

RHESSI OBSERVATIONS OF A SIMPLE LARGE X-RAY FLARE ON 2003 NOVEMBER 3

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ABSTRACT

We present data analysis and interpretation of a simple X-class flare observed with *RHESSI* on 2003 November 3. In contrast to other X-class flares observed previously, this flare shows a very simple morphology with well-defined looptop (LT) and footpoint (FP) sources. The almost monotonic upward motion of the LT source and increase in separation of the two FP sources are consistent with magnetic reconnection models proposed for solar flares. In addition, we find that the source motions are relatively slower during the more active phases of hard X-ray emission; the emission centroid of the LT source shifts toward higher altitudes with the increase of energy; and the separation between the LT emission centroids at two different photon energies is anticorrelated with the FP flux. Nonuniformity of the reconnecting magnetic fields could be a possible explanation of these features.

Subject headings: acceleration of particles — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

With its high temporal, spatial, and spectral resolution and broad energy coverage, *RHESSI* has revealed many features of solar flares with unprecedented details (Lin et al. 2002). Since its launch on 2002 February 5, *RHESSI* has observed several X-class flares and thousands of midclass and small flares. The compactness of microflares limits our access to details of the energy release and particle acceleration processes (Krucker et al. 2002). On the other hand, large and well-resolved flares usually involve multiple loops with complex structures, and the looptop (LT) and associated footpoint (FP) sources are not readily identified and separated (Gallagher et al. 2002; Lin et al. 2003). This makes a direct comparison of theoretical models with observations a challenging task (Alexander & Metcalf 2002; Sui et al. 2002). This task would be easier for a large flare with a simple morphology, where one can identify source positions and evolutions with certainty (Tsuneta 1996; Tsuneta et al. 1992, 1997).

In late October and early November of 2003, *RHESSI* and other instruments observed a series of X-class flares from solar Active Regions 0486 and 0488 (reminiscent of the 1991 June flares of the previous solar cycle; Schmieder et al. 1994). Among these flares, we studied an event that occurred on November 3 in AR 0488 at heliographic coordinate N09°, W77°. Unlike other X-class flares, e.g., the 2002 April 21 flare (Gallagher et al. 2002) and the gamma-ray flare on 2002 July 23 (Lin et al. 2003), this flare shows a surprisingly simple morphology with one well-defined LT source and two well-defined FP sources.

In this Letter we present a brief description of the spatial evolution of the various emission regions of this flare. As we show, this provides an excellent example of the classical solar flare model of magnetic reconnection and energy release in an inverted Y magnetic field configuration (Kopp & Pneuman 1976; Forbes & Acton 1996; Aschwanden 2002), whereby reconnection in the oppositely directed field lines leads to particle acceleration near the LT. The energy release and particle acceleration processes are not well understood; nevertheless, it

is expected that the reconnection will produce closed loops at lower altitudes first and progress to higher overlying loops as time advances. Consequently, the altitude of the LT source and the separation of the two FPs should increase with time. The flare studied here shows this exact behavior.

On the other hand, we also see evidence for deviations from the simplest reconnection models. Our study indicates that the reconnecting fields could be nonuniform and may have a shearing component. In the next section, we present the observations, data analysis, and our results. Their implications are discussed in § 3.

2. OBSERVATIONS AND DATA ANALYSIS

The flare under study, classified as a *GOES* X3.9-class flare, was observed by *RHESSI*, *SOHO*, etc. Figure 1a shows the *RHESSI* light curves. In lower energy channels (<25 keV), the count rates started to rise at around 09:43 UT, peaked about 9 minutes later, and then began a monotonic declining phase until 10:01:20 UT when *RHESSI* entered the Earth's night region. The higher energy channel (>50 keV) light curves exhibit two broad impulsive bursts, each of them consisting of several pulses with a more quiescent part in between, suggesting a persistent but episodic energy release process. Impulsive radio activities were also observed by the Nançay Observatory (N. Vilmer 2003, private communication). A partial halo coronal mass ejection with a speed of $\sim 1375 \text{ km s}^{-1}$ was observed by the Large Angle and Spectrometric Coronagraph on *SOHO*.

To study the hard X-ray (HXR) source motion and structure, we obtained images at different energies in 20 s intervals from 09:46:20 through 10:01:00 UT using the CLEAN algorithm (Hurford et al. 2002) and front segments of detectors 3–8 to achieve a FWHM of 9''8 with a 0''5 pixel size. Figure 2 shows the HXR emission contours during the two main activity peaks. There are three sources: an LT, a northern FP (N-FP), and a southern FP (S-FP). The LT source dominates at low energies while the FPs dominate at high energies. As evident from the background preflare magnetogram obtained with the Michelson Doppler Imager (MDI), the N-FP is around a negative magnetic polarity region while the S-FP remains in a region of positive polarity. Note that early in the event there is a partial overlap between the N-FP and the LT source. Grids with higher spatial resolution will not help for this flare because grid 2 is in a severely degraded condition (Smith et al. 2002) and grid 1 will

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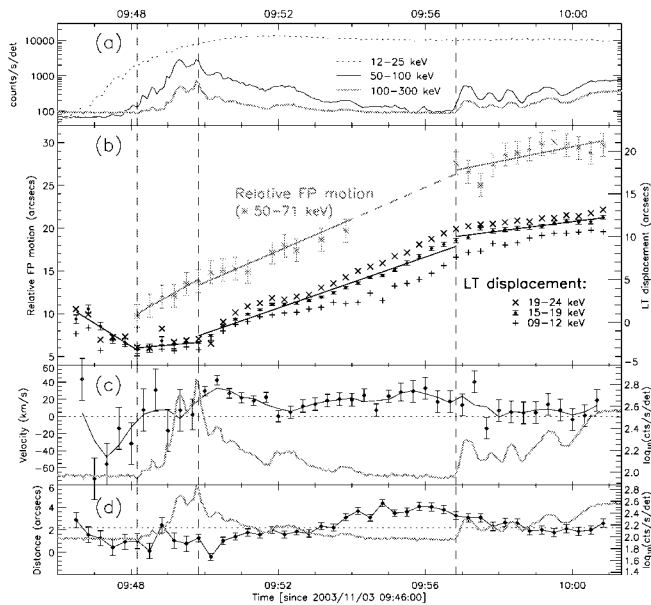


FIG. 1.—(a) *RHESSI* light curves (counts/second/detector). (b) The evolution of the altitude of the LT centroid (right scale) and the separation of the two FPs (left scale). The LT altitude here refers to the displacement along the main direction of motion that is nearly perpendicular to the solar limb. The straight lines are fits to the FP separation and LT altitude at 15–19 keV with vertical dashed lines separating the four phases as described in the text. The uncertainty of the centroid location at 15–19 keV is shown with the vertical error bars, which are similar to those at 9–12 and 19–24 keV (not shown). The uncertainty of the relative FP motion is also indicated. (c) The corresponding LT velocity at 15–19 keV. The thin curve is the velocity smoothed over 1 minute intervals. The thick gray curve is the logarithm of the 100–300 keV count rate (right scale). (d) Separation of the LT centroids at 19–24 and 9–12 keV (panel b) as a function of time. The dotted horizontal line marks the mean of this separation and the logarithm of the count rate (same as panel c).

overresolve the sources (see Schmahl & Hurford 2003 for technical details). A postflare (10:35:43 UT) EUV Imaging Telescope 195 Å image (not shown) shows a loop structure that agrees well with the *RHESSI* sources.

As shown in Figure 2, the LT and FPs have well-defined and correlated motions, with the symbols indicating their emission centroids at different times. The yellow dashed line represents the main direction of the LT motion, which is roughly at a right angle to the solar limb. We refer to the motion along this direction as changes in altitude. The motion perpendicular to this direction might be due to asymmetry of the reconnecting loops or the LT motion along an arcade. Before the rise of the impulsive HXR emission, there is an apparent downward LT motion. This downward motion could indicate a shrinkage of newly formed loops. It may also be due to the formation of nearby sources (Krucker et al. 2003) or to projection effects should the LT source move eastward along an arcade of loops (Sato 2001). Qualitatively similar features have been seen in several other flares (Krucker et al. 2003; Sui & Holman 2003), suggesting that this may be a common characteristic of solar flares. However, for the remainder of the flare duration the LT source rises systematically. The apparent separation of the FP sources, whenever detectable, also increases with comparable speed. As emphasized above, this is expected in a simple continuous reconnection process that moves up to the corona, accelerating particles and energizing plasma higher up into overlying larger loops.

To analyze the FP motion quantitatively, one needs to take into account projection effects because any motion and its associated uncertainty in the east-west direction are amplified by

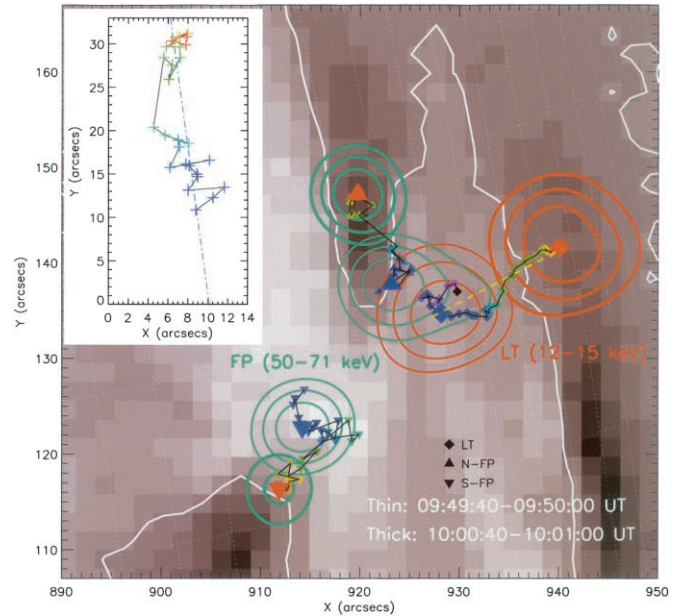


FIG. 2.—Temporal evolution of HXR source centroids, overlaid on an MDI magnetogram (09:32:30 UT). Black line segments connect the centroids obtained from CLEAN images in successive 20 s intervals chronologically from black (09:46:20 UT) through violet, blue, green, yellow, and to red (10:01:00 UT). The LT (12–15 keV) centroid is the brightness-weighted source center within the 70% level contour, but each FP (50–71 keV) centroid is the peak position obtained with a 3×3 pixel parabolic fit around the brightest pixel. The yellow dashed line represents the main direction of motion of the LT source. To estimate the uncertainty in the LT centroid location, we fitted the LT data points with four straight lines within the time intervals, 09:46:20–09:49:40, 09:49:40–09:52:00, 09:52:00–09:55:20, and 09:55:20–10:01:00 UT, respectively. For each interval, following Krucker et al. (2003), the standard deviation of the offset of the data from the corresponding straight line was used as the error in the location. The insert shows the relative positions of the N-FP with respect to the S-FP, which is fixed at the origin. We attribute the motion perpendicular to the straight line to uncertainties in the locations (see text for details). Four HXR images in two time intervals, 09:49:40–09:50:00 (inner) and 10:00:40–10:01:00 UT (outer), and in two energy channels, 12–15 (red) and 50–71 keV (cyan), are overlaid as contours (at 55%, 70%, and 85% levels of the maximum brightness of the image), which clearly depict the LT and FPs, respectively. The centroids corresponding to these two intervals are indicated with larger symbols. The magnetogram shows the line-of-sight magnetic field in a gray scale ranging from -979 (black: pointing away from the observer) to $+1004$ (white) G. The apparent neutral lines are marked in white.

a factor of about $\csc 77^\circ \approx 4.4$. Motions in this direction are highly uncertain, and the motion of both FPs appears to have an east-west component. Magnetic reconnection, on the other hand, is characterized by the change in the size of newly formed loops rather than their absolute motions. Thus one may concentrate on the relative motion of the two conjugate FPs. In the insert panel of Figure 2, we illustrate this relative motion by fixing the S-FP at the origin of the coordinates and showing the relative locations of the N-FP. The relative motion is obviously systematic. The fact that the line tracing the location of the N-FP is not exactly aligned with the lines connecting the two FPs shows that there is another component of the relative motion introducing a small rotation of the plane containing the newly formed loop. Because this line is nearly parallel to the longitudinal line, one can ignore the projection effects. We quantify the relative motion along this line, and the standard deviation of the displacement (apparently) perpendicular to this line is used as an upper limit for the uncertainties of this relative motion.

Figure 1b shows this relative motion of the FPs (at 50–

TABLE 1
LT VELOCITIES AND FP SEPARATION SPEED^a

TIME RANGE (UT)	LT VELOCITIES				FP SPEED 50–71 keV
	9–12 keV	12–15 keV	15–19 keV	19–24 keV	
09:46:20–09:48:10	-18.3 ± 3.7	-22.5 ± 4.6	-32.5 ± 4.1	-30.8 ± 4.7	...
09:48:10–09:49:50	3.5 ± 3.3	4.0 ± 3.0	4.7 ± 2.6	4.3 ± 2.7	29.1 ± 11.6
09:49:50–09:56:50	14.6 ± 0.4	16.5 ± 0.2	18.0 ± 0.2	20.9 ± 0.1	22.4 ± 2.5
09:56:50–10:01:00	9.3 ± 0.9	8.6 ± 0.7	6.6 ± 0.7	5.9 ± 0.5	10.4 ± 3.6

^a In units of kilometers per second.

71 keV) along with the location of the emission centroids of the LT source in three energy bands projected onto its main direction of motion. As evident, the two motions are correlated and the two sets of data points are nearly parallel to each other indicating comparable velocities. To further investigate these motions we divide the observed flare duration into four phases: a preimpulsive phase (before 09:48:10 UT) when there is no significant high-energy HXR emission, a rising phase (from 09:48:10 to 09:49:50 UT), a declining phase (from 09:49:50 to 09:56:50 UT), and a second active phase (from 09:56:50 to 10:01:00 UT). We then fit straight lines to each segment and determine the corresponding average velocities. The results are summarized in Table 1. Surprisingly, the LT velocity is highest in the declining phase, when the X-ray emission is relatively weaker (Fig. 1c). In the simplest model of reconnection of *uniform* and oppositely directed magnetic fields, one would expect the opposite correlation, i.e., a higher rate of energy release when the velocity is larger. However, this would be true if the observed HXR flux were actually proportional to the total energy release and if reconnection were indeed occurring in a uniform background plasma, neither one of which is exactly true.

Another interesting morphological evolution is the change of the centroid of the LT source with energy. In Figure 3 we show the *RHESSI* 75% contours and centroids at several energies superposed on an MDI continuum image showing sun-

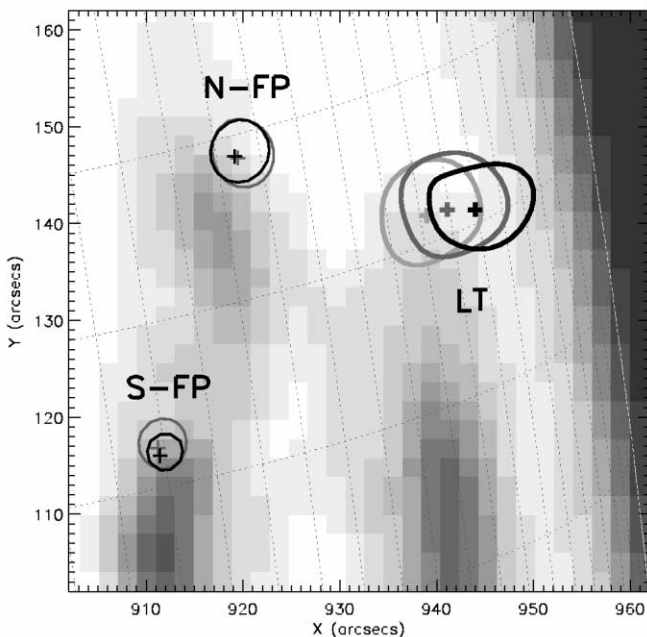


FIG. 3.—*RHESSI* image contours (75%) and the corresponding brightness-weighted centroids (*plus signs*) in the interval 10:01:00–10:01:20 UT. The LT contours are for 12–14 (*light gray*), 18–21 (*gray*), and 27–31 keV (*dark gray*), and the FP contours are for 40–46 (*gray*) and 60–73 (*dark gray*). The background is an MDI continuum map taken at 09:36:00 UT. The dark areas inside the limb are three sunspots.

spots. Compared with the two FPs, the LT source shows a clear and systematic displacement of the centroid of the higher energy emissions toward higher altitudes, as seen in two other flares (Sui & Holman 2003; Gallagher et al. 2002). To investigate what this separation of the LT centroids is related to, we looked for its correlations with other characteristics. We found an anticorrelation between the centroid separation and the high-energy (100–300 keV) count rate, which comes mainly from the FPs (Fig. 1d). The continuous curve in Figure 4 shows their cross-correlation function, which gives a peak correlation coefficient of -0.51 ± 0.08 with a time lag of $\Delta t = -22 \pm 39$ s. The data points (LT separation vs. HXR count rate) used for evaluating the correlation and a straight-line fit are also shown in the same figure.

3. DISCUSSION

We have investigated the 2003 November 3 X3.9 flare, having a simple morphology with well-defined LT and FP sources. The high flux combined with the simple loop structure allows

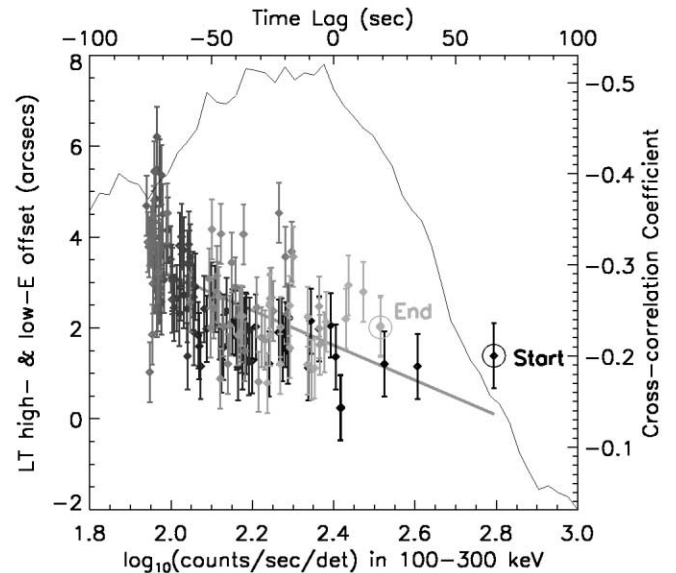


FIG. 4.—Correlation between the LT structure and the 100–300 keV (mainly FPs) light curve. The thin curve (with the top and right axis) shows the cross-correlation coefficient of the logarithm of the count rate and the separation between the 19–24 and 9–12 keV centroids of the LT source, showing a 22 ± 39 s delay relative to the light curve. The separation is similar to that shown in Fig. 1d but with a higher time resolution, obtained by imaging at a 4 s cadence (same as the light curve) with an integration time of one spacecraft spin period (~ 4 s) from 09:49:48 to 10:01:00 UT. We excluded the first two phases of the flare duration when the spatial contamination to the LT source by the N-FP is severe. The diamond symbols (with the bottom and left axis) show the LT separation vs. the logarithm of the count rate shifted by +24 s, corresponding to the peak of the correlation coefficient. The vertical error bars represent the uncertainty in the centroid separation. The darkness of the symbols represents time with the start and end point being circled. The gray thick line is a linear fit to the data with a slope of -3.84 ± 0.34 .

us to determine the spatial evolution of the LT and FP sources clearly and to compare with the simple reconnection models. Similar studies of flares have been limited to the investigation of the motion of the FPs alone (Sakao et al. 1998; Qiu et al. 2002; Fletcher & Hudson 2002) or have dealt with complex loop structures (Krucker et al. 2003; Qiu et al. 2004). This has made the comparison with models more difficult. Our analysis of *RHESSI* data has yielded several new and interesting results:

1. We observe a systematic rise of the LT source and a comparable increase in the separation of the FPs as the flare proceeds. This agrees very well with the canonical solar flare model of magnetic reconnection in an inverted Y configuration. Similar behaviors have been reported previously using soft X-ray or EUV observations (Švestka et al. 1987; Tsuneta et al. 1992; Gallagher et al. 2002) during later thermal gradual phases of flares. However, these emissions are not directly related to the impulsive particle acceleration processes (Forbes & Acton 1996).

2. The LT source seems to move more slowly during the HXR peaks than during the declining and more quiescent phases, in apparent disagreement with reconnection of *uniform* and oppositely directed field lines, where one would expect a correlation between the velocity of the LT source and the energy release rate. However, we note that the HXR flux is not a good proxy for the energy release rate, and the magnetic fields in the reconnection region are likely to be nonuniform. Stronger magnetic fields would require a smaller volume of reconnecting

fields and possibly slower motion. However, in an inhomogeneous case other factors such as the geometry and Alfvén velocity variation can also come into play. This problem needs further exploration.

3. The centroid of the LT source appears to be at higher altitudes for higher photon energies. This suggests that the energy releasing process happens above the LT and that harder spectra, implying more efficient acceleration, are produced at higher altitudes. In the stochastic acceleration model by turbulence where the acceleration efficiency depends on the intensity of turbulence, this would indicate a decrease of the intensity with decreasing altitudes, presumably because of decay of turbulence away from its source at a higher altitude (Petrosian & Liu 2004).

4. The above shift of the centroids decreases with the increase of HXR flux from the FPs. Such an anticorrelation will be difficult to produce in simple models. In the above-mentioned model, this would imply a more homogeneous distribution of turbulence during more active phases.

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REFERENCES

- Alexander, D., & Metcalf, T. R. 2002, *Sol. Phys.*, 210, 323
 Aschwanden, M. J. 2002, *Space Sci. Rev.*, 101, 1
 Fletcher, L., & Hudson, H. S. 2002, *Sol. Phys.*, 210, 307
 Forbes, T. G., & Acton, L. W. 1996, *ApJ*, 459, 330
 Gallagher, P. T., Dennis, B. R., Krucker, S., Schwartz, R. A., & Tolbert, A. K. 2002, *Sol. Phys.*, 210, 341
 Hurford, G. J., et al. 2002, *Sol. Phys.*, 210, 61
 Kopp, R. A., & Pneuman, G. W. 1976, *Sol. Phys.*, 50, 85
 Krucker, S., Christe, S., Lin, R. P., Hurford, G. J., & Schwartz, R. A. 2002, *Sol. Phys.*, 210, 445
 Krucker, S., Hurford, G. J., & Lin, R. P. 2003, *ApJ*, 595, L103
 Lin, R. P., et al. 2002, *Sol. Phys.*, 210, 3
 ———. 2003, *ApJ*, 595, L69
 Petrosian, V., & Liu, S. 2004, *ApJ*, in press
 Qiu, J., Lee, J., & Gary, D. E. 2004, *ApJ*, 603, 335
 Qiu, J., Lee, J., Gary, D. E., & Wang, H. 2002, *ApJ*, 565, 1335
 Sakao, T., Kosugi, T., & Masuda, S. 1998, in *ASSL Vol. 229, Observational Plasma Astrophysics: Five Years of Yohkoh and Beyond*, ed. T. Watanabe, T. Kosugi, & A. C. Sterling (Boston: Kluwer), 273
 Sato, J. 2001, *ApJ*, 558, L137
 Schmahl, E. J., & Hurford, G. J. 2003, *Adv. Space Res.*, 32, 2477
 Schmieder, B., et al. 1994, *Sol. Phys.*, 150, 199
 Smith, D. M., et al. 2002, *Sol. Phys.*, 210, 33
 Sui, L., & Holman, G. D. 2003, *ApJ*, 596, L251
 Sui, L., Holman, G. D., Dennis, B. R., Krucker, S., Schwartz, R. A., & Tolbert, K. 2002, *Sol. Phys.*, 210, 245
 Švestka, Z. F., Fontenla, J. M., Machado, M. E., Martin, S. F., Neidig, D. F., & Poletto, G. 1987, *Sol. Phys.*, 108, 237
 Tsuneta, S. 1996, *ApJ*, 456, 840
 Tsuneta, S., Hara, H., Shimizu, T., Acton, L. W., Strong, K. T., Hudson, H. S., & Ogawara, Y. 1992, *PASJ*, 44, L63
 Tsuneta, S., Masuda, S., Kosugi, T., & Sato, J. 1997, *ApJ*, 478, 787