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Downflow as a Reconnection Outflow

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Abstract. We present a detailed examination about the evolution of TRACE downflow motions (sunward motions) seen above post-flare loops. We found that the times when the downflow motions are seen correspond to those of the bursts of nonthermal emissions in hard X-rays and microwave. These results mean that the downflows occurred when strong magnetic energy was released, and that they are, or at least correlated with, the reconnection outflows. We also propose an observation of downflows as the reconnection outflows by Solar-B.

1. Introduction

The finding of supra-arcade downflow motions (downflows) in a long duration event (LDE) flare is one of the most important results that the Soft X-Ray Telescope (SXT) aboard Yohkoh achieved. McKenzie & Hudson (1999, 2001), and McKenzie (2000) examined, in detail, these dark and sometimes bright features moving sunward from the high corona. They suggested that the downflows consist of low density and high temperature plasma, and that they are moving voids. These voids are pushed downward because of magnetic reconnection which occurred at higher altitudes, and therefore, they are thought to be new observational and morphological evidence of magnetic reconnection. Recently, Gallagher et al. (2002) and Innes, McKenzie, & Wang (2003a) reported similar downflows in extreme ultraviolet (EUV) images obtained with the *Transition Region and Coronal Explorer* (TRACE). By using the TRACE images, we have been able to examine downflows with higher spatial resolution than was done with Yohkoh/SXT. Innes et al. (2003a) also reported spectroscopic information about the downflow by using the data obtained with the Solar Ultraviolet Measurements of Emitted Radiation instrument (SUMER) aboard the *Solar and Heliospheric Observatory* (SOHO). The report by Innes et al. (2003a) supports a model in which the downflows are moving voids. We examine in detail the downflows seen in the 2002 July 23 solar flare, which showed downflows in

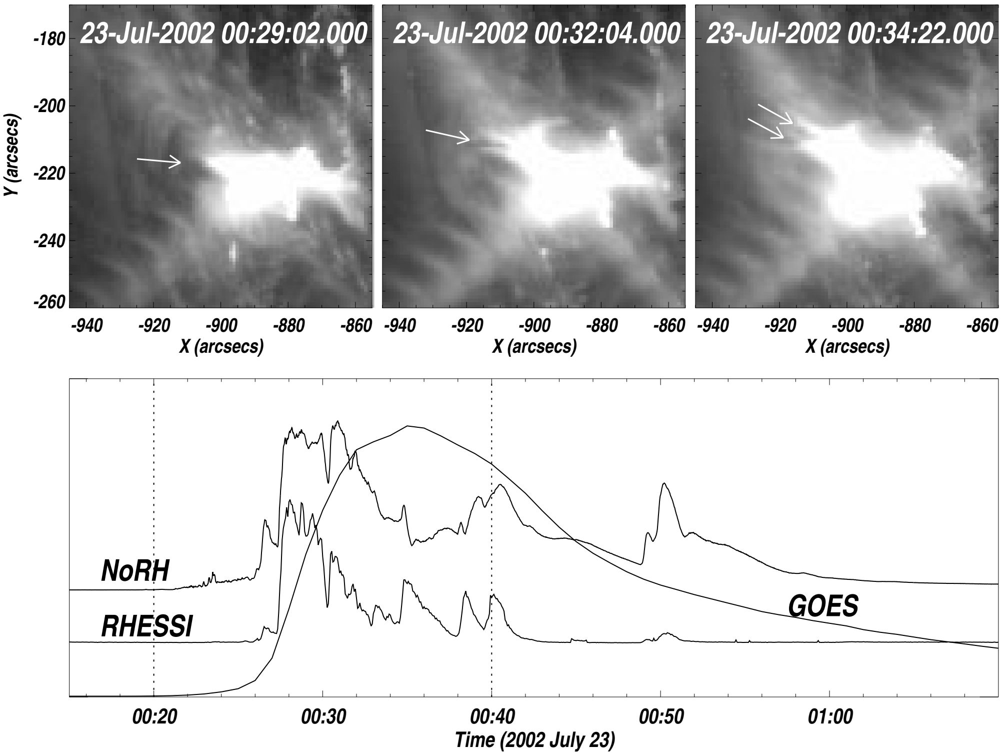

Figure 1. *Top*: Temporal evolution of the 2002 July 23 flare in TRACE 195 Å data. The white arrows indicate the downflows. *Bottom*: Light curves of the flare (scaled arbitrary). From top to bottom: radio correlation plot observed at 17 GHz with NoRH; hard X-ray count rate measured with RHESSI (50–100 keV); soft X-ray flux in the GOES 1.0–8.0 Å channel. Two dotted vertical lines show the time range of the time slice images in Fig. 2.

TRACE images associated with impulsive nonthermal emission. We also propose an observation of downflows as the reconnection outflows by Solar-B.

1.1. Observation and Data

A large solar flare (X4.8 on the GOES scale) occurred in NOAA 10039 at 00:18 UT, 2002 July 23. The vertical evolution, such as ejections, formation of post-flare loops, downflows, and so on, are clearly seen, since the flare site is located near the southeast limb. EUV images of the flare were obtained with TRACE. We used 195 Å images, in which emission from the Fe XII line formed at ~ 1 MK is dominant, while emission from the Fe XXIV line formed at ~ 20 MK, is also contained, though it is usually much weaker (Handy et al. 1999). The top panels of Fig. 1 shows the temporal evolution of the flare in the EUV. We cannot see clearly the post-flare loops due to saturation of the images, but we can see a cross-shaped fringe pattern, like fish bones, due to diffracted light. Although the super hot plasma region is much fainter than the post-flare loops, it is visibly spread above the loops. This region consists of plasma with quite high temper-

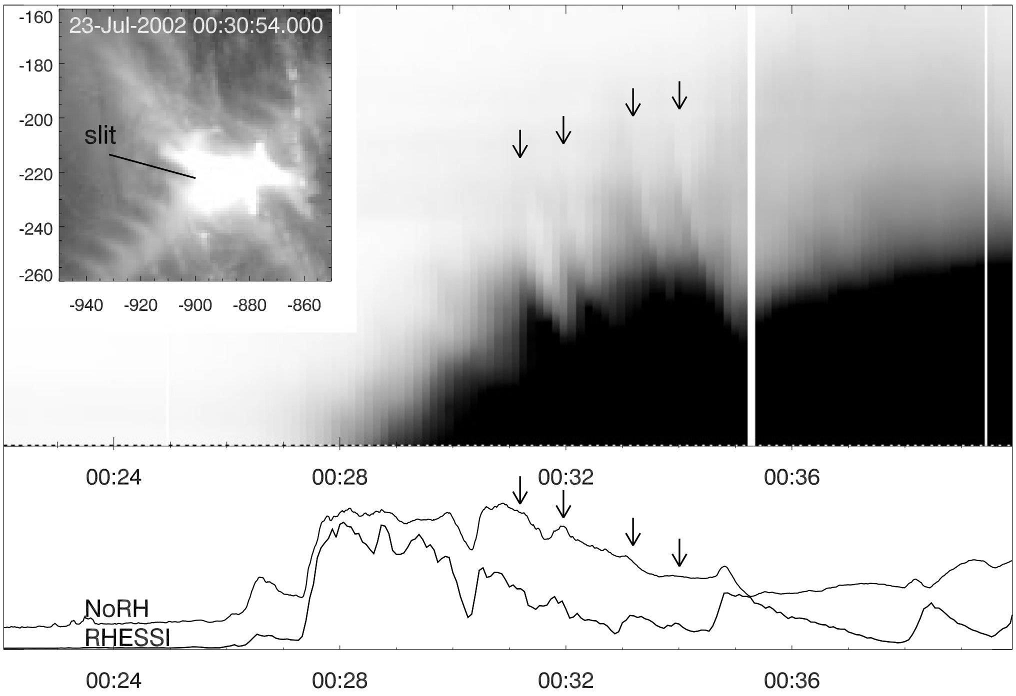

Figure 2. *Top*: Time-sequenced EUV (195 Å) images along the slit line shown by a black solid line in the inset at upper left, which is a TRACE EUV image of the flare. *Bottom*: microwave (17 GHz) and HXR (50–100 keV) light curves obtained with NoRH and RHESSI, respectively.

ature and is spread above post-flare loops. To examine nonthermal electrons, we also used the microwave total flux measured with the Nobeyama Radioheliograph (NoRH; Nakajima et al. 1994) and hard X-ray (HXR) data taken with the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (RHESSI). The bottom panel of Fig. 1 shows the light curves of the flare in microwave, HXR, and soft X-ray (SXR).

2. TRACE Downflows

In the flare we can see some dark downflows above the post-flare loops between about 00:26 and 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. 1). Here, we concentrate on the vertical motion and the timing of the downflows. The top panel in Fig. 2 shows the time slice image from 00:20 to 00:40 UT (negative images). This time range of the time slice images corresponds to the impulsive phase, as shown in the bottom panel of Fig. 1. The bottom dark (bright in the real images) regions are post-flare loops. They are so bright in the TRACE images because of saturation that no fine structures is identified. Above this region, we can see a much fainter dark region — the super hot region. Several downflows can be seen which are pointed out with arrows. The apparent speeds of the downflows are between 100 and 250 $\mathrm{km\,s^{-1}}$. They are decelerated at the top of the post-flare loops. The bottom panel in Fig. 2 shows the HXR and microwave light curves obtained with RHESSI (50–100 keV) and the NoRH (17 GHz), respectively. The arrows point out the same times shown in the upper panels. They correspond to the times when nonthermal bursts occur. The HXR and microwave intensities are thought to be proportional to the amount of the magnetic energy released per unit time (Neupert 1968; Wu et al. 1986; Hudson 1991). Therefore, the results imply that the downflows appear when strong magnetic energy release occurs, and that they are, or are correlated with, reconnection outflows.

On the X-ray plasmoid ejections, similar observational results have been reported by several authors (e.g. Ohyama & Shibata 1997, 1998). Kahler et al. (1988) reported the similar relationship between filament eruptions and HXR emissions. These observations revealed a close relationship between plasmoid/filament ejections and HXR emissions and showed that plasmoids/filaments are strongly accelerated during the impulsive phase (i.e. during HXR burst). From these results, we suppose that both the downflows and the plasmoid ejections are reconnection outflows. Plasmoids are generated in the current sheet, and are ejected as downward (downflows) and upward (X-ray plasmoid ejections), when strong energy releases occur. Therefore, the correlations between plasmoid ejections, or downflow, and HXR bursts represent a plasmoid-induced, nonsteady reconnection (Shibata 1999; Shibata & Tanuma 2001). Of course, there are still some discrepancies against the suggestion that downflows and plasmoid ejections are reconnection outflows. For example, the speed is slower than Alvén velocity. We have to compare simulation results with observed phenomena, in more detail. Moreover, we have to confirm whether downflows and plasmoid ejections are simultaneously observed, which support the suggestion. These are to be solved in future. Downflows show common features with X-ray plasmoid ejections (Table 1).

Table 1. Comparison between the features of the plasmoid ejection and those of the downflow

	Velocity $[\mathrm{km\,s^{-1}}]$	Size [km]	Density $[\mathrm{cm^{-3}}]$	Impulsive phase	Decay phase	HXR/ μ-wave
Plasmoid Ejection	30–500	$1\text{–}10\times10^4$	$1\text{–}10\times10^9$	Yes	No	Yes
Downflow	45–500	$2\text{–}10\times10^3$	$\sim10^9$(?)	Yes	Yes	Yes

3. Observation of Downflows by Solar-B

Here, we discuss observations of downflows by Solar-B. Downflows show the following features, based on the current work and the previous reports. Downflows are low emission features, and it is very difficult to extract physical parameters like temperature and density. Nevertheless, some solar physicists have tried to derive them. McKenzie & Hudson (1999) and McKenzie (2000) reported that

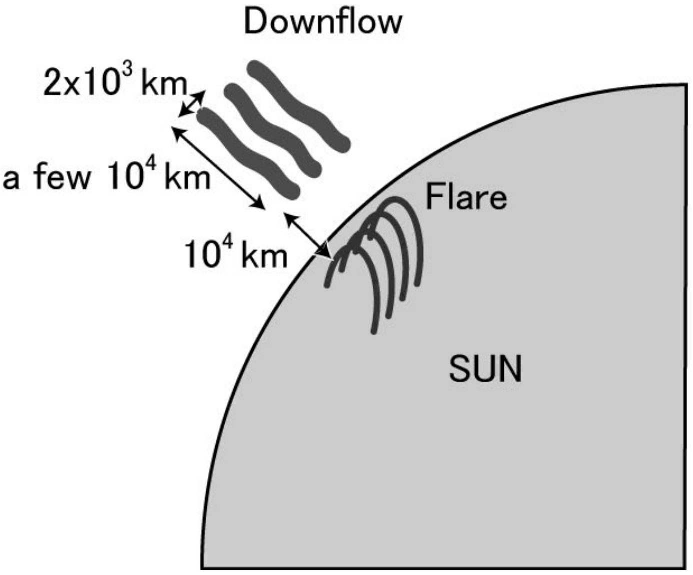

Figure 3. Cartoon of the downflows associated with a flare.

the downflows consist of low density and high temperature plasma of about 10^9 cm^{-3} and 10^7 K, although these values contain considerable uncertainties.

To examine such high temperature plasma, observations by Solar-B/XRT are required. Flares which occur near the solar limb are suitable to observe such faint and upper coronal features. They sometimes appear 1–5 × 10^4 km above post-flare loops. The width of downflow is about 2000 km ($\sim$ 3 arcsec) or larger, and the length is about a few times of 10^4 km (Fig. 3). Apparent velocity has been reported to be about 50–450 km s^{-1}, based on a statistical study about Yohkoh/SXT downflows (McKenzie 2000). Innes, McKenzie, & Wang (2003b) reported high Doppler velocity is associated with downflows by using SOHO/SUMER spectroscopic data. To confirm this, observation by Solar-B/EIS is needed. Moreover, duration of each downflow is fairly short and about a few minutes, and therefore, high time cadence, which is less than 5 second, is required. We summarize these physical parameters in Table 2.

Table 2. Physical parameters about downflows (Mc: McKenzie 2000; In: Innes et al. 2003b)

Apparent velocity	45–500 km s^{-1}	(Mc)
Doppler velocity	< 1000 km s^{-1}	(In)
Width	> 2000 km	
Length	a few $\times 10^4$ km	
Temperature	$\sim 10^7$? K	(Mc)
Column density	a few $\times 10^{27}$ cm^{-5}	(In)
Density	$\sim 10^9$ cm^{-3}	(Mc)

4. Summary and Discussion

We have examined in detail the evolution of a big two-ribbon flare which occurred on 2002 July 23. We found downflows above the post-flare loops in the impulsive phase, which is associated with impulsive nonthermal emissions. Furthermore, they appear to correspond to the times when nonthermal bursts in microwaves and HXRs occurred. This result implies that the downflow motions occurred when strong magnetic energy was released, and suggests that they are correlated with reconnection outflows. Thus, we have been able to add a new piece of observational evidence to the model that downflows are reconnection outflow (McKenzie & Hudson 1999; McKenzie 2000). We have also discussed observations of the downflows by Solar-B. It may help to explain what the downflows are.

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