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STUDY OF FLARE-ASSOCIATED X-RAY PLASMA EJECTIONS : II. MORPHOLOGICAL CLASSIFICATION

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ABSTRACT

X-ray plasma ejections often occurred around the impulsive phases of solar flares and have been well observed by the SXT aboard Yohkoh. Though the X-ray plasma ejections show various morphological shapes, there has been no attempt at classifying the morphological groups for a large sample of the X-ray plasma ejections. In this study, we have classified 137 X-ray plasma ejections according to their shape for the first time. Our classification criteria are as follows: (1) a loop type shows ejecting plasma with the shape of loops, (2) a spray type has a continuous stream of plasma without showing any typical shape, (3) a jet type shows collimated motions of plasma, (4) a confined ejection shows limited motions of plasma near a flaring site. As a result, we classified the flare-associated X-ray plasma ejections into five groups as follows: loop-type (60 events), spray-type (40 events), jet-type (11 events), confined ejection (18 events), and others (8 events). As an illustration, we presented time sequence images of several typical events to discuss their morphological characteristics, speed, CME association, and magnetic field configuration. We found that the jet-type events tend to have higher speeds and better association with CMEs than those of the loop-type events. It is also found that the CME association (11/11) of the jet-type events is much higher than that (5/18) of the confined ejections. These facts imply that the physical characteristics of the X-ray plasma ejections are closely associated with magnetic field configurations near the reconnection regions.

Key words : Sun: activity – Sun: corona – Sun : coronal mass ejections (CMEs) – Sun : flares – Sun : X-rays, gamma rays

I. INTRODUCTION

Many flare-associated X-ray plasma ejections have been observed by the Soft X-ray Telescope (SXT: Tsuneta et al. 1991) aboard Yohkoh since 1991 (Shibata et al. 1995; Ohyama & Shibata 1996). They usually occurred around the impulsive phase of flare and especially, simultaneously with the peak time of hard X-ray flare (Kim et al. 2004, Paper I). They have often been found to be associated with long duration event (LDE) flares (Svestka et al. 1995) as well as compact impulsive flares (Tsuneta 1997; Nitta 1996; Ohyama et al. 1997).

Morphologically, they showed various shapes such as expanding loops, detached plasmoids, and so on. Since the first report on the flare-associated X-ray plasma ejection by Shibata et al. (1995), only a few individual plasma ejections having plasmoid-like or loop-like shape were analyzed and discussed in detail. Ohyama & Shibata (1997) described an X-ray plasma ejection associated with the 1993 November 11 C9.7 flare. Since the plasma ejection occurred on or behind the east solar limb and observed before the onset of impulsive phase of the flare, the morphological evolutions and physical conditions were well investigated without being affected by the bright flare loop. The shape of the ejecta was a loop before the start of ejection and then it looked like detached plasmoids. The ejected material showed a slow rising motion in the preplare phase and sudden acceleration coincident with the eruptive phase of the flare. Ohyama & Shibata (1998) also examined an X-ray plasma ejection having the morphological feature of plasmoid and expanding loop. This plasma ejection was associated with an impulsive flare on 1992 October 5. In this case, the ejected material started to rise before the main peak of the hard X-ray emission, although its initial altitude was not known because it was hidden by the bright flare loop in the early phase. The ejected material was accelerated during the impulsive phase with the speed from 250 to 500 km s^{-1}.

In our previous study (Paper I), we identified 137 X-ray plasma ejections from 279 limb flares for two years (1999 April - 2001 March) in order to examine their association with coronal mass ejections (CMEs). As a result, we presented a comprehensive list of 137 X-ray plasma ejections. The speed of X-ray plasma ejections ranges from 10 to 1300 km s^{-1} and the mean speed is about 230 km s^{-1}. Most of X-ray plasma ejections have relatively slow speeds below 200 km s^{-1}. We also found that the X-ray plasma ejections are highly associated with the CMEs and the expanding features of X-ray

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plasma ejections do not seem to be coincident with the CME fronts.

This paper is the second paper in a series of papers studying X-ray plasma ejections. In this paper, we classify the morphological shape of 137 X-ray plasma ejections. The identified X-ray plasma ejections showed various morphological shapes. Since the morphology of X-ray plasma ejections would be affected by the magnetic topology of the flaring site, there may be many different physical characteristics among morphological groups. To our knowledge, this study is the first attempt at classifying the morphological types of X-ray plasma ejections using such a large sample of X-ray plasma ejection data.

The paper is organized as follows. The observations and analysis methods are summarized in Section II and the results are described in Section III. Finally, we summarize and discuss our results in Section IV.

II. OBSERVATIONS

The SXT, which is sensitive in the range 1-2 KeV, takes full frame images (FFIs) or partial frame images (PFIs) through various wavebands according to observing mode of the spacecraft. The SXT has two observing modes: flare mode and quiet mode. In quiet mode, i.e., when the Sun is quiet, whole-Sun images are taken together with up to four bright active regions which are monitored at a moderate telemetry rate. In flare mode, when a flare occurs, the observation is concentrated on the brightest region by taking PFIs with up to 0.5 s time resolution. In this case the interval between SXT images is determined by the number of PFIs in the observing region. For a single PFI the image cadence is 2 s at high telemetry rate. FFIs are taken using the full CCD frame with a temporal resolution from a few minutes to several hours. PFIs are taken using a selected part of the CCD frame with an image repetition time of 10-20 s for the observation of fast ejections like X-ray jets. PFIs have the size of 64 $\times$ 64 pixels with a field of view of $2.6' \times 2.6'$ and the pixel resolution of $2.46''$ (full-resolution images). In addition, PFIs have half-resolution (2 $\times$ 2 pixel summation) and quarter-resolution (4 $\times$ 4) images, whose fields of view are $5.2' \times 5.2'$ and $10.4' \times 10.4'$, respectively.

We consider 279 limb flares ($> 60°$) observed by all flare mode data from 1999 April to 2001 March. We inspected whether there exist X-ray plasma ejections associated with the flares or not. Our identification procedure is as follows. First, we made movie files from the processed images using the standard Yohkoh analysis routine (sxt_prep.pro) which includes the procedures to subtract the dark current and the stray light, and to register images. Second, we took a look at half and quarter resolution movies to identify the motions of hot plasma ejecta near the impulsive phase of the flares. Third, for the events without plasma ejections, we inspected full resolution movies. Some ejections (mostly confined ejections) do not show any eruptive motions in half and quarter resolution images but they show ejection features in full resolution images. From these inspections, we identified X-ray plasma ejections only when the motions of X-ray plasma are evident by visual inspection. For these events, the brightness contrast between ejecting plasma and background is found to be in the range from 50% for faint ejections to 600% for well-identified ejections. As a result, we identified 137 X-ray plasma ejections and their event times. Their detailed information is summarized in the Table 1 of Paper I.

III. MORPHOLOGICAL EVOLUTION OF INDIVIDUAL EVENTS

We divided 137 identified X-ray plasma ejections into 5 groups such as loop-type, spray-type, jet-type, confined ejection, and others. Our classification criteria are as follows: (1) a loop type shows ejecting plasma with the shape of loops, (2) a spray type has a continuous stream of plasma without showing any typical shape, (3) a jet type shows collimated motions of plasma, and (4) a confined ejection shows limited motions of plasma near a flaring site, which is usually seen in only the full-resolution flare mode movie. In this section, we present the typical examples for each group and describe their morphological evolution and other characteristics such as speed and magnetic configuration.

(a) Loop-Type

Figure 1 shows an example of the loop-type X-ray plasma ejection. This plasma ejection is associated with a M2.4 X-ray flare that occurred on 1999 July 25. This LDE (long duration event, over 1 hour) flare started at 13:08 UT and ended at 14:17 UT. The X-ray flux of the flare came to its peak value at 13:38 UT. The figure shows the temporal evolution of X-ray structures above the flare site. Above the well developed arcade structure, we can see the loop-like X-ray plasma ejection. Diffuse loops were continuously expanded outward until they went out of the SXT field of view. When the flare mode observation started, the X-ray expanding loops were already located at 1.2 solar radii, implying that the X-ray plasma started to rise before the start time of the soft X-ray flare. This argument is independently supported by the fact that there was a slow rising motion of X-ray plasmas in three FFIs long before the onset of the flare. We estimated ejecting speeds of the X-ray plasma ejection from FFIs in the preflare phase and PFIs after the flare onset. In the preflare phase, the X-ray structure has a speed at $\sim$20 km s^{-1}, while in the main phase, the speed increases up to over 300 km s^{-1}.

Out of 137 X-ray plasma ejections, 60 events are included in this type and 77% (46/60) of the loop-type X-ray plasma ejections are associated with CMEs. Their speeds range from 50 to 750 km s^{-1} with the mean speed of 255 km s^{-1}.

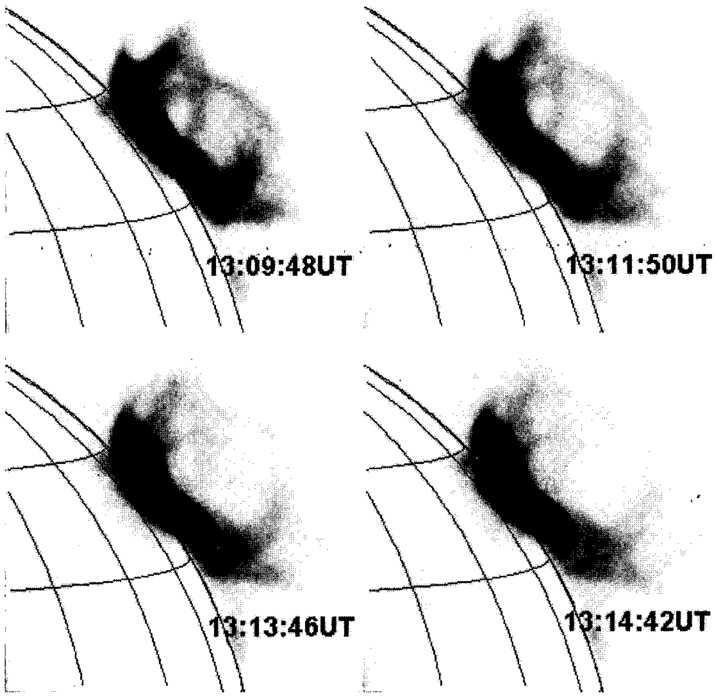

Fig. 1.— A loop-type X-ray plasma ejection occurred on 1999 July 25. It looks like continuous outward expansion of X-ray plasma loop itself.

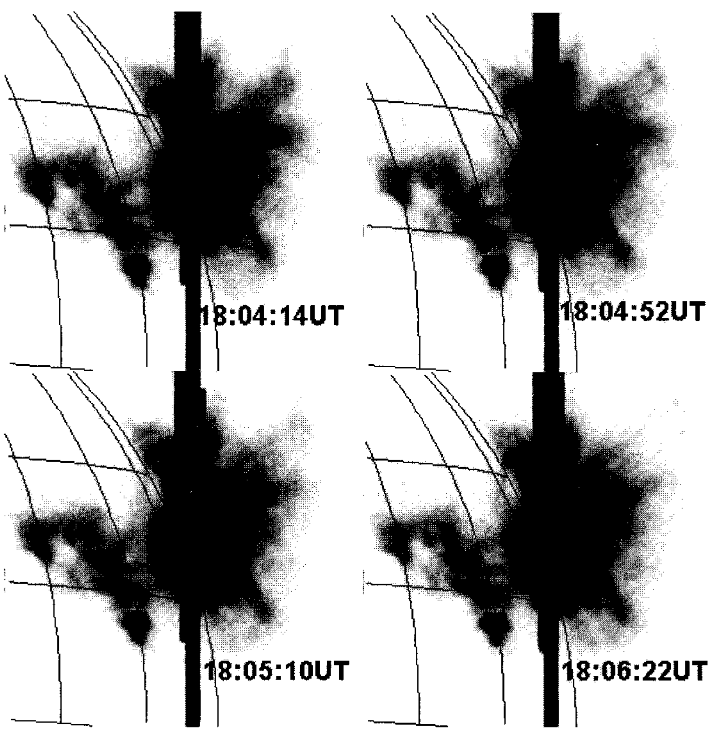

Fig. 2.— An example of spray-type X-ray plasma ejection that occurred on 1999 May 9.

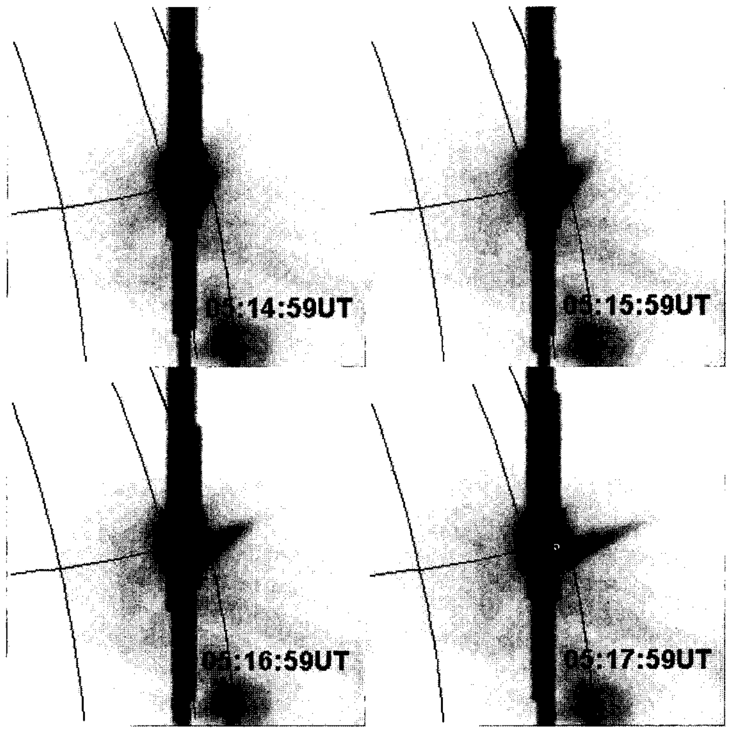

Fig. 3.— A jet-type X-ray plasma ejection associated with C3.7 limb flare occurred on 2000 October 26.

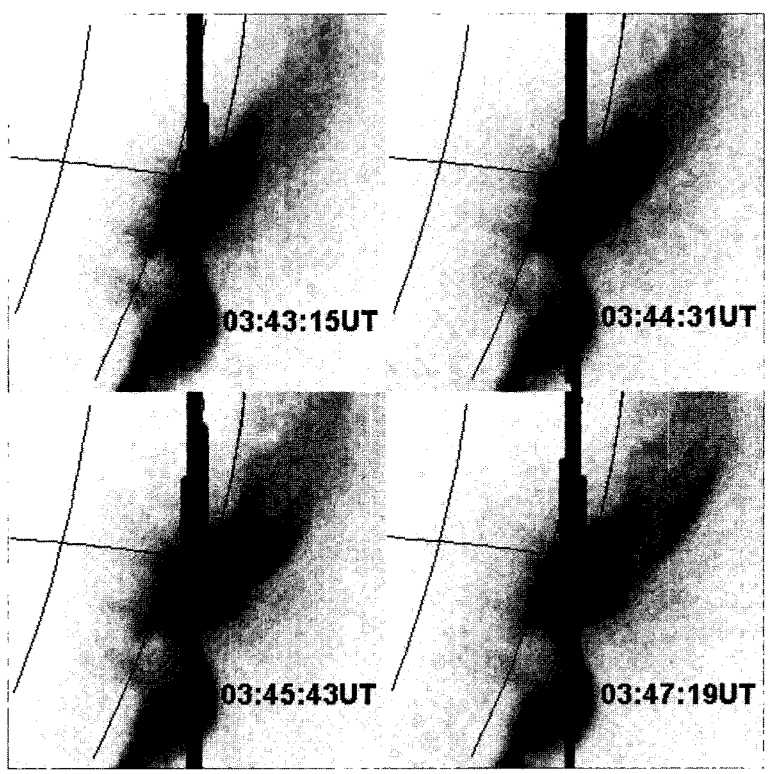

Fig. 4.— Another jet-type X-ray plasma ejection associated with a C3.9 limb flare that occurred on 1999 May 17.

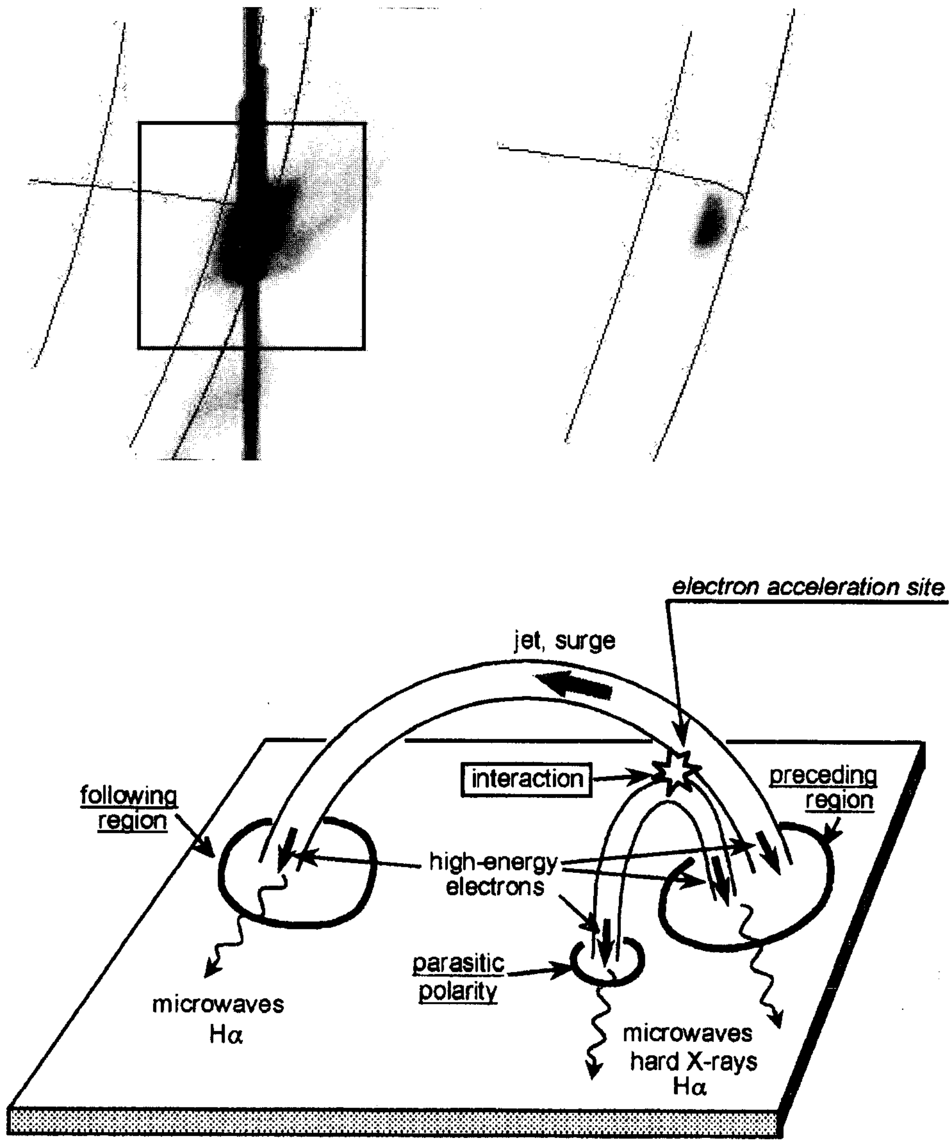

Fig. 5.— Half and full resolution images (upper panel) of the X-ray plasma ejection of the same event as Figure 4 and a related magnetic field configuration (lower panel). A central box of the upper left image corresponds to the field of view ($2.6' \times 2.6'$) of the upper right image. The magnetic field configuration (lower panel) based on interacting loops was originally suggested by Hanaoka (2000). The reconnection region of the two loops is the source of high energy electrons and thermal plasma flows, such as jets and surges.

Fig. 6.— An example of confined ejection.

(b) Spray-Type

Figure 2 shows an example of spray-type X-ray plasma ejections. This event was associated with a M7.6 LDE flare that occurred at the north-west limb. The flare started at 17:53 UT on 1999 May 9 and reached its peak flux at 18:07 UT. The flare mode observation of this flare started at 18:04 UT. This does not include the impulsive phase of flare. For this type of plasma ejections, we could not see any loop structures related to plasma motion. It just looked like a continuous stream of material without showing any structures such as loops and jets. The speeds of spray-type X-ray plasma ejections have a relatively wide range, 20-900 km s^{-1}. Their mean value is 242 km s^{-1}, which is similar to that of loop-type events. For this type of X-ray plasma ejections, 70% of the events (28/40) are associated with the CMEs.

(c) Jet-Type

Figure 3 shows a jet-type X-ray plasma ejection that was associated with a C3.7 limb flare. It started at 05:00 UT and came to its peak flux at 05:17 UT. The plasma ejection had a relatively high speed (~360 km s^{-1}). Like other jet-type plasma ejections, this event also showed collimated motions along the loops.

Figure 4 shows another jet-type X-ray plasma ejection that occurred on 1999 May 17. In this event, the associated flare is a C3.9 SDE (short duration event, less than 1 hour) flare. It started at 03:39 UT and came to its peak flux at 03:45 UT. Unlike Figure 3, the plasma ejection started from one footpoint of large overlying loop and flowed along the magnetic field structure. Figure 5 shows X-ray plasma loops (upper panel) of the same event as Figure 4 and a related magnetic field configuration (lower panel). A central box of the upper left image corresponds to a field of view ($2.6' \times 2.6'$) of the full-resolution image seen in the upper right image of Figure 5. As seen in the upper two figures of Figure 5, we can see a large overlying loop (upper left image) and a small emerging loop (upper right image), which is quite similar to the magnetic field configuration (lower panel of Figure 5) suggested by Hanaoka (2000) in which the magnetic reconnection occurred at the interaction region between overlying loop and emerging loop.

We also note that all jet-type X-ray plasma ejections (11 events) have their associated CMEs. The mean speed of these events is estimated to be 417 km s^{-1}, which is relatively larger than those of other types of events. These two facts seem to be related to magnetic field structures near the reconnection regions.

(d) Confined Ejection

There are three kinds of images in Yohkoh flare mode observation such as full, half, and quarter-resolution images as described in Section II. The confined X-ray plasma ejections could not be identified in half or quarter-resolution images but in full-resolution images only with the smallest field of view ($2.6' \times 2.6'$) of the flare mode data. Figure 6 shows a confined-type plasma ejection. Its size is about 10 Mm, which is quite small relative to those of others. The X-ray plasma ejection was associated with a C4.6 X-ray flare that occurred on 1999 November 6. As seen in the figure, it was ejected to the north-east limb and had ejecting structures. This event was not associated with any coronal mass ejections. The speed of the confined ejection ranges from 50 to 310 km s^{-1} with the mean speed of 152 km s^{-1}. Their speeds are relatively low relative to those of other types. It is also noted that their CME association is estimated to be 28 % (5/18), which is the lowest value among the all groups.

TABLE 1.
MORPHOLOGICAL CLASSIFICATION OF FLARE-ASSOCIATED X-RAY PLASMA EJECTIONS AND THEIR CHARACTERISTICS.

Morphological Class	Loop-type	Spray-type	Jet-type	Confined Ejection	Others
No. of Events	60	40	11	18	8
CME Association	77%(46/60)	70%(28/40)	100%(11/11)	28%(5/18)	62.5%(5/8)
Speed Range (km s^{-1})	50-750	20-900	200-1000	50-310	10-270
Mean Speed (km s^{-1})	255	242	417	152	116

IV. SUMMARY AND DISCUSSION

In this paper, we have classified the 137 X-ray plasma ejections into five groups according to their shape: loop-type (60 events), spray-type (40 events), jet-type (11 events), confined ejection (18 events), and others (8 events). This is the first trial to classify the X-ray plasma ejections using a large sample of data. Table 1 summarizes their basic characteristics such as CME association, speed range and mean speed. It is noted that most of the events (73 %, 100/137) are categorized into loop-type or spray-type. Their associations with CMEs are about 70 $\sim$ 80 %.

The classification may depend on individual subjectivity or classification criteria. In our classification, the major difference between the loop-type and jet-type ejections is whether the plasma motions are along (jet-type) or across (loop-type) the magnetic field structure. We note two major differences : jet-type events tend to have higher speeds and better association with CMEs. It is also noted that while the jet type events have the highest association with CMEs, the confined ejections have the lowest association. These facts imply that the physcial characteristics of the X-ray plasma ejections such as speed and CME associations, be associated with magnetic field configurations near the field reconnection regions.

We are examining several physical characteristics of X-ray plasma ejections such as kinematic properties, related X-ray waves, and their associations with other solar activities. The results will be appeared in a series of papers.

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