TRACE DOWNFLOWS AND ENERGY RELEASE

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ABSTRACT

We have examined in detail the evolution of a big two-ribbon flare which occurred on 2002 July 23. The extreme ultraviolet images obtained with TRACE show dark downflow motions (sunward motions) above the post-flare loop, not only in the decay phase but also in the impulsive and main phase. We found that the times when the downflow motions are seen correspond to those of the bursts of nonthermal emissions in hard X-ray and microwave. This result means that the downflow motions occurred when strong magnetic energy was released, and that they are, or correlated with, the reconnection outflows. We also found the ascending motions of super hot plasma region seen in TRACE and RHESSI associating with the light curves in hard X-rays and microwaves. This result supports the Neupert effect.

1. INTRODUCTION

Observation of downflows is one of the most important findings achieved by the Soft X-Ray Telescope (SXT; [1]) aboard *Yohkoh* [2]. McKenzie and Hudson [3] and McKenzie [4] examined in detail these dark features moving sunward or downward above post-flare loops. The speeds are between 45 and 500 km s^{-1}, and are normally about a few hundreds km s^{-1}. They are often seen in the decay phase of long duration events (LDEs). They suggested that the downflows consist of low density plasma, and that they are moving voids. These voids are pushed downward because of magnetic reconnection occurring at further higher points, and therefore, they are thought to be new observational and morphological evidence of magnetic reconnection.

Recently, the *Transition Region and Coronal Explorer* (TRACE; [5, 6]) has also observed similar downflows above post-flare loops. By using the TRACE images, we have been able to examine such downflows with higher spatial resolution than was done with *Yohkoh*/SXT. Moreover, Innes, Wang, and McKenzie [7, 8] examined the downflows, by using spectroscopy with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER; [9]) aboard the *Solar and Heliospheric Observatory* (*SOHO*; [10]), and reported that they consist of low density plasma, which supports the model that the downflows are moving voids.

However, there are still many open questions about the downflows, such as why they are seen only in the decay phase of LDE flares. In this paper we present the results of a detail examination of the downflows seen in the 2002 July 23 solar flare. We also discuss the evolution of the superhot region where the downflows are seen.

2. OBSERVATIONS

Here is a summary of the flare and the data which we used. The large solar flare occurred in NOAA Active Region 0039 (S12°, E72°) at 00:18 UT, 2002 July 23. It was X4.8 on the scale of the *Geosynchronos Operational Enviromental Satellites* (*GOES*). It showed a lot of spectacular features, which have been reported in a number of papers (e.g. [11]), and is famous as the first event for which the γ-ray images are successfully obtained [12] with Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; [13]). Moreover, the vertical evolutions, such as ejections, formation of post-flare loops, downflows, and so on, are clearly seen, since the flare site is located on near the south-east limb.

The EUV images were obtained with TRACE. We used the 195 Å data, in which Fe XII line formed at 1 MK is dominant, but Fe XXIV line formed at 20 MK is also contained, though it is usually much weaker [5]. The pixel size is $1''.0$, and the temporal is about 9

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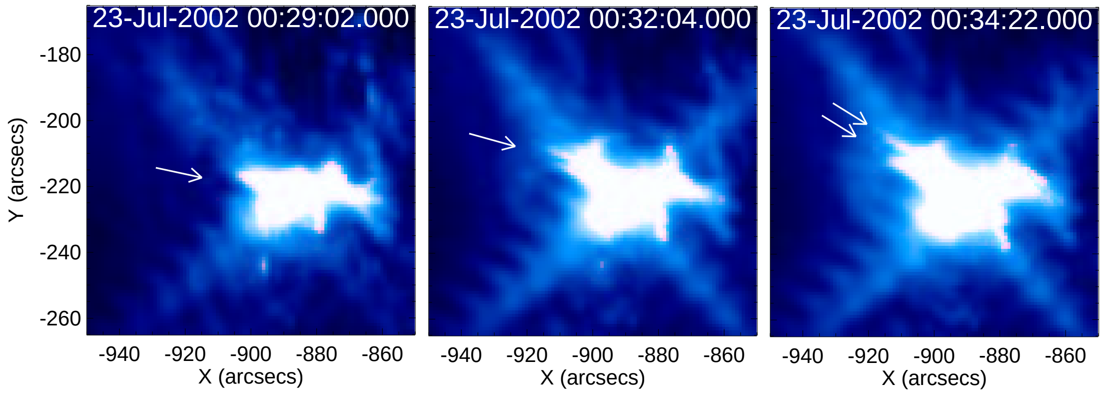

Fig. 1. Temporal evolutions of the 2002 July 23 flare in EUV 195 Å obtained with *TRACE*. Solar north is up, and west is to the right. The horizontal and vertical axes give the distance from the disk center in arcseconds. The *white* arrows point the downflows. The cross-shape fringe structure is the pattern of the scattered light.

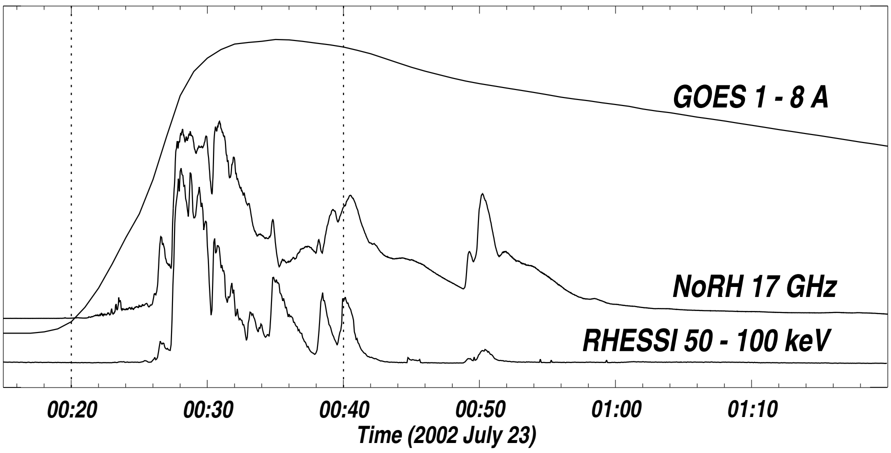

Fig. 2. Light curves of the 2002 July 23 flare. From top to bottom: soft X-ray flux in the GOES 1.0 - 8.0 Å channel; radio correlation plot observed at 17 GHz with NoRH; hard X-ray count rate measured with RHESSI (50 - 100 keV). Two *dotted* vertical lines show the time range of the time slice images in Figure 3.

s. Figure 1 shows the temporal evolution of the flare in the TRACE 195 Å images. In the images, which show bright post-flare loops, the features of 1 MK plasma are dominant. However, in the data, we can also see superhot features from 20 MK plasma, above the post-flare loops during flares. This region corresponds to the "superhot regions" which are located on the regions within cusp structure above post-flare loops ([14, 15]). The TRACE downflows are seen in the super hot plasma regions.

We used the hard X-ray (HXR) data obtained with RHESSI. Emslie et al. [16] performed the imaging spectroscopy of the source with the RHESSI data, and reported that the region consists of thermal plasma which have high temperature up to 40 MK. We also used the microwave flux measured with the Nobeyama Radioheliograph (NoRH; [17]). Figure 2 shows the light curves of the flare in microwave, HXR, and soft X-ray (SXR). The top line is that of RHESSI 50 - 100 keV, the middle one for NoRH 17 GHz, the bottom one for the GOES 1.0 - 8.0 Å channel. As White et al. [18] reported, the light curve in microwave is quite similar to that in HXR high energy range (greater than 50 keV). The HXR and microwave light curves of the flare show some bursts. It means that strong energy release occurred at those times.

3. TRACE DOWNFLOWS

The top panel of Figure 3 is a "time slice image", that is, the time-sequenced images of the TRACE 195 Å images along the slit. The horizontal and vertical axes show time and position along the slit, respectively. In the time slice image, we can easily identify the two temperature structure, superhot region and post-flare loops. The downflows are seen in the superhot region. They are ascending as the flare progresses. We will discuss this ascending motion later.

Firstly, we measured the velocity of the downflows. The velocity of each downflow is between 100 and 250 km s^{-1}. This value is comparable to the previous works [3, 4, 7, 8].

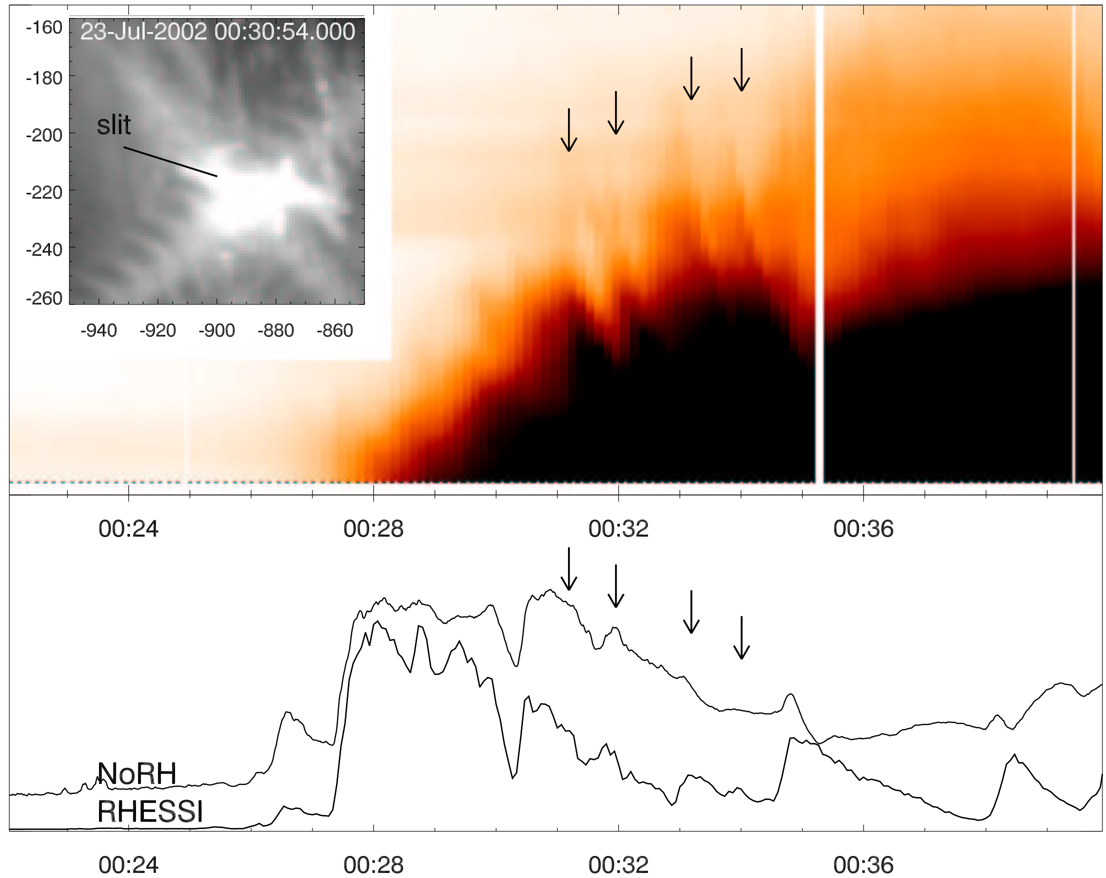

Fig. 3. *Top left*: an EUV image of the flare obtained with *TRACE*. The *black* solid line illustrate the position of the slit line. *Top right*: time slice image obtained with *TRACE* (195 Å) along the slit line. The horizontal axis is time (UT), and the vertical axis is the space along the slits. *Bottom*: microwave (17GHz) and HXR (50 - 100 keV) light curves obtained with NoRH and RHESSI, respectively.

Next, we examined when the TRACE downflows are seen. They appear not only in the decay phase, but also in the impulsive and main phases. This means that the downflows are not a specific phenomenon in the decay phase of a flare. It was one of the unresolved mysteries about *Yohkoh*/SXT downflows that they were seen only in the decay phase of LDE flare. In the 2002 July 23 flare, however, we can see some dark downflows above the post-flare loops from about 00:26 to about 01:20 UT. This time range corresponds not only to the decay phase but also to the impulsive and main phases of the flare (see the light curves of Fig. 2).

Furthermore, we examined the timings of the down flows in more detail. We overlaid a HXR and microwave light curve on the time slice images and found that the downflows show correlations with the bursts of those light curves. The bottom panel in Figure 3 shows the light curves of HXR and microwave obtained with RHESSI (50 - 100 keV) and NoRH (17 GHz), respectively. The arrows point the same times shown in the upper panels. The arrows in Figure 3 point the times when the downflows are seen. The light curves of the nonthermal emission show some bursts when strong energy release occurred, as we mentioned. Moreover, the HXR and microwave intensities are thought to be proportional the amount of the magnetic energy released per unit time [19, 20, 21]. Therefore, the result implies that the downflows appear when strong magnetic energy release occurs, and that they are, or at least they are correlated with, the reconnection outflows.

4. ASCENDING MOTION

Now, we focus on the evolution of the super hot region where the downflows are seen. In the time slice image such as Figure 3, we can see the rising motions of the superhot region and the post-flare loops. Their speeds are 40 and 20 km s^{-1}, respectively.

Figure 4 shows a detailed examination of the acending motion of the superhot region above the post-flare loops. The *red* plot follows the top edge of the superhot region. The arrows point the start time of the downflows. Then, we compared the ascending speed with the light curves of nonthermal emission. We derived the time profile of the ascending speed (*blue* plot) as the time derivative of the time profile of the height. The vertical *gray* thick lines in Figure 4 show the tims when the ascending speeds are enhanced. We can see the correlation between the enhancements of the ascending speed and the bursts

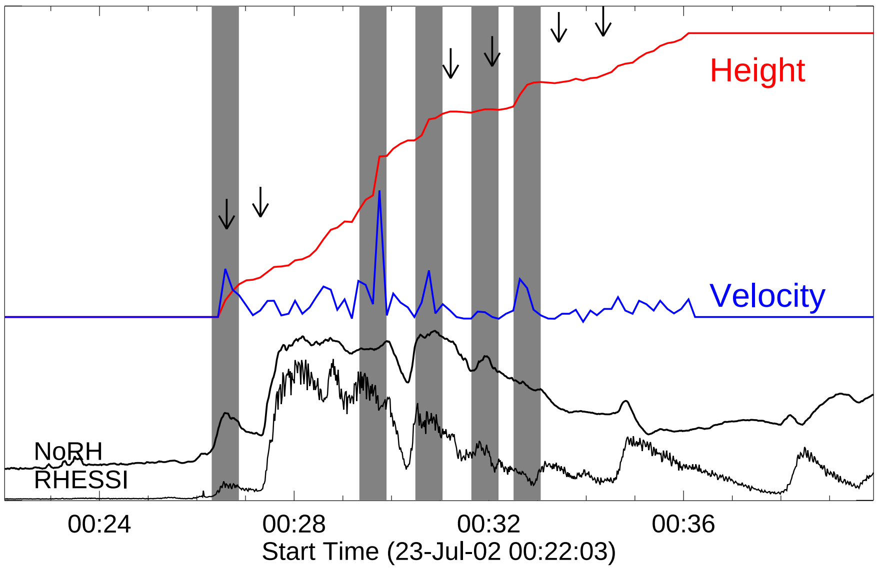

Fig. 4. Ascending motion of superhot region. From top to bottom: height of the top edge of the superhot region (*red*); ascending velocity of the superhot region, that is, time derivative of the height (*blue*); HXR light curve measured with RHESSI (50 - 100 keV); radio correlation plot observed at 17 GHz with NoRH. The arrows point the times when downflows are seen.

of the nonthermal emission. Therefore, the superhot region is pushed upward, and the ascending speed is enhanced at the time of the strong energy release. Furthermore, the downflows begin to be seen, at the time, or just after the time that the superhot region ascends. The results related to the ascending motion are consistent with the well-known "Neupert effect". In the other words, it is another aspect of the Neupert effect.

Krucker et al. [22] reported similar ascending motions in the HXR coronal source. The correlation is seen for the HXR sources in the low energy band, such as 13 - 18 keV, and are thought to be a superhot, thermal component. The ascending motions are also enhanced when the nonthermal bursts occur.

Table 1. Comparison between the features of plasmoid ejection and those of (SXT and TRACE) downflow.

	Plasmoid Ejection	Downflow
velocity [km s^{-1}]	30-500	45-500
size [km]	1-10 $\times 10^4$	2-10 $\times 10^3$
density [cm^{-3}]	1-10 $\times 10^9$	$\sim 10^9$
impulsive phase	Yes	Yes
decay phase	No	Yes
HXR/μ-wave	Yes	Yes

5. RECONNECTION OUTFLOW

Here, we discuss what the downflows are. Recently, H. Takasaki(in private communication) found similar correlations between X-ray plasmoid ejections and HXR bursts. They analyzed a flare which occurred on 2000 November 24, and reported that each of the ejections appears at a time corresponding to a HXR burst.

From the result, we suppose that both the downflows and the plasmoid ejections are the reconnection outflows, and they are ejected when strong energy releases occur, downward and upward, respectively. In Table 1 we summarize the features of downflows and plasmoid ejections.

To answer the question what the downflows are, we have to examine the mechanism and the process of the magnetic reconnection and the relation between the reconnection outflow and the downflow in more detail. The reconnection model and the numerical simulation based on the model, which is consistent with all the features of the downflows, such as low density, high Doppler-shift, relation with the bursts of nonthermal emission, are required. Recently, Tandokoro and Fujimoto [23] have examined the instability at the leading edge of a reconnection jet in his new 3D numerical simulation. Figure 5 shows the comparison between the result of TanDokoro's simulation (*left*) and the observed TRACE downflows (*right*). The color of the simulation shows the magnetic field strength in the direction perpendicular to the paper. The reconstructed leading edge is narrow and elongated structure, and is similar to the shape of downflows. This kind of works may help to explain what downflows are.

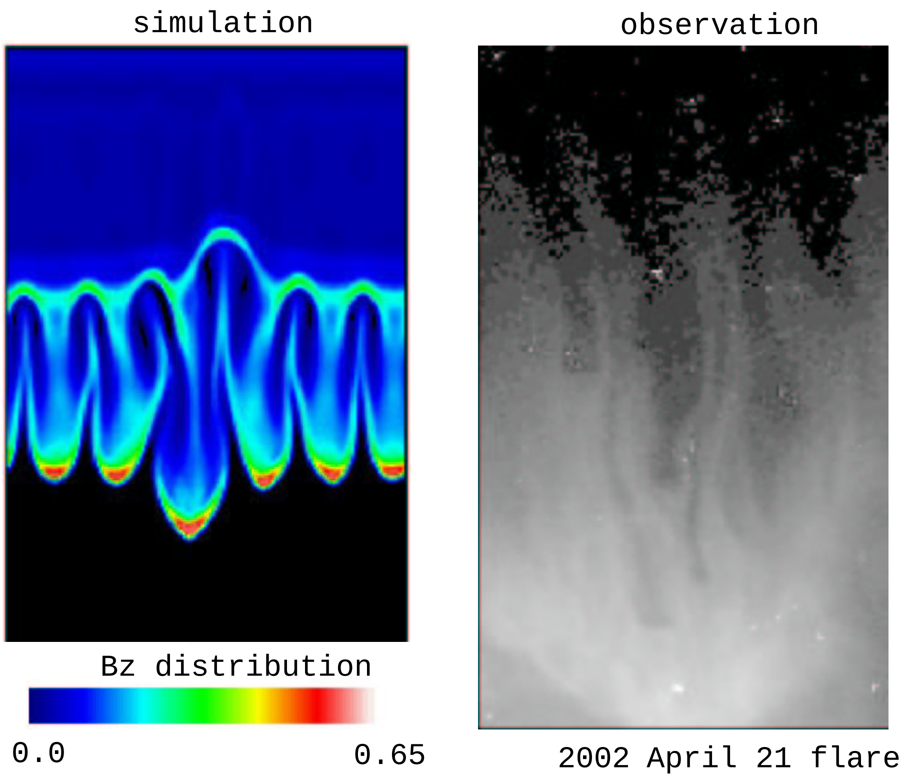

Fig. 5. Comparison between the TanDokoro's simulation and the observed downflows. *Left* panel: B_z distribution derived from TanDokoro's numerical simulation. Color shows the magnetic field strength in perpendicular direction to the paper. *Right* panel: other examples of TRACE downflows observed on 2002 April 21 (see Innes et al. [7, 8]).

6. SUMMARY

We have examined in detail the evolution of a big two-ribbon flare which occurred on 2002 July 23. We found TRACE downflows above the post-flare loops, and that they are seen not only in the decay phase, but also in the impulsive and main phases. Moreover, they appear to correspond to the times when the nonthermal bursts in microwaves and HXRs occurred. This result means that the downflow motions occurred when strong magnetic energy was released, and that they are, or are correlated with, the reconnection outflows. These results on the behaviors of the downflows are a new piece of observational evidence to add to the existing evidence for reconnection outflows. The superhot region ascends when the nonthermal bursts occur, and this result supports the Neupert effect.

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