Results from the study of an M7.6 flare and its associated CME

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Abstract

An M7.6 flare was well observed on October 24, 2003 in active region 10486 by a few instruments and satellites, including GOES, TRACE, SOHO, RHESSI and NoRH. Multi-wavelength study shows that this flare underwent two episodes. During the first episode, only a looptop source of <40 keV was observed in reconstructed RHESSI images, which showed shrinkage with a velocity of 12–14 km s\(^{-1}\) in a period of about 12 min. During the second process, in addition to the looptop source, two footpoint sources were observed in energy channel of as high as \(>200\) keV. One of them showed fast propagation along one of the two TRACE 1600 Å flare ribbons and the 195 Å loop footpoints, which could be explained by successive magnetic reconnection. The associated CME showed a mass pickup process with decreasing center-of-mass velocity. The decrease of the CME kinetic energy and the increase of its potential energy lead to an almost constant total energy during the CME propagation. Our results reveal that the flare and its associated CME have comparable energy content, and the flare is of non-thermal property.

Keywords: Solar flare; Coronal mass ejection (CME); Hard X-ray

1. Introduction

The energy source of solar flares is generally believed to be the energy stored in non-potential magnetic structures. This energy can be suddenly released and then leads to acceleration of particles, plasma heating, and plasma motion. The so-called thermal and non-thermal models concern two extreme cases of flare models. Thermal models assume that most of the released energy goes into the impulsive heating of the plasma near the release site (Brown et al., 1979), and the non-thermal thick target models assume that most of the released energy goes into the acceleration of particles (Brown, 1971). The energy content (thermal vs. non-thermal) is far from being resolved. The ratio of the non-thermal to thermal energies calculated for different flares are different (McDonald et al., 1999; Berlicki et al., 2004; Li et al., 2005; Saint-Hilaire and Benz, 2005), and its value determines the dominant heating mechanism during the flare.

Solar flares have long been taken as the main source of catastrophic space weather due to the large amount of energy released during it and the accelerated high energy particles. However, this was doubted in recent years (Gosling, 1993) because some authors argued that coronal mass ejection (CME) contains more energy than solar flare (Gosling, 1993; Emslie et al., 2004), contrary to previous results (e.g., Lin and Hudson, 1976). More recently refined estimation indicates that energy in solar flare and CME is comparable (Emslie et al., 2005). More work needs to be done to tell which of solar flare and CME contains more energy.

A new kind of motion in solar flares was detected in recent years: flare loop shrinkage in the early impulsive phase of solar flares. It can last 2–4 min and was first detected by Sui and Holman in 2003 from X-ray looptop source of RHESSI observations (Sui and Holman, 2003). Flare loop shrinkage was confirmed by subsequent studies not only in X-ray (Krucker et al., 2003; Liu et al., 2004; Sui et al., 2004; Veronig et al., 2006) but also in microwave (Li and Gan, 2005) and EUV (Li and Gan, 2006) wavebands. The shrinkage of flare loops was taken to be evidence of magnetic reconnection.
In this paper, we will address the above-mentioned problems from a case study of the M7.6 flare of October 24, 2003 and its associated CME. We first describe the observations and data used in this paper in Section 2, and then present our results in Section 3. Discussion and summary will be given in Section 4.

2. Observations and data

This 1N/M7.6 flare took place in active region 10486. The Solar Geophysical Data (SGD) register indicates it started at 02:27 UT, peaked at 02:54 UT and ended at 03:14 UT in X-ray and started at 02:22 UT, peaked at 02:47 UT and ended at 03:28 UT in Hα. It was observed by a few ground-based and space-borne instruments, including the Multi-channel Infrared Solar Spectrograph (MISS) (Li et al., 1999, 2002) at Purple Mountain Observatory (PMO), the Nobeyama Radioheliograph (NoRH), the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) (Lin et al., 2002), the Geostationary Operational Environmental Satellites (GOES), the Transition Region and Coronal Explorer (TRACE) (Handy et al., 1999) and the Solar and Heliospheric Observatory (SOHO) (Dominigo et al., 1995).

Microwave images at 34 GHz are from NoRH, which is a solar radio telescope dedicated to full-disk observations. It observes the Sun at 34 GHz in intensity with a spatial resolution of about 2.45°/pixel. The EUV images at 195 and 1600 Å were observed by TRACE with a high spatial resolution of 0.5°/pixel.

RHESSI observations allow us to reconstruct the spectra in the X-ray energy range of 3–200 keV for this flare. These observed spectra can be reproduced by calculations based on different theoretical models. We apply a model consisting of a thermal and a non-thermal components. The thermal component represents the flare energy contained in the thermal plasma, while the non-thermal one gives us some information about the importance of non-thermal particles in the overall energy budget of the flare.

CME data used in this paper were obtained by the C2 and C3 coronagraphs of the Large Angle Spectroscopic Coronagraph (LASCO) (Brueckner et al., 1995) package on board SOHO. These two coronagraphs image the solar corona from 1.5 to 30 solar radii. The average time interval of each two successive images is about 20 and 30 min for the C2 and C3 coronagraphs, respectively.

3. Results

We present our observational results in this section for the flare and the associated CME.

3.1. GOES and RHESSI light-curves

We retrieved the RHESSI light curves in energy ranges of 6–12 keV, 12–25 keV, 25–50 keV, 50–100 keV and 100–300 keV, and plotted them in Fig. 1 together with GOES 1–8 Å and 0.5–4 Å X-ray fluxes. Both the RHESSI light curves and the GOES X-ray fluxes indicate that this flare underwent two episodes: the first episode covers the time range before 02:44 UT and the second after 02:44 UT. The GOES 0.5–4 Å flux reached its first peak around 02:40 UT and then slightly decreased until 02:44 UT when...

Fig. 1. RHESSI light-curves in different energy ranges. Also plotted are the time profiles of GOES X-ray fluxes in 1–8 Å (solid black line) and 0.5–4 Å (dashed black line).
it began increasing again. And it reached its second (main) peak around 02:50 UT.

The RHESSI light-curves show that during the first episode X-ray emissions are dominant in low energy channels while during the second episode high energy channels have more photons. In other words, it seems that the second episode is more energetic (Gan et al., 2004). However, as we will see in Section 3.4, the non-thermal energy flux in the two episodes is comparable.

3.2. RHESSI X-ray loop shrinkage

We reconstructed X-ray images of this M7.6 flare from RHESSI observation using CLEAN algorithm in different energy ranges, and computed the altitude of the centroid of brightness for the looptop source in 6–12 keV and 12–25 keV. The time profile of the calculated altitude of centroid is plotted in Fig. 2 together with the RHESSI 6–12 keV light-curve for comparison. This figure clearly shows the shrinkage of the looptop source in the period from 02:25 to 02:35 UT. Linear fit to the altitude time profile in this period gives a shrinking speed of 13.6 and 11.7 km s$^{-1}$ for the 6–12 keV and 12–25 keV looptop sources, respectively, which are consistent with previous results (Sui and Holman, 2003; Krucker et al., 2003; Liu et al., 2004; Sui et al., 2004; Veronig et al., 2006; Li and Gan, 2005, 2006). However, the shrinkage lasts at least 10 min, which is longer than previous results. This may be related to the complicate loop systems involved in this flare. We will discuss this point in details in Section 4.

3.3. HXR footpoint source motion

RHESSI hard X-ray (HXR) images show that there were two footpoint sources during the second episode, which we marked with ‘FP1’ and ‘FP2’ in Fig. 3a. During the second episode the two sources show different behaviors. FP2 appeared later than FP1 (Gan et al., 2004) and did not display detectable motion. FP1 showed fast motion along one of the two TRACE 1600 Å flare ribbons and the footpoints of the TRACE 195 Å loops (Fig. 4a). The derived velocity in the plane of the sky was plotted in Fig. 4b.

3.4. Flare energy

We retrieved energy spectrum data from RHESSI observation with a time interval of 20 s and carried out energy spectrum analysis using a model consisting of a thermal component and a non-thermal thick-target component to fit the observed energy spectrum. In our fit, we set the broken energy and the high energy cutoff of electrons to be 10 MeV (equivalent to a single power-law) and let the low energy cutoff to be a free parameter, i.e., to be varying from time to time. From the fit, we got a set of parameters including emission measure $EM$, temperature $T$, spectral index $\gamma$, total electrons $n_e$ above the low energy cutoff, etc.

We use the formulae given in (Li et al., 2005) to compute the thermal energy $E_{\text{therm}}$, non-thermal energy flux $F_{\text{ntherm}}$ of the flare. We use the formula $V = A^{3/2}$ (Emslie et al., 2004) to compute the volume $V$ of thermal plasma from the area $A$ of the 50% contour of RHESSI 12–25 keV images as did in (Emslie et al., 2004). The total non-thermal energy $E_{\text{nths inn}}$ injected into the flare plasma up to a given time was obtained by integrating $F_{\text{ntherm}}$ over time from the flare onset to that time. The computed energy and flux are plotted in Fig. 5. It is shown in the figure that the total injected non-thermal energy is about $1.36 \times 10^{31}$ ergs. The total energy (total non-thermal energy plus maximum thermal energy) in the flare is about $1.6 \times 10^{31}$ ergs if taken the
Fig. 3. (a) and (d) Reconstructed RHESSI image in 40–50 keV and 29–42 keV, respectively; (b) and (c) NoRH 34 GHz images. ‘FP1’ and ‘FP2’ in (a) mark the two HXR footpoint sources discussed in text. Observation times are shown in each image.

Fig. 4. (a) TRACE 195 Å image at 02:42:11 UT (background image) overlaid with contours of TRACE 1600 Å flare ribbon. The arrows indicate the trajectory of the north-east 40–50 keV RHESSI HXR footpoint source. (b) Derived velocity of the north-east HXR footpoint source from 40–50 keV RHESSI images.
maximum of \(E_{\text{therm}}\) as the thermal energy content in the flare plasma.

### 3.5. Parameters of the associated CME

A CME associated with this M7.6 flare was well observed by LASCO onboard SOHO. The CME was in the field-of-view (FOV) of C2 from 02:54 to 03:54 UT, and in the FOV of C3 from 03:42 UT. We use the method given in Vourlidas et al. (2000) to compute the evolution of its mass (\(M_{\text{cme}}\)), center of mass velocity (\(v_{\text{cme}}\)), acceleration (\(a_{\text{cme}}\)), kinetic (\(E_k\)) and potential (\(E_p\)) energy. The computed results are shown in Fig. 6.

The velocity \(v_{\text{cme}}\) was calculated by a second order fitting to the height–time curve of the center-of-mass. Fig. 6 shows that the CME mass increases with time while the center-of-mass velocity decreases with time with an acceleration of \(a = -28 \text{ m/s}^2\) (Fig. 6a). The kinetic \(E_k\) and potential \(E_p\) energy, as expected, change oppositely with time. Namely, \(E_p\) increases and \(E_k\) decreases with time. However, the total energy of the CME does not show significant temporal variation and is about \(3.2 \times 10^{31}\) ergs.

### 4. Discussions and summary

We studied the M7.6 flare of October 24, 2003 and its associated CME. The flaring process can be clearly divided into two episodes which behavior differently. No HXR footpoint source was detected in RHESSI images in the first episode (Fig. 3d), indicating that electrons were not accelerated to high energy enough for the electrons to propagate to the low atmosphere. Two HXR footpoint sources up to 200 keV were observed in the second episode, which appeared successively. It seems from RHESSI light-curves that the second episode is more energetic than the first one (Gan et al., 2004). However, RHESSI energy spec-

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**Fig. 5.** Time profiles of the thermal energy, total injected non-thermal energy, non-thermal energy flux (power) and low energy cutoff (\(E_{\text{cutoff}}\)) of the flare deduced from RHESSI energy spectrum analysis using a model of thermal plus thick-target non-thermal components.

**Fig. 6.** Time profiles of the CME parameters. (a) CME mass and center-of-mass velocity. (b) Potential, kinetic and total energy of the CME.
trum analysis reveals that non-thermal energy fluxes in the main time periods of the two episodes are equivalent (Fig. 5). This can be interpreted as that large amount of low energy electrons in the first episode and small amount of high energy electrons in the second episode carry about comparable amount of non-thermal energy. The total non-thermal energy injected into this flare is about 10 times the maximum thermal energy. In other words, the flare is of non-thermal property.

Fast motion of one of the two HXR footpoint sources (FP1 in Fig. 3a) was detected from RHESSI 40–50 keV images, which had a velocity of about 50 km s⁻¹ in the beginning and gradually decreased to about zero and then increased once more (Fig. 4b). This source moved along the TRACE 1600 Å flare ribbon as it rapidly extended its area and along the TRACE 195 Å loop footpoints as they successively brightened. This fact together with that the two HXR sources appeared not simultaneously and the following long time shrinkage of the flare loop can be well explained by the successive magnetic reconnections (Grigis and Benz, 2005; Tripathi et al., 2006).

Long loop-top shrinkage was detected in this flare which displayed similar velocity to previous results. This long time shrinkage is probably related to the complicate loop structures. Presented in Figs. 3(b and c) are the NoRH 34 GHz images at 02:34:33 UT and 02:39:03 UT, respectively. They clearly show the alternative brightening of different loops, which may lead to long shrinkage because one may measure loop-top sources related to different loops at various times.

The associated CME shows mass pickup as it propagated outwards and a decreasing center-of-mass speed. Meanwhile, we clearly see from Fig. 6 the transfer of thermal and non-thermal energy fluxes driven by magnetic reconnections observed in a confined flare. A&A 343, 325–339, 2005.


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