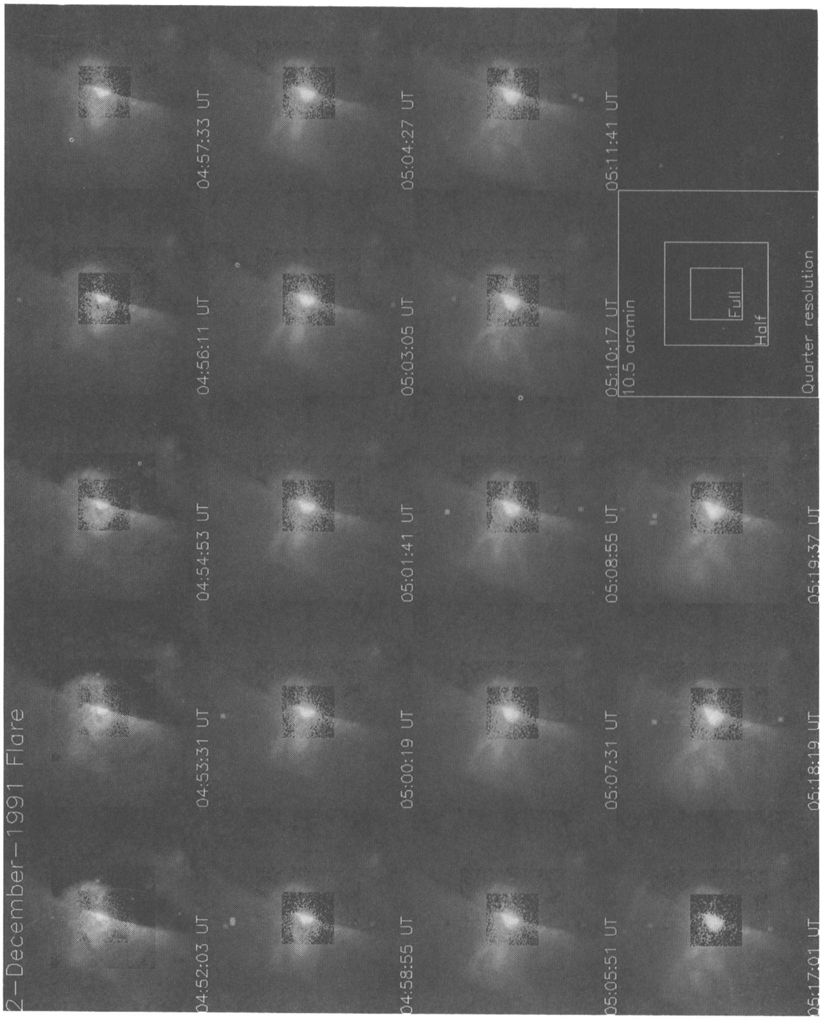

Fig. 3. Soft X-ray images from the start of the hard X-ray flare through the long decay phase. Each image consists of 5 different exposures: three coarse (quarter) resolution images, a medium (half) resolution and a fine (full) resolution image for wider field of view and higher dynamic range. The field of view is 10.5 arcmin, and the central area where the flare loop is located has the highest spatial resolution as indicated in the figure. Note the rising motion of the plasmoid around the peak phase of the hard X-rays after 4:57 UT.

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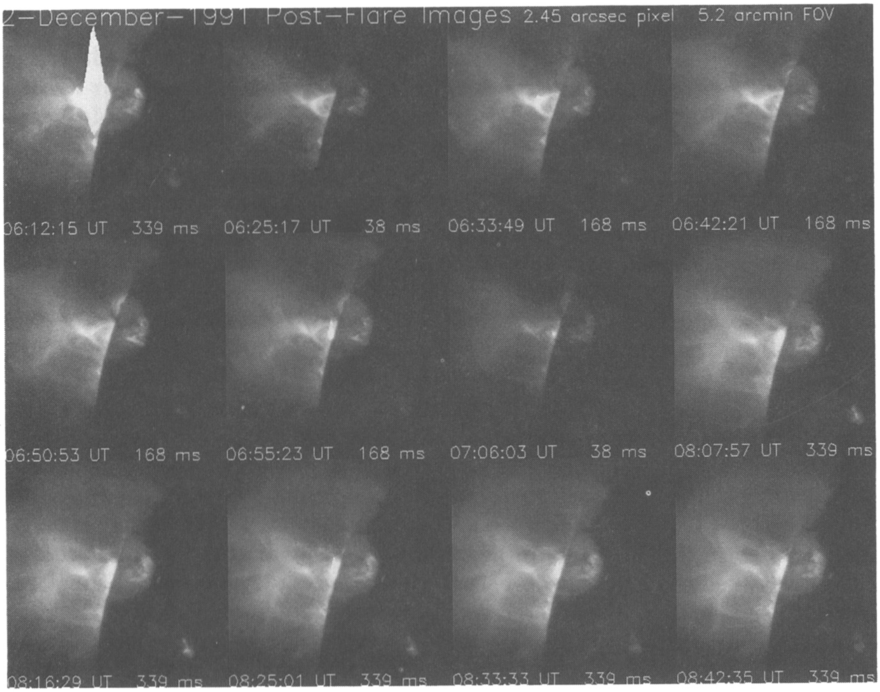

Fig. 4. Post-flare X-ray images of 1991 December 2 flare from 80 min through 4 hours after the start of the hard X-ray flare. The field of view is 5.2 arcmin, and the pixel size is 2.5 arcsec.

phase, and is much brighter than the surrounding structure. (Note that the display table used in Figure 3 is highly non-linear to reveal the dark features, and that the flare loop is a factor of 100-1000 brighter than the surrounding X-ray structure. Note also that the exposure time is optimized for each image in Figure 3, and differs about a factor of 10 during the sequence.)

The hard X-ray source observed by the *Yohkoh* Hard X-ray Telescope generally coincides in position and shape with the soft X-ray flare loop. The overlying loop continues to expand throughout the rising phase of hard X-rays.

Surprisingly, this rising loop further evolves into a large-scale circular-shaped blob or plasmoid a few arcmin above the flare loop in the peak and decay phases of hard X-rays (5:00 - 5:10 UT). Figure 4 shows the post-flare images of the active region one to three hours after the hard X-ray flare. A bright vertical structure is located just on top of the rising post-flare X-ray loop. This structure rises with the loop. The vertical structure appears to be connected to another region within the active region.

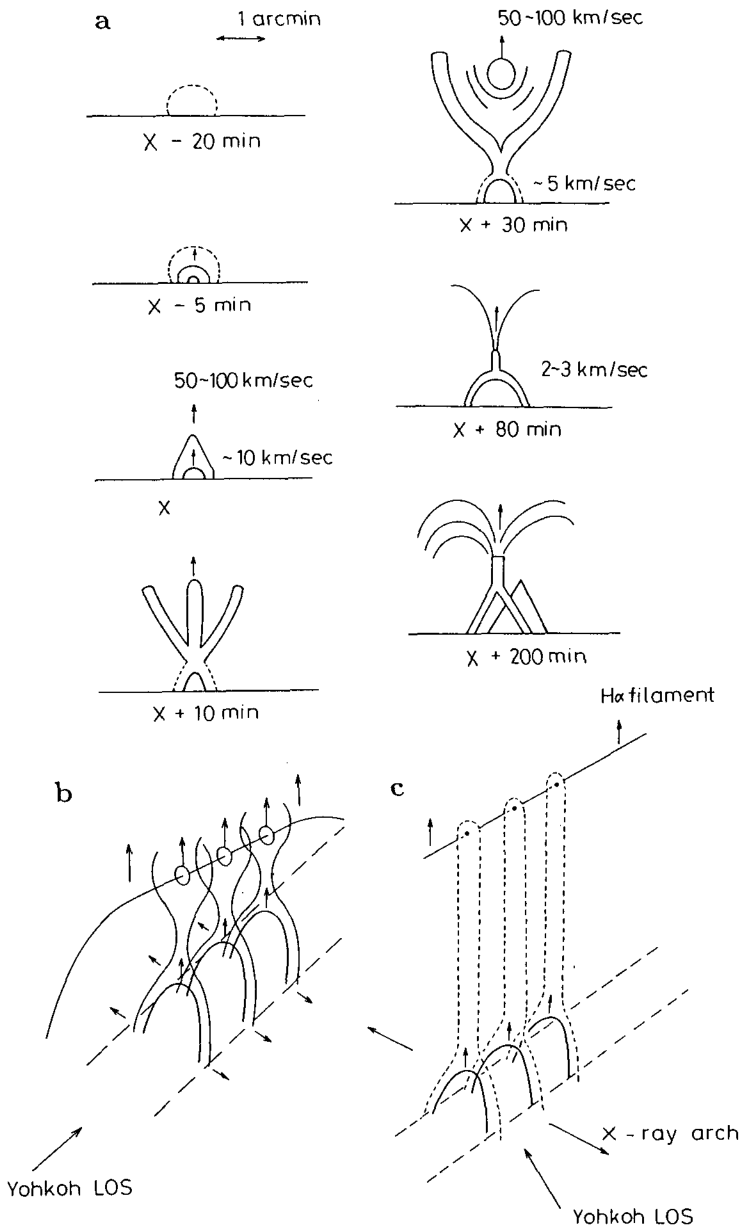

Fig. 5. (a) Evolution of 1991 December 2 flare. X is the starting time of the hard X-ray flare (4:50 UT). (b) Magnetic structure of 1991 December 2 flare. (c) Filament eruption and the formation of X-ray arcade on 1992, July 31.

Evolution of the flare

The evolution of the X-ray morphology is schematically shown in Figure 5(a). A steady overlying loop is seen about one hour prior to the flare. About 5 minutes before the flare, a rapidly expanding loop appears, followed by the start of the hard X-ray flare. This loop evolves into the rising plasmoid in the hard X-ray decay phase. The rising blob appears to be a side view of the overlying loop system sheared with respect to the flare loop as shown in Figure 5(b).

This rising loop appears to stretch the closed field lines, and to create the neutral sheet beneath it (Hirayama 1974, Pneuman 1981). The neutral sheet is about 20 arcsec long, comparable in size to the flare loop. The rising speed of the overlying loop is about 50-100 km/s and is rather steady until the end of the spacecraft flare mode observation (5:20 UT), whereas the rise speed of the flare loop gradually decreases from 10 to 2 km/s in the decay phase (Kato, 1992). The speed of the rising H-alpha loop is about 5 km/s, consistent with the rise speed in soft X-rays (Kitai, 1992).

The vertical structure seen in the post flare X-ray loop appears to be a neutral sheet formed by the rising filament system during the initial phase of the flare. The neutral sheet is still very bright, and continues to be the energy source during the post-flare phase. In the very late phase, the post flare loop appears more like a triangular-shaped loop (around 8:30 UT) rather than the potential-shaped loop seen in earlier times (around 6:30 UT), possibly because the loops just reconnected are rapidly cooled down and become invisible due to the smaller energy supplied by magnetic reconnection compared with the earlier phase. This triangular-shaped structure indicates the location of the separatrix of the reconnected magnetic fields.

Solar flares as an ongoing magnetic reconnection

We have several pieces of evidence that magnetic reconnection of an X-type neutral sheet formed at the loop top participates in the flare energy release: (1) Hard and soft X-ray emissions from the flare loop increase with the rising separate loop overlying the flare loop. (2) An X-shaped structure is formed under the blob with rising speed of 50-100 km/s (Figure 3). The plasmoid would be the cross-sectional view of the field lines sheared with respect to the flare loop. (3) The flare loop increases its height and footpoint separation at 5-10 km/s. (4) The bright vertical neutral sheet on top of the flare loop is clearly seen in the long decay phase of soft X-rays (Figure 4). (5) In the very late phase, the post flare X-ray loop has a triangular structure. The triangular structure indicates the location of the separatrix of the reconnected magnetic fields. (6) The outer X-ray arches generally have higher temperatures in the flare loop, suggesting that the flare loop results from the reconnected magnetic fields. (This is more clearly seen in the *Yohkoh* observation of 1992 February 21 flare (Tsuneta *et al.* 1992a). Tsuneta (1985, 1987) also concluded that the current interruption model is not consistent with the *Hinotori* hard X-ray observation. The accumulation of observational facts supporting the magnetic reconnection model is evident.

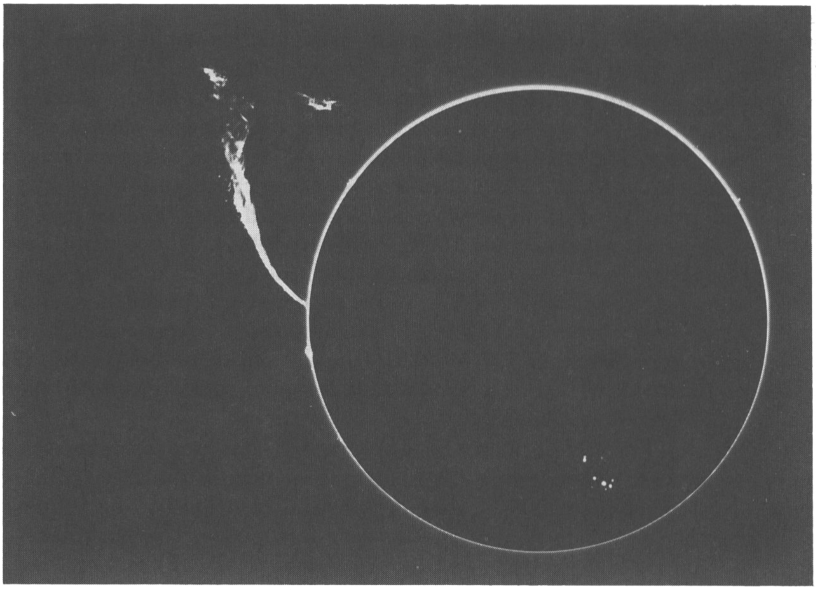

Fig. 6. A spectacular eruption of a filament seen in Hα on 1992 July 31 (1:14 UT). Courtesy of the Norikura Solar Observatory, National Astronomical Observatory, Japan (Miyazaki 1992).

GLOBAL RESTRUCTURING OF QUIET SUN MAGNETIC FIELDS

Formation of X-ray arch and filament eruption

Figure 6 is the spectacular eruption of an Hα filament observed by the Norikura Solar Observatory of NAO at 1:14 UT on July 31 (Miyazaki 1992). The rise speed of the filament is about 30 km/s. Figure 7 shows X-ray images of the same region. A thin long structure forms in the 0:38 UT frame. The structure is as long as 5 arcmin or more. This is followed by the formation of an arcade over a period of 7 hours. The formation starts when the Hα filament reaches about 600 Mm above the photosphere (1:32 - 3:17 UT). The height of the loop is about 1 arcmin, whereas the height of the erupting prominence reaches 10 arcmin above the photosphere. The height and the footpoint separation of the X-ray arch increase with time from 30 arcsec to 1-2 arcmin.

Since the formation of the X-ray arch starts after the filament eruption, it is reasonable to conclude that there is a causal relationship between the eruption and the formation of the arch: The X-ray arch would be formed by the filament eruption through the reconnection process (Figure 5(c)). The magnetic configuration is very similar to that of the 1991 December 2 flare (Figure 5(b)). In this case, however, the reconnection starts when the magnetic field is stretched about 10 times as high as the X-ray loop, whereas the flare starts when the height of the expanding loop is only 2 times as high as the flare loop. Magnetic reconnection may not be started in this case until the magnetic field in the neutral sheet reaches a certain state or a threshold value.

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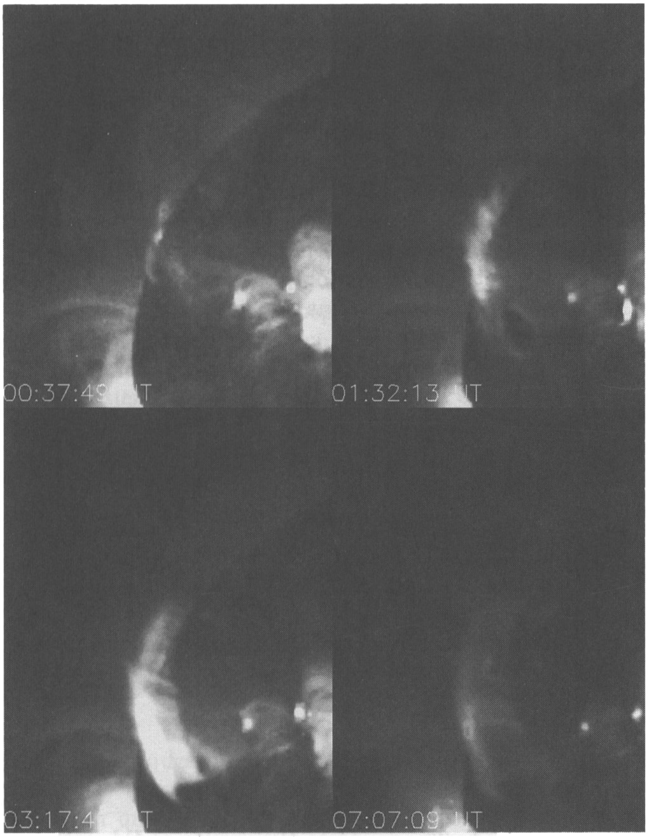

Fig. 7. Formation of the X-ray loop associated with the filament eruption on 1992 July 31. The pixel size is 9.8 arcsec, and the analysis filter used is thin aluminum.

Global restructuring of the coronal magnetic fields

Another clear example of the formation of arches can be found in Tsuneta *et al.* (1992b). In X-ray movies, we see many examples of much more complex restructuring of the coronal magnetic fields, some of which are associated with filament eruptions. We suspect that magnetic reconnection is also responsible for these complex phenomena.

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Present observations demonstrate that a process very similar to that of flares is also responsible for the restructuring of global magnetic fields on a larger spatial dimension and with a much smaller energy scale. The only difference is the difference of the magnetic field strength: The magnetic field strength of the large-scale restructuring is much smaller than that of flares, because these events occur in the quiet corona with a larger scale size. Nevertheless, magnetic reconnection appears to play a fundamental role both for long duration flares and non-explosive restructuring of the quiet sun.

Another important question is the driving force of the filament eruption. The open field structure would have a magnetic energy higher than the closed potential loop structure with the same photospheric boundary condition. The rising filament apparently needs to overcome this potential difference. The energy released in the magnetic reconnection consumes this potential difference. The eruption and the reconnection are thus two key mechanisms for global coronal restructuring and for solar flares.

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