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Post–CME events: cool jets and current sheet evolution

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Abstract. In this work we focus on UVCS data acquired during the November 2002 SOHO–Ulysses quadrature, at an altitude of 1.7 $R_\odot$ over a range of latitudes centered around 27°N in the western quadrant. A couple of hours before our observations started, a CME event (November 26, 17:00 UT) originating at about 27°N, disrupted the coronal configuration of the region.
In the $\sim$ 2.3 days following the event UVCS detected emission in the neutral H $Ly\beta$ and $Ly\gamma$ lines as well as in lines from both high and low ionization ions such as C III, O VI, Si VIII, IX and XII, Fe X and XVIII. Enhanced emission from the hot Fe XVIII ion ($\log T_{max} = 6.7$), lasting nearly to the end of our observations and originating in a region between 10°N and 30°N, has been identified with a post–CME current sheet. Our interpretation is supported by EIT Fe XII images which show a system of loops at increasingly higher altitudes after the event. Northward of the CME, UVCS observed repeated, sudden and short lived emission peaks in the "cool" $Ly\beta$, $Ly\gamma$, C III and O VI lines. These events seem to be the extension at higher altitudes of the chromospheric plasma jets observed in the EIT He II images. Electron temperatures of both the hot and cool region will be presented here and their time evolution will also be illustrated.

Keywords. Sun: coronal mass ejections (CMEs), UV radiation.

1. Introduction

Many CMEs have been observed by SOHO instrumentation: the combination of white light (LASCO coronagraphs) and EUV (EIT telescope) images with UV spectral data (CDS, SUMER and UVCS instruments) have provided a comprehensive view of Coronal Mass Ejections (CMEs) structure and evolution. However, mainly because of the uncertainties in the determination of their three–dimensional structure (as they are always seen projected onto the plane of the sky) and in the coronal magnetic field measurements, this phenomenon is far from being completely understood. Recent theoretical works (see e.g. Lin *et al.* 2004) suggest that magnetic reconnection can play a key role, in particular in the CME development and the plasma heating during and after the eruption. CME models predict that open magnetic fields relax, via magnetic reconnection, into a closed configuration, with the formation, between the chromosphere and the ejected bubble, of a current sheet (CS); moreover reconnection heats the plasma converting magnetic energy into kinetic and thermal energies. In the last few years, observations made by the UVCS instrument (see, e.g., Akmal *et al.* 2001; Ciaravella *et al.* 2002; Ko *et al.* 2003) described CSs as long lasting ($\sim$ 2 days) structures with high plasma temperature ($\log T \sim 6.6$ – 6.8 K), as inferred from the observed Fe XVIII emission. Such temperatures have been also observed *in situ* by ACE as high Fe charge state associated with ICMEs (Lepri *et al.* 2001; Lepri & Zurbuchen 2004). However, the CS evolution and the explanation for its very long lifetime are still under discussion.

Figure 1. The coronal morphology in the North-West quadrant as seen by LASCO/C2 coronagraph from the beginning (left panel) to the end (right panel) of UVCS observations; in the figure we show also the position of the UVCS slit.

In this work we focus on CME data acquired over ~ 2.3 days by UVCS instrument during the SOHO–Sun–Ulysses quadrature (Suess *et al.* 2000; Poletto *et al.* 2002; Bemporad *et al.* 2003a; Suess *et al.* 2004) of November 2002. In section 2 we describe the post–CME evolution as seen in LASCO and EIT images, while in section 3 we describe the UVCS observations and data analysis. The origin for the high temperature plasma observed by UVCS is discussed in section 4, while in section 5 we focus on the comparison with Ulysses *in situ* data. A short discussion of our results concludes the paper.

2. LASCO and EIT observations

As shown in figure 1, on November 26, 2002 LASCO/C2 (*Large Angle Spectroscopic COronagraph*, see Brueckner *et al.* 1995) images show in the NW quadrant two coronal streamers centered at about 10°N and 50°N (hereafter, respectively, "streamer 1" and "streamer 2"). Starting from about 17:00 UT a CME occurs on the northward side of streamer 1: a plasma bubble is ejected at a latitude of about 27°N with an initial speed (as we estimate from LASCO images) of ~ 120 km/s. The CME partially disrupts streamer 1, which appears displaced southward by about 7° after the event; on the contrary, streamer 2 seems to be unaffected by the CME.

EIT (*Extreme ultraviolet Imaging Telescope*, see Delaboudiniere *et al.* 1995) Fe XII images show, in the NW quadrant, two Active Regions (ARs USAF/NOAA 10197 and 10199) respectively at 25°N and 28°N, close to the position of the southward edge of streamer 2. These ARs approximately cross the solar limb on November 26-27: if the CME material originates from these ARs, the plasma is likely to propagate mainly on and around the plane of the sky. Moreover, before and after the CME, EIT He II images show recursive ejections of chromospheric plasma from these ARs. Radial speeds of these short lived $(30 - 60$ $min)$ jets, evaluated from the variation with time of their altitude, are strongly variable with time ($\sim$ 20–200 km/s) and the motion of each jet has peculiar kinematical properties. On the plane of the sky the plasma is ejected at an angle of about 20°N with respect to the radial from the Sun, hence towards latitudes higher than $25 - 28$°N.

3. UVCS observations

3.1. *UVCS instrumental settings*

The UVCS (*Ultra Violet Coronagraph Spectrometer*, see Kohl *et al.* 1995) observations start on November 26, 18:39 UT (left panel in figure 1) and last through November 29, 02:56 UT (right panel). This time interval (~ 2.3 days) is covered with a time resolution

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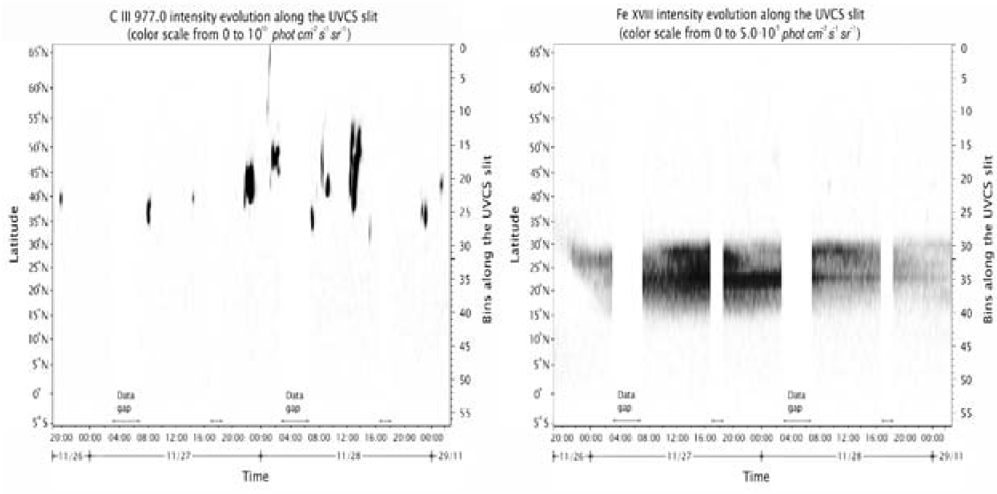

Figure 2. Intensity evolution along the UVCS slit for the "cool" C III ($\log T_{max} = 4.9$, left panel) and the "hot" Fe XVIII spectral lines ($\log T_{max} = 6.7$, right panel).

of 120 s and some gaps in the observations cut the total observing time to $\sim$ 1.8 days (see also Bemporad *et al.* 2003b for a preliminary analysis of the initial $\sim$ 7 hours of observations). The spectrometer slit is at an altitude of 1.7 $R_\odot$ and is centered at a latitude of 27°N (North – West quadrant), as shown in figure 1; the slit width was 100 μm. In this position UVCS observes the solar corona between the latitudes of 5.8°S and 67.3°N with a spatial binning of 42 $arcsec/bin$. Because at the beginning of UVCS observations the CME flux rope is, in LASCO images, between $\sim$ 2.4 and 2.6 $R_\odot$, hence above the UVCS slit height, in this work we focus on the post CME evolution. The UVCS grating position has been choosen in order to observe line emission from ions with both high and low temperature of maximum formation T_{max}, such as the O VI 1031.91 Å – 1037.61 Å ($\log T_{max} = 5.5$), the Si XII 520.67 Å – 499.37 Å ($\log T_{max} = 6.3$) and the Si VIII 949.35 Å – 944.47 Å ($\log T_{max} = 5.9$) doublets, the Si IX 950.15 Å ($\log T_{max} = 6.0$), the H $Ly\beta$ 1025.67 Å and $Ly\gamma$ 972.54 Å, the Fe X 1028.06 Å($\log T_{max} = 6.0$), Fe XV 481 Å ($\log T_{max} = 6.3$), Fe XVIII 974.86 Å ($\log T_{max} = 6.7$), C III 977.02 Å ($\log T_{max} = 4.9$) and Ca XIV 943.61 Å ($\log T_{max} = 6.5$) lines; these lines are observed with a spectral binning of 0.1986 Å$/bin$. The line intensities are derived summing over the line profile and subtracting an average background evaluated over a spectral interval near the line.

3.2. *UVCS data analysis & interpretation*

As shown in figure 2 (left panel), many peaks in the C III spectral line intensity are detected by UVCS in the northward half of the UVCS slit. Because of the very low T_{max} value of the C III ion, this spectral line is usually absent in coronal spectra. Taking into account a), the position and time when these "cold" C III peaks appear in the UVCS slit and b), the analogous evolution of other "cold" spectral lines like $Ly\beta$ and $Ly\gamma$, we conclude that we are sampling the low temperature ($T \approx 8 \times 10^4$ K) plasma jets observed in the EIT He II images. Doppler line shifts up to 250 km/s indicate that these jets have also a strong inclination away from the plane of the sky.

As shown in figure 2 (right panel), between the latitudes of $\sim$ 15 – 30°N, UVCS data reveal intense emission from the Fe XVIII ion, whose T_{max} is unusually high for coronal plasma even above ARs (see e.g. Ko *et al.* 2002). At the latitude where the main Fe XVIII

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974.4 Å emission is concentrated (2.5°N) the line intensity increases continuously up to a value of about $4.2{\cdot}10^9\, phot\, cm^{-2} s^{-1} sr^{-1}$ on November 27, ∼15:30 UT. Such intensity increase is unusual, because the energy released by reconnection is expected to decrease with time. Over the following hours, the Fe XVIII emission decreases down to $\simeq 1.0 \cdot 10^9\, phot\, cm^{-2} s^{-1} sr^{-1}$ at the end of UVCS observations (November 29, 02:56 UT). At the same latitude the Fe XV line intensity, initially undetectable, increases progressively up to a value of $4.6{\cdot}10^8\, phot\, cm^{-2} s^{-1} sr^{-1}$ at the end of UVCS observations. To understand this peculiar behaviour of different spectral lines from the same element, we have to consider that in coronal conditions, spectral lines form mainly by electron collisional excitation followed by spontaneous emission. Hence in general, the line intensity I_{line} is:

$$I_{line} = \frac{1}{4\pi} \int_{LOS} \epsilon_{line} n_e^2 \, dl \quad ; \quad \epsilon_{line} = h\nu_{line} \frac{n_{el}}{n_H} \frac{n_{ion}}{n_{el}} (T_e)\, B_{line} q_{line}(T_e)$$

where n_{el}/n_H is the elemental abundance relative to H, n_{ion}/n_{el} is the ionic fraction, q_{line} is the collisional excitation rate (both function of the electron temperature T_e), B_{line} is the branching ratio for the line transition, n_e is the electron density and ϵ_{line} is the line emissivity. From this formula we can see that, in first approximation, the ratio between the observed intensities of spectral lines from different ions of the same element is equal to the ratio between their emissivities, hence depends only on T_e: this implies that from the observed ratio we can estimate T_e. Using the Fe XV/Fe XVIII line intensity ratio observed at 22.5°N and the theoretical line emissivities from the CHIANTI spectral code (v. 4.01, computed with the ionization equilibria of Mazzotta *et al.* 1998), we find $\log T_e > 6.94$ at the beginning of our observations, followed by a continuous, slow decrease over the following ~ 2.3 days down to $\log T_e \simeq 6.52$. The Fe XVIII intensity increase and the following decrease can be explained with the continuous decrease in T_e we derived, because the $\epsilon_{FeXVIII}$ peaks at $\log T = 6.7$. For the same reason, because the ϵ_{FeXV} peaks at $\log T = 6.3$, the plasma cooling gives rise to a continuous increase in the Fe XV intensity. In the next section we discuss the origin of this high temperature plasma.

4. The post–CME high temperature plasma

Because the position of the Fe XVIII 974.4 Å main emission and the CME ejection latitude are about the same, we identify this high temperature plasma as the CS, associated with the post CME magnetic field reconfiguration. However, the slow T_e decrease we derived might as well be ascribed either to plasma cooling inside the CS or to plasma cooling in the newly closed loops. To distinguish between these possibilities we need to know whether, during our observations, the height of the rising neutral point (approximately equal, at each time, to the height of the last newly formed loop) was below or above the height of the UVCS slit. The speed of the rising neutral point depends on the local Alfvèn speed, hence is in general unknown. However, EIT images show a system of newly formed loops after the CME above the ARs: the loops rising speed is, on average, nearly constant and equal to $\sim$1.8 km/s: with this speed, it takes 3.4 days for the rising neutral point to reach the UVCS slit (0.7 $R_\odot$ above the solar limb). We conclude that, during our observations, the neutral point could not have reached the height of the UVCS slit: hence, we are looking at the CS plasma. Moreover, order of magnitude estimates of the conductive and radiative cooling time for a semi–circular loop of height of 0.7 $R_\odot$ shows that the loops cool mainly by conduction over times on the order of 1h, hence much faster than the slow cooling we may infer from the temperature vs. time profile derived from the line ratio technique: again, we conclude that the high temperature plasma we observe with UVCS was not in closed loops, but inside the CS.

5. Ulysses *in situ* observations

During the November 2002 quadrature the Ulysses spacecraft was at a distance of about 4.3 AU. The November 26, 2002 CME has been identified with the *in situ* plasma (see Poletto *et al.* 2004) observed at Ulysses on 14–15 December, 2002 (DoY 348–349). During this time interval the Ulysses/SWICS (*Solar Wind Ion Composition Spectrometer*) instrument observed an unusual abundance of the high charge ion (Fe^{16+}), in agreement with remote observations of high temperature plasma in the aftermath of the CME event, implying that the source temperature was $\sim$ 6–7.5$\cdot 10^6$K. We refer the reader to Poletto *et al.* 2004 for further details on the association between coronal and *in situ* plasma.

6. Conclusions

In this brief paper we have provided evidence for the presence of a CS in the aftermath of a CME event, as inferred from UVCS observations of very hot plasma at the position where closed loops form at increasingly high altitudes. While this is not the first time that CS have been observed by UVCS, this event is unique in that the behavior of the CS has been followed over a two day time interval and evidence for the same hot plasma sampled in the corona has been found *in situ* at about 4 AU. We have given here a qualitative view of the electron temperature profile with time at the current sheet position, showing how temperature slowly decreases with time. A more thorough description of the physical properties of the post-CME ambient is in progress (Bemporad *et al.* 2005). Jets of "cold" plasma have been detected over the same time interval when the hot CS plasma was observed, but there is apparently no relationship between the cold jets and the behavior of the reconnecting magnetic field in the CME region.

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Discussion

BOTHMER : Why are the conclusions unambiguous? - i.e, why is the hot coronal plasma really the one seen at Ulysses?

BEMPORAD: The quadrature geometry allows us to identify the plasma sampled at Ulysses with the CME plasma remotely observed by SOHO by extrapolating backwards from the time of Ulysses observations to the time when the plasma was ejected from the Sun. The extrapolation has been made using, as a first approximation, the average solar wind speed; then this first extrapolation has been refined taking into account typical CME signatures such as counterstreaming electrons, magnetic clouds, low plasma β and high α particles flux.