Mem. S.A.It. Vol. 78, 600

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Results from recent studies of CMEs with SOHO/UVCS

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Abstract. In this work we review recent results obtained in the study of Coronal Mass Ejections (CMEs) from analysis of data acquired by the UltraViolet Coronagraph Spectrometer (UVCS) on SOHO. These studies gave us the opportunity to identify, during an event observed on November 2002, the presence of a Current Sheet (CS) formed as a consequence of the post–CME magnetic reconnection. We derived the temporal evolution of CS physical parameters, at present not completely known and essential for the development of better CME models. In a second study, based both on UV and white light pB observations of an event occurred on January 2000, we inferred the density and temperature distribution in the core of a CME and in the surrounding region.
In a further research area we studied CME events characterized by a small angular extension (narrow CMEs): in a first work we proposed a mechanism for their production, while in a second work we derived physical parameters of the plasma ejected in a series of homologous events. At present other studies are in progress, focussing on the CSs development from the time they first appear at lower coronal levels up to the time they reach higher heliocentric and interplanetary distances, where these structures are observed by respectively white light coronagraphs in *in situ* instruments.

Key words. Sun: coronal mass ejections – UV spectroscopy – WL observations.

1. Introduction

Coronal Mass Ejections (CMEs) are sporadic events (~ 1 event/day as an average over a solar cycle) where a mass on the order of 10^{14}–10^{16}g is ejected into the solar corona with speed of ~ 500 – 1500 km/s. In white light images these events appear to have a large variety of geometrical shapes such as complex curved and twisted helical structures, expanding arcades, hemispherical shells, unstructured "narrow" eruptions, etc... This large morphological variety is related both to intrinsic differences in the events and to projection effects due to their different propagation angles. Despite these differences, in the larger events it is often possible to identify a typical three-part structure: a bright arc–shaped front (the *leading edge*) surrounding a dark cavity (the *void*) and including a bright prominence *core*. In the last decade UV observations from the SOHO mission gave relevant informations on the distribution of physical parameters in these events; nevertheless the temperature structure within the CME bubble is still debated and there are only a few studies on possible plasma heating source within CMEs.

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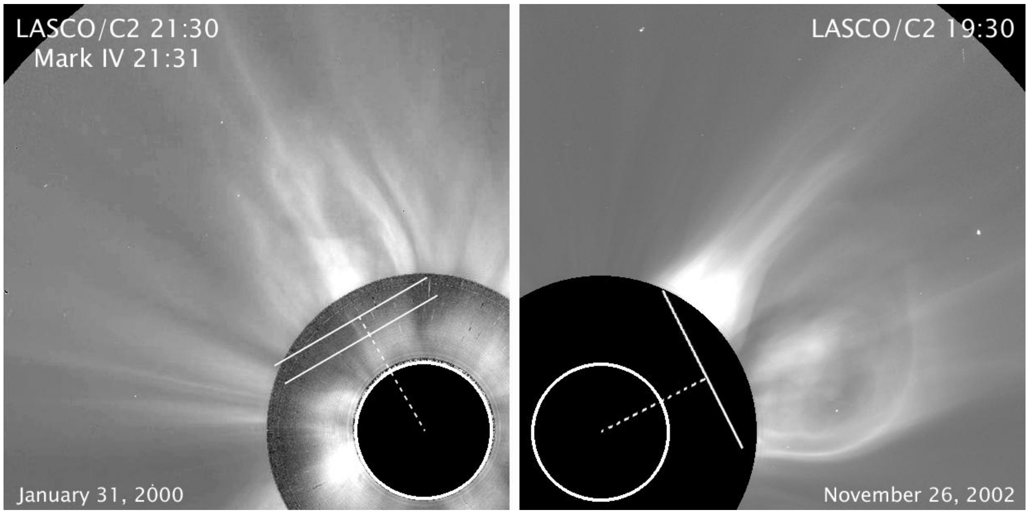

Fig. 1. The January 31, 2000 (left) and November 26, 2002 (right) CMEs as seen by the SOHO and Mauna Loa coronagraphs; solid white lines show the position of the UVCS slit during our observations.

In this paper we briefly review the main results recently obtained at the Arcetri Astrophysical Observatory on the study of CMEs from data acquired by the SOHO UV Coronagraph Spectrometer (UVCS; see Kohl et al. (1995)) and other SOHO instruments. In the next paragraph (§ 2) we concentrate on the physical parameters of a CME in its early stages and on the evolution of a post–CME Current Sheet (CS). In the following paragraphs we review recent results on narrow CMEs (§ 3) and briefly describe the future perspectives of our work (§ 4).

2. Evolution of the CME bubble and the post–CME CS

Recently Bemporad et al. (2007) analyzed a CME that occurred on January 31, 2000 in the North-East quadrant, centered at a latitude of ∼ 60°N (Fig. 1, left). This slow event (∼ 100 km/s at 2 $R_\odot$) was observed in white light by the SOHO/LASCO coronagraphs and by the Mark IV Coronameter at the Mauna Loa Observatory. The CME started around ∼18:00 UT on January 31, 2000. UVCS acquired data from 17:05 UT on that day to February 1, 02:00 UT, with the spectrometer slit centered alternatively at 1.6 and 1.9 $R_\odot$ at the CME latitude; hence we have simultaneous observations in UV and pB of the early CME evolution below the LASCO lower occulter edge.

The observed pB intensity depends only on the spatial distribution along the line of sight of the plasma electron density n_e, while the UV line intensities depend also on the plasma electron temperature T_e, the elemental abundances N_X and, for lines which have a radiative component, on the plasma outflow speed v_{out}. In this work we had the rare opportunity to disentangle the n_e from the (T_e, N_X, v_{out}) dependence of the UV intensities during the CME. We first estimated n_e from the observed pB and v_{out} from the CME rising speed; then, assuming typical coronal streamer abundances, we derived the value of T_e in the front, void and core that allows us to reproduce the intensities of the Lyman-α λ 1216 Å, O vi λ 1032 Å and Si xii λ 1040 Å lines.

From this technique we found that during the CME transit at 1.6 $R_\odot$ density increases by respectively 34%, 26% and 47% in the front, void and core over a background density of $7.6 \cdot 10^6$ cm^{-3}, i.e., as expected, the density maximizes at the core. On the contrary, we got an unexpected result from the T_e determination: the CME core region turns out to have a temperature of about $2.8 \cdot 10^6$ K (∼ 76% higher than the $1.6 \cdot 10^6$ K background corona and ~ 40% higher than the CME front), hence, opposite to what envisaged in some CME models (see e.g. Lin et al. (2004)), in this event T_e maximizes at the core. Moreover, from a comparison between the 1.6 and 1.9 $R_\odot$ data, we inferred a temperature increase during the CME propagation by about 10%, opposite to the common belief that the CME temperature decreases in the expansion via adiabatic cooling. This new result seems to be confirmed by laboratory experiments on the free expansion of plasma spheromaks (Yee & Bellan 2000), where the dissipation of magnetic energy leads to a plasma heating that dominates over the cooling by adiabatic expansion. A similar behaviour has been predicted also by Kumar & Rust (1996) who found that the conservation of magnetic helicity in an expanding flux rope requires a dissipation of magnetic energy leading to plasma heating.

In another work (Bemporad et al. 2006) we concentrated on the evolution of a post–CME CS: in particular on November 26, 2002 a CME occurred in the North–West quadrant, centered at a latitude of about 30°N (Fig. 1, right). The CME started before 16:00 UT and the UVCS data, acquired with the spectrometer slit centered at a latitude of 27°N and an altitude of 1.7 $R_\odot$, covered the time interval between November 26, 18:39 UT and November 29, 02:56 UT. Thanks to this very long time coverage (about 2.3 days) we had the unique opportunity to study the evolution of the plasma physical parameters in the post–CME CS.

Over those days the UV emission was characterized by a strong intensity in the Fe XVIII λ 975 Å line: the Fe XVIII ion has a temperature of maximum formation $T_{max} = 10^{6.7}$ K, hence unusually high for coronal plasma even above Active Regions (AR). In agreement with previous authors (see e.g. Ko et al. (2003)), we identified this line as a signature of the very high plasma temperature inside the CS. In the data analysis we then assumed that the CS was responsible for the whole Fe XVIII λ 975 Å observed emission, while spectral lines such as the O VI λ 1032 Å ($\log T_{max} = 5.5$), Si VIII λ 949 Å ($\log T_{max} = 5.9$) and Si IX λ 950 Å ($\log T_{max} = 6.0$) were typical of the lower temperature coronal plasma. This helped us in the separation between UV emission coming from the higher temperature CS and the lower temperature external corona.

With this separation we have been able to estimate, by using the standard line ratio techniques, plasma densities and temperatures inside and outside the CS. In particular we found that the temperature of the external corona keeps approximately constant around $10^{6.0}$ K, while, interestingly, the CS temperature decreases continuously from $T_e > 10^{6.9}$ K at the beginning of our dataset down to ~ $10^{6.5}$ K 2.3 days later. This is in agreement with the picture of a slow and progressive CS erosion and a decrease in the strength of the reconnecting magnetic fields. From the knowledge of plasma parameters inside and outside the CS we derived informations on the plasma heating: it turns out that adiabatic compression of coronal plasma flowing toward the CS can account for its high temperatures only at the end of our observations, while at earlier times other physical processes (ohmic or wave heating) have to be invoked. We note also that the November 26, 2002 event generated an Interplanetary CME (ICME) that has been detected about three weeks later by the Ulysses spacecraft, located at a distance of ~ 4.3 AU. In particular data acquired by the Solar Wind Ion Composition Spectrometer (SWICS) showed a Fe charge state higher than average solar wind values, leading us to unambiguously relate the high freeze–in temperatures observed *in situ* with their source in the low corona CS (Poletto et al. 2004).

3. Properties of Narrow CMEs

In a further part of our research we concentrated on the study of ejections characterized by a small angular extension (< 15°), dubbed "narrow CMEs". These events are interesting in that, according to Gilbert et al. (2001) and Dobrzycka et al. (2003), are neither ususal CMEs originated from expanding closed field structures, nor "UV jets", that are created by the reconnection with open field lines close to the coronal hole boundaries. Even if the surface association of narrow CMEs, thanks to their small angular extension, is in general unambiguously identified, the origin and evolution of these events are at present not well known.

In a first work (Bemporad et al. 2005) we had the opportunity to study a series of narrow homologous ejections occurring over 26–29 November, 2002 in the North-West quadrant. Images acquired by the SOHO Extreme UV Imaging Telescope (EIT) in the He II λ304 Å line show these events to originate from the same AR and to propagate outward in the LASCO C3 field of view. We classified these narrow ($\sim 5^\circ$) ejections as a new variety of CMEs, dubbed "streamer puffs": these events were different from previously studied narrow CMEs in that they originated from a compact explosion in the flank of a streamer leaving the streamer intact after the ejection. Moreover the transit of the ejected material into the UVCS field of view leads to sudden increases in the C III λ 977 Å and O VI λ 1032 Å line intensities, indicating a plasma temperature of $\sim 6 \cdot 10^4$K, much lower than observed in other eruptive events. In a more recent paper (Corti et al. 2007) the authors studied a series of short-lived ejections occurred between May 25–28, 2003 at the East limb and imaged by the EIT instrument in the He II filter. Spectra acquired by UVCS (with the spectrometer slit centered at an heliocentric distance of 1.7 $R_\odot$) showed unusually high emission in cool lines, lasting for about 10–25 minutes. From the observed evolution of the C III, O VI and Hydrogen Lyman-β λ 1025 Å lines the authors concluded that these jets have a constant temperature over their lifetime lower than $\sim 2 \cdot 10^5$K. The extrapolated potential magnetic field line configuration indicates that these events were probably produced by the reconnection of closed loops in an AR with adjacent open field lines (similar to what happens for the production of UV jets). Moreover Corti et al. (2007) concluded that, neglecting energetic particles, the energy fed via magnetic reconnection into the jets is mostly gravitational, while thermal energy is much smaller.

4. Future perspectives

Magnetic reconnection has been invoked as the process responsible for small and large scale solar eruptive events. Hence, in the next future we will focus on the study of CS properties from the lower solar atmosphere to distances of the order of a few astronomical units; this will be done by using white light data from LASCO, UV spectra from UVCS, data from other SOHO instruments and data acquired by the Ulysses instruments during the SOHO–Sun–Ulysses quadratures.

We recently selected three events observed by UVCS: a couple of CMEs that occurred on May 28, 2004 in the South-East quadrant and a third CME that occurred on December 11, 2005. These events are interesting in that, respectively, UVCS data show a clear signature of reconnecting X–point transit and the formation of a post–CME secondary CS. Understanding and fully characterizing reconnection signatures by inferring their physical parameters would be of tremendous help for comprehending solar eruptive phenomena and for their modeling. We expect the analysis of data of these events will provide us with new important informations on the plasma physical conditions favouring magnetic reconnection.

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