ERUPTING FLUX ROPE, RISING X-RAY SOURCE AND A SLOW CME ON 16 APRIL 2002

C.P. Goff[1], L. van Driel-Gesztelyi[1,2,3], L.K. Harra[1], S.A. Matthews[1] & C.H. Mandrini[4]

[1]*MSSL, University College London, Holmbury, Surrey, RH5 6NT, UK, lvdg@mssl.ucl.ac.uk*
[2]*LESIA, Observatoire de Paris, FRE 2461 (CNRS) F-92195, France, Lidia.vanDriel@obspm.fr*
[3]*Konkoly Observatory, Pf. 67, H-1525, Budapest, Hungary, vandriel@konkoly.hu*
[4]*IAFE, CONICET-UBA, CC. 67, Suc. 28, 1428 Buenos Aires, Argentina, mandrini@iafe.uba.ar*

ABSTRACT

A long-duration event (LDE) linked to a slow coronal mass ejection (CME) was observed at the NW solar limb on 16 April 2002. A multi-wavelength analysis involving TRACE, RHESSI, SOHO/EIT, CDS and LASCO observations as well as magnetic modelling (SOHO/MDI) provided several new pieces of evidence supporting the classical LDE/CME scenario: the event started with the eruption of a filament, which was found to have helical mass motions when crossing the CDS spectrograph slit situated 50" above the limb. Rising with the filament, a coronal X-ray source was identified as a plasmoid originating from the interaction between upward reconnection outflow and the closed magnetic structure of the erupting filament. We also found down-flows of plasma in hot, newly reconnected flare loops and an exponential acceleration of the erupting filament between the TRACE and LASCO/C2 fields of view.

1. INTRODUCTION

The most popular, though not universally accepted, model of coronal mass ejections (CMEs) belongs to the storage and release models (Klimchuk, 2000). Here a slow build-up of magnetic stress precedes the onset of some kind of instability. The CME starts with the rise of an active region filament (and its overlaying arcade) due to an eruptive instability. Then, below the rising filament as the stretched field lines start to reconnect, an impulsive energy release occurs. In the main flare phase continuing reconnection forms hot X-ray loops and Hα ribbons at their footpoints, where the particles accelerated during the reconnection process impact the chromosphere. As field lines increasingly distant from the magnetic inversion line reconnect, the reconnection region rises. Therefore the resulting X-ray loop footpoints and the Hα ribbons move apart. The initial instability may be triggered by (i) a twisted flux tube, where the twist or height of the filament is too great (kink instability, see e.g. Török and Kliem, 2005); or (ii) a sheared magnetic arcade, in which free magnetic energy is built up by shearing motions (e.g. Mikic and Linker, 1994) and the overlying field gets weakened/removed by magnetic reconnections (Antiochos, DeVore and Klimchuk,1999).

Most CME studies are based on coronagraph data, which are limited to observations above a certain altitude. By the time the CME has reached the point of detection, it has normally finished accelerating and continues at a constant velocity (St. Cyr et al., 1997). A few recent analyses of filament rise in the lower corona revealed periods of exponential acceleration (Gallagher et al., 2003; Vrsnak, 2001, Williams et al., 2005), suggesting the effect of some kind of instability. Regardless of the mechanism, the plasma and associated magnetic field are accelerated from the low atmosphere at velocities that can reach in excess of 1000 km s^{-1}. The event presented here is significantly slower than the average CME speed and therefore observations of the acceleration profile of the CME, before it reaches the coronagraph field of view, can provide valuable insights into the underlying process.

Below a lifting flux rope/CME a long current sheet forms and magnetic reconnection is expected to start, accelerating particles and forming shocks traveling both towards the solar surface and upwards. The downward moving shocks reaching the reconnected flare loops form a loop-top hard X-ray source (Masuda et al., 1994). Related to upward moving reconnection outflow and shock, moving high-temperature (15 MK) source has been reported by Tsuneta (1997) in an LDE. This plasmoid formed during the impulsive phase, above the X-point (the presumed magnetic reconnection region), and rose with a velocity of 96 km s^{-1}. Ohyama and Shibata (1998) found an X-ray plasma ejection (a

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small, blob-like feature, suggestive of a closed-field plasmoid) above soft X-ray flare loops in Yohkoh/SXT observations of an LDE. Due to the symmetrical nature of the reconnection, outflows must occur both upward as well as downward and it is believed that the upward flows are responsible for the plasmoid. However, these earlier findings did not establish, through multi-wavelength observations, the link between the rising plasmoid and the erupting filament.

The event we present was part of a homologous series (14-16 April 2002) first analysed by Veronig and Brown (2004) and Sui et al. (2004). This paper concentrates on the last flare/CME of this series. We analyse an extensive array of data and will use this to investigate the acceleration of the CME, as well as a rising coronal hard X-ray source and its relationship to the erupting filament.

2. OBSERVATIONS AND MODELLING

An LDE linked to a slow CME was observed at the NW solar limb on 16 April 2002. We carried out a multi-wavelength and multi-instrument analysis of this event involving TRACE 195 Å, RHESSI hard X-ray, SOHO/EIT EUV, time-series of CDS Fe XIX spectra taken 50" above the solar limb, LASCO/C2 observations as well as magnetic modelling (SOHO/MDI). We present the results in a series of Figures (1-7) below and summarise our findings in Section 3.

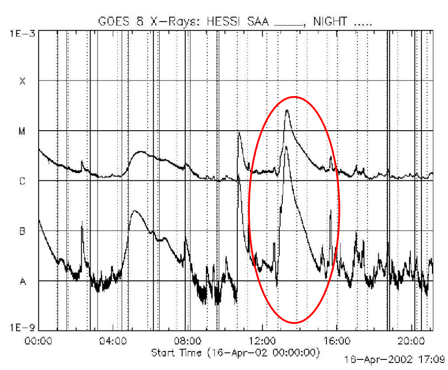

Figure 1. GOES light-curve on 16 April 2002 with the studied long-duration event (LDE) encircled.

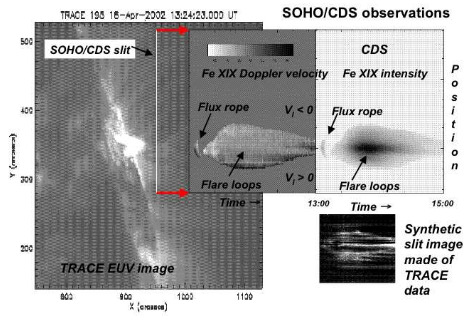

Figure 2. Left panel: TRACE image with the position of the CDS slit indicated. Upper right panels: CDS time series of Doppler velocity and intensity images in the hot Fe XIX line. CDS was in "sit and stare" mode. Lower right panel: TRACE image slices mimic the CDS intensity data. In these CDS time series we first see the passage of a crescent-like feature, a mirror image of the erupting filament observed by TRACE. The red-, then blue-shifted velocity indicates helical flows. After this we expect the passage of the current sheet, or reconnection region – featureless in CDS. The broadening feature, observed somewhat later represents velocity in growing flare loops: red-shifted on the South, blue-shifted on the North.

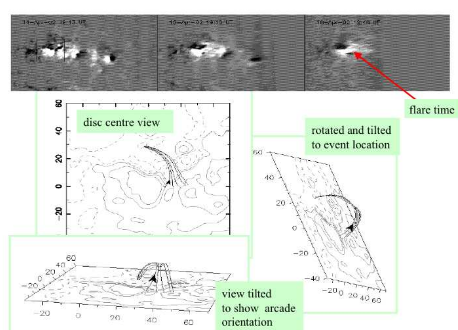

Figure 3. Magnetic field lines extrapolated in the linear force-free approximation (α=0.015 Mm^{-1}) using a SOHO/MDI magnetic map two days prior to the event in the region shown in the MDI magnetic field map on 14 April above. The extrapolations were carried out to provide the best match between computed filed lines and observed flare loops. Magnetic modelling enables us to determine the (3-D) spatial orientation of the flare loop and in combination with Doppler velocities observed by CDS allows us to deduce the direction of plasma flows along the loops.

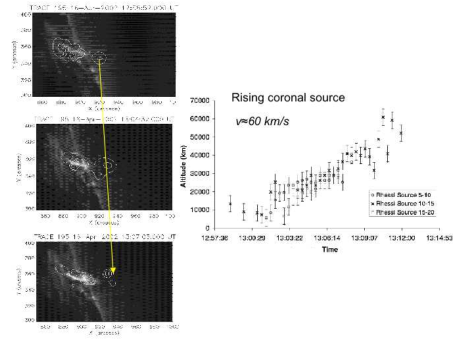

Figure 4. RHESSI 10-15 keV contours (made with the PIXON method; left panels, over-plotted on TRACE images) show a rising coronal X-ray source with a speed of about 60 km s^{-1}. Images reconstructed in the energy ranges of 5-10 keV and 15-20 keV showed a very similar trend, as the hight-time plot combining these three energy ranges indicates.

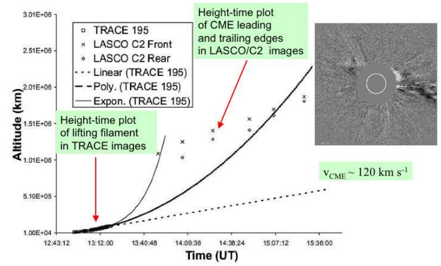

Figure 6. Hight-time plot combining TRACE data for the lifting filament and LASCO/C2 data for the leading and trailing edges of the CME. An exponential growth makes the link between the two curves, while neither the linear nor the polynomial fit can reach the required height by the appearance time of the CME. The right-hand panel shows the start of the CME in the NW quadrant at 13:50 UT (LASCO/C2 observation).

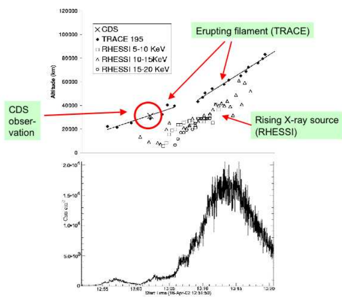

Figure 5. Upper panel: height - time plot of the lifting flux rope as seen by TRACE. The cross in the red circle represents the leading edge of the flux rope as seen by CDS. Below the best-fit lines are data points from the coronal hard X-ray source. The HXR source follows the rising filament keeping a distance of about 20,000 kms. Lower panel: HXR RHESSI light curve between 5-50 keV.

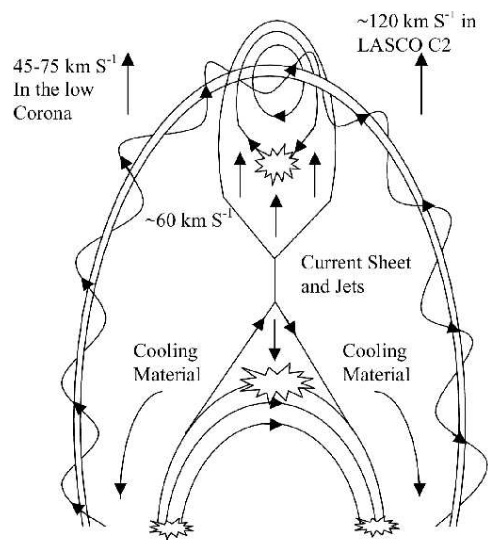

Figure 7. Cartoon summarizing different aspects of the event learned from the combination of multi-wavelength and multi-instrument observations. Some elements of this cartoon follows the one by Shibata et al. (1995).

3. SUMMARY AND CONCLUSIONS

An eruptive flare/coronal mass ejection (CME) event on 16 April 2002 was observed on the NW limb. The GOES light-curve showed a long-duration event (LDE; Fig. 1.). The event started with a lifting filament observed by TRACE in 195 Å; CDS observations indicated the helical (flux rope) nature of the structure (Fig. 2). Similar helical flows in an erupting filament were reported by Pike and Mason (2002).

Under the erupting filament a rising hard X-ray source (v~60 km s^{-1}) was observed by RHESSI (Fig. 4). The latter showed no velocity signal measurable with CDS. The CDS slit, which was positioned about 50" above the limb, started to observe a velocity signal in the hot Fe XIX line after the passage of the rising RHESSI source and the start of the flare (Fig. 2). The redshift-blueshift pattern (blue-shifted on the North, red-shifted on the South) was broadening as the underlying cusped EUV flare loops were getting taller (Fig. 2). Magnetic modelling in the linear force-free approximation, using SOHO/MDI observations, indicated that the North legs of the flare loop arcade point away from us, while the South legs point towards us (Fig. 3). The CDS Doppler velocity observations combined with the magnetic field model indicated down-flow of material along hot, newly reconnected loops.

Combining hight-time plots of the rising filament and rising X-ray coronal source (Fig. 5) we find that they were rising together, the X-ray source keeping an about 20,000 km distance from the filament. These observations suggest that the coronal X-ray source is not the heated up filament but rather an interaction region between (upward) reconnection outflows/shocks and the closed magnetic system of the filament/flux rope.

Using LASCO C2 observations we combined the height-time profiles of the rising flux rope and the white-light CME (Fig. 6). We found that the rising flux rope must grow exponentially before reaching constant speed and getting into the LASCO/C2 field of view.

These observations support classical CME scenarios in which the eruption of a filament showing helical motions precedes flaring activity. Cusped flare loops appear when the eruption of the flux rope is under way and the height of the flare loops increases with time. The rising hard X-ray source is interpreted as an interaction site between the upward directed reconnection outflow and the closed magnetic structure of the erupting flux rope. Connecting the height-time profile of the erupting filament in TRACE data to the one of the CME, we find evidence for an exponential acceleration phase, indicating MHD instability of the erupting structure. More details of this analysis are published in Goff et al. (2005).

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