LINKING REMOTE IMAGERY OF A CORONAL MASS EJECTION TO ITS IN SITU SIGNATURES AT 1 AU

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ABSTRACT

In a case study (2008 June 6–7) we report on how the internal structure of a coronal mass ejection (CME) at 1 AU can be anticipated from remote observations of white-light images of the heliosphere. Favorable circumstances are the absence of fast equatorial solar wind streams and a low CME velocity which allow us to relate the imaging and in situ data in a straightforward way. The STEREO-B spacecraft encountered typical signatures of a magnetic flux rope inside an interplanetary CME (ICME) whose axis was inclined at 45° to the solar equatorial plane. Various CME direction-finding techniques yield consistent results to within 15°. Further, remote images from STEREO-A show that (1) the CME is unambiguously connected to the ICME and can be tracked all the way to 1 AU, (2) the particular arc-like morphology of the CME points to an inclined axis, and (3) the three-part structure of the CME may be plausibly related to the in situ data. This is a first step in predicting both the direction of travel and the internal structure of CMEs from complete remote observations between the Sun and 1 AU, which is one of the main requirements for forecasting the geo-effectiveness of CMEs.

Key words: interplanetary medium – solar – terrestrial relations – Sun: coronal mass ejections (CMEs)

Online-only material: animations

1. INTRODUCTION

Coronal mass ejections (CMEs) are violent expulsions of plasma and magnetic flux from the outer solar atmosphere. Understanding their propagation characteristics and their internal structure is one of the main goals of the NASA twin-spacecraft STEREO (Kaiser et al. 2008). Recently, there have been many efforts to obtain the direction of propagation of CMEs both close to the Sun and in interplanetary space (e.g., Mierla et al. 2008; Themisien et al. 2009; Temmer et al. 2009; Davies et al. 2009). Using interplanetary observations by the STEREO Heliospheric Imagers (HIs; Eyles et al. 2009; Harrison et al. 2009), Davis et al. (2009) were able to predict the CME direction of propagation and arrival time at Earth with good accuracy. However, a major issue in forecasting the geo-effects of a given CME is its orientation and its internal magnetic field since long-duration southward fields lead to strong geomagnetic activity (e.g., Farrugia et al. 1993; Zhao & Hoeksema 1998). Thus, the above-mentioned techniques need to be compared with the magnetic field and plasma signatures of CMEs as measured in situ in the solar wind (interplanetary CMEs, ICMEs). Those ICMEs containing a rotating magnetic field vector are particularly suited for these comparisons. These are generally called magnetic flux ropes (MFRs), and may be magnetic clouds (MCs) if they satisfy other criteria, namely, above-average magnetic field strengths B, low proton temperature (T_p) and beta (\beta_p), and a large rotation of B (Burlaga et al. 1981).

Using SOHO/LASCO coronagraph images, Cremades & Bothmer (2004) have shown that CMEs have a different morphology seen along or perpendicular to the axis of symmetry. In this Letter we relate, for the first time, both the morphology and direction of a CME seen with the STEREO-HI instrument imaging the heliosphere to properties of the associated ICME measured in situ. Our study thus extends previous efforts to predict the magnetic field orientation in MFRs from solar disk and coronagraph observations (e.g., Bothmer & Schwenn 1998; Yurchyshyn et al. 2001; Yurchyshyn 2008). The big advantage is that the CME can be seen in the HI images from a distant spacecraft (STEREO-Ahead) passing over the other spacecraft (STEREO-Behind) at 1 AU, thus bridging the gap between remote and in situ observations that existed before the STEREO era.

The CME in question left the Sun at 21:00 UT, 2008 June 1 and its front boundary arrived at STEREO-B at 22:39 UT on 2008 June 6. In previous work, Robbrecht et al. (2009) used coronagraph and on-disk extreme-ultraviolet (EUV) images to show that this CME was not accompanied by typical on-disk signatures (filament eruption, flare, dimming, EUV wave), the main reason being that the CME was of the streamer-blowout-type lifting off slowly from high in the corona (R_⊙ ≈ 1.15–1.4). This previously unrecognized type of CME is a good candidate for causing so-called “problem storms,” i.e., those without an obvious solar origin (e.g., Zhang et al. 2007). In this Letter, we complement and extend the study of Robbrecht et al. (2009) by modeling STEREO-B observations to obtain a more complete view of the MFR inside the ICME at 1 AU and discuss how its structure and direction could have been forecast from remote observations. CME–ICME events suitable for this kind of study are very rare during this unusually quiet solar minimum (see Davies et al. 2009; Möstl et al. 2009a). This event is extraordinarily well suited for this kind of analysis because (1) the absence of equatorial coronal holes (and thus fast solar wind streams) allows a straightforward interpretation of the HI images (Lugaz et al. 2008) and (2) it is a slow CME, justifying partly an assumption of constant velocity inherent to one of the applied techniques.
2. IN SITU OBSERVATIONS OF THE ICME AT STEREO-B

At 00:00 UT, 2008 June 7, STEREO-B was 25:38 east of Earth at 1.0545 AU and STEREO-A 29:26 west at 0.9567 AU, with a separation of 54:64. Figure 1 plots STEREO-B magnetic field data in Radial–Tangential–Normal (RTN) coordinates and plasma bulk parameters at 1 minute resolution, from the IMPACT/MAG (Acuña et al. 2008; Luhmann et al. 2008) and PLASTIC (Galvin et al. 2008) instruments, respectively. STEREO-B encountered an MFR between 22:39 UT, 2008 June 6 and 12:27 UT, 2008 June 7 (inner two vertical solid lines). This interval is partly an outcome of our reconstruction technique (see Hu et al. 2004) and partly determined by eye so that it encompasses the smoothly rotating B vector.

The two outer solid lines indicate a forward ($t_s$ = June 6 15:35 UT) and a very weak reverse shock ($t_r$ = June 7 20:48 UT), see, e.g., Gosling et al. (1998). There are two clear proton enhancements of $N_p \approx 30$ cm$^{-3}$ on either side of the MFR, the first one being, in part, the sheath behind the forward shock. The front of the second density peak arrives at $t_c \approx 12:00$ UT, June 7. For most of the MFR, $T_p$, is higher than that expected for normal solar wind expansion (red trace; Lopez 1987). This precludes the MFR from being an MC.

We modeled these data using Grad–Shafranov reconstruction (Hu & Sonnerup 2002) and force-free fitting (the latter shown in parentheses; Lepping et al. 1990). (For recent multi-spacecraft validation of the GS method, see Liu et al. (2008) and Möstl et al. (2009a, 2009b)). The MFR is right-handed with an axis orientation of $\theta = 51(37)^\circ$, $\varphi = 278(326)^\circ$ in RTN coordinates ($\theta$ is the inclination to the RT plane, $\varphi$ is measured from R ($0^\circ$) toward T ($90^\circ$)). Thus, the MFR axis points roughly northeast as shown in Figure 2. The modeled axial field strength $B_0 = 15.4 (20.3)$ nT, the radial scale size (diameter) $D = 0.130(0.155)$ AU, and the impact parameter (the closest distance of the spacecraft to the MFR axis) is $p = 0.81(0.60) \times D$. The toroidal and poloidal magnetic fluxes are $\Phi_t = 0.72(0.37) \times 10^{21}$ Mx and $\Phi_p = 1.19(1.47) \times 10^{21}$ Mx AU$^{-1}$. These values are rather typical for ICMEs which are associated with medium-sized flares (Qiu et al. 2007).

Figure 2 shows a three-dimensional plot of the local MFR reconstruction in the heliosphere (color contour) in a coordinate system centered on STEREO-B, seen from north looking down on the RT plane (close to the solar equatorial plane, top) and from another viewpoint (bottom). For further details see the text.

(An animation of this figure is available in the online journal.)
CME Directions and Velocities from Various Techniques

| Technique                  | Instruments | $R_\odot$ | $\Phi$ (deg) | $V$ (km s$^{-1}$) |
|----------------------------|-------------|----------|--------------|------------------|
| Triangulation (TR)         | C2/C3 COR2A| 3–14     | $-45 \pm 5$  | 235              |
| Forward modeling (FM)$^a$  | COR2A/COR2B| 2–15     | $-37 \pm 10$ | 265              |
| Elongation fitting (EF)$^b$| HI1A/HI2A  | 15–226   | $-26(\pm 25)\pm 3$ | 401 (340) $\pm 15$ |
| Kinematic fixed-$\Phi$ (KP)$^b$ | HI1A/HI2A | 80–226   | $-30(\pm 26)\pm 5$ | 440 $\pm 120^\circ$ |
| In situ modeling           | IMPACT/PLASTIC | 226 | $-24$ to $-39$ | 403/392/384$^d$ |

Notes. Angle $\Phi$ is the longitude measured from the Earth (negative means eastward). $R_\odot$ gives the distance from the Sun of the observations used for the respective technique and $V$ is the velocity for this distance range.

$^a$ Taken from Thernisien et al. (2009).

$^b$ Results for the CME core are in brackets after those for the leading edge.

$^c$ Here $V$ is the median velocity from 80–226 $R_\odot$ in a $V(r)$ plot. In this range $V(r)$ is roughly constant.

$^d$ The in situ $V$ are means over the sheath region, the deHoffmann–Teller velocity of the MFR region, and a mean over the second density peak, respectively.

4. CME THREE-PART STRUCTURE AND HELIOSPHERIC PROPAGATION

We now compare the results of direction-finding results applied close to the solar surface (2–20 $R_\odot$) with those used in the interplanetary medium (20–220 $R_\odot$), and the ICME structure at 1 AU.

First, the elongation $\epsilon(t)$ of the LE and core were manually measured in the HI FoVs and fitted with the Sheeley et al. (2008) formula (e.g., Rouillard et al. 2008; Davies et al. 2009) to infer a constant velocity and direction (see Table 1) as well as the arrival times (18:34 UT, June 6 [LE] and 13:08 UT, June 7 [core]). The technique assumes that the CME is well represented by the features tracked in the white-light images which result from line-of-sight integration and Thomson scattering effects (Vourlidas & Howard 2006). The error bars for the direction and velocity follow from an error in $\epsilon(t)$ of $\pm 3^\circ$. The arrival times correspond very well with the arrival of the two density peaks on either side of the plasma void region (dashed vertical lines in Figure 1). It thus becomes plausible how, in this case, the classic CME features seen in coronagraphs (Illing & Hundhausen 1985) correspond to the ICME observations. The extended bright front, with the LE as its outermost edge, corresponds to the interval of the first density enhancement reaching up to the MFR; the void or dark cavity is the MFR; and the core is the dense material trailing the MFR. We speculate that each double density peak bracketing the MFR in Figure 1 arises from material originating in the corona (innermost density peaks adjacent to the MFR) and solar wind swept up by the CME in interplanetary space (outermost peaks), i.e., the sheaths (see also Riley et al. 2008).

Figure 4 presents the time–distance plot from Sun to Earth. To convert $\epsilon(t)$ to distance from the Sun $r(t)$ in Figure 4, two simple...
methods have been put forward: the “Point-P” and “Fixed-$\Phi$” methods (Kahler & Webb 2007; Wood et al. 2009). Basically, Point-P assumes that the CME’s LE is a spherical front centered on the Sun, which yields (Howard et al. 2007)

$$r(t) = d \sin \epsilon(t),$$

where $d$ is the distance of the observer from the Sun. Fixed-$\Phi$ assumes the CME to be point-like, propagating radially along a constant angle $\Phi'$ to the observer,

$$r(t) = \frac{d \sin \epsilon}{\sin (\epsilon + \Phi')}.$$

The results are shown in Figure 4. Linking the observations with the timing $t_s(t_c)$ when the CME LE (core) hits STEREO-B located at 226 $R_\odot$, the angle $\Phi$ can be derived with $\Phi = -30(-26)^\circ$. (Angle $\Phi$ is measured from Earth, while $\Phi'$ is measured from an observer, negative means east of Earth.) In Figure 2, the mean of the two directions is plotted. It is also seen in Figure 4 that until $r \approx 140 R_\odot$ or 0.62 AU, the Point-P and Fixed-$\Phi$ methods yield quite similar values for $r(t)$, with $r(t)$ being slightly lower for Point-P close to the Sun (see also Wood et al. 2009). After this, the unphysical assumption of Point-P that the CME cannot be tracked farther than $d$ leads to a divergence from Fixed-$\Phi$ to smaller values of $r(t)$.

We now compare the directions obtained from the interplanetary techniques with direction-finding techniques derived from coronagraph observations. Figure 4 (inset) shows the kinematics of a distinct feature along the CME leading edge, one that could be observed and measured from LASCO C2/C3 and COR2A images. As the feature is seen from different viewing angles, the de-projected propagation direction of the CME is derived by applying a geometrical triangulation method as described in

\textbf{Figure 3.} Evolution of the CME in STEREO-A HI1 (top four images) and HI2 (bottom four images), compared to Figure 2. Earth (E), STEREO-B (B) are indicated as well as the elongation of Mercury. The tracked features of the CME leading edge and core for Figure 4 are given by yellow crosses. The last image was taken approximately at the shock arrival time at STEREO-B (15:35 UT). Note the distinct appearance of the CME in both fields of view as an arc-like shape, i.e., a CME seen perpendicular to the axis of symmetry. (Animations of this figure are available in the online journal.).

\textbf{Figure 4.} Time–distance plot of the CME leading edge and core. The elongation of the features in the HI images has been converted to distance by using the Point-P and Fixed-$\Phi$ methods ($\Phi = -30^\circ$ for the leading edge and $\Phi = -26^\circ$ for the core). The in situ measured arrival times $t_s$ (shock) and $t_c$ (core) are indicated as “×” at the position of STEREO-B (226 $R_\odot$). The inset shows the STEREO-A/COR2 and SOHO/LASCO observations used for the TR method.
used instruments, radial outward motion of CME). However, underlying assumptions (the same CME feature distinguished in between the averaged velocities of the two in situ density peaks L184 Möstl et al. (2009). The same feature has been tracked in the STEREO-B equator, and the measurements for EF and KP were also taken within that range. This also means that STEREO-B encounters the apex or nose of the CME and not one of its “legs.”

The CME velocities clearly show an acceleration between the coronagraphs and the heliospheric imagers as well as a consistency of the latter with the proton bulk velocities as measured in situ. From EF a velocity difference of ΔV = 60 km s⁻¹ between the leading edge (401 km s⁻¹) and the core (340 km s⁻¹) is consistent with ΔV = 49 km s⁻¹ between the MFR front and back boundary. These are values typical of ICMEs at 1 AU during solar minimum (ΔV ≈ 60–70 km s⁻¹: Jian et al. 2006; compared to 45 km s⁻¹ found by Burlaga & Behannon 1982). Note that both are larger than ΔV = 19 km s⁻¹ between the averaged velocities of the two in situ density peaks which correspond to the white-light features.

5. CONCLUSION

We described observations of a CME as it propagates from the Sun to 1 AU and detailed the relationship to its modeled in situ signatures. From this we found various interesting clues useful for forecasting the geo-effects of CMEs.

1. How can the internal structure of the MFR be inferred from remote observations? The distinct arc-like morphology points to an inclined MFR axis and, from the intensity evolution perpendicular to the ecliptic plane (northern part vanishes earlier than the southern), we estimated θ ≈ ±45°. The MFR’s axis and poloidal field directions are consistent with the global solar dipole field (see the PFSS model in Robbrecht et al. 2009) and indicated by black arrows in Figure 2: the poloidal field goes from south to north and the eruption comes from the southern hemisphere, which yields a right-handed MFR (as observed), and thus an axial field to the east (away from the observer, thus θ ≈ +45°, φ ≈ 270°). The MFR’s axial field at the Sun is likely to be close to the solar equator. This can be seen in an accompanying movie in Robbrecht et al. (2009), which shows a more compact CME shape closer to the Sun in accordance with the Crema”es & Bothmer (2004) interpretation. A slight subsequent clockwise rotation (consistent with positive chirality for a twist-to-writhe conversion) of roughly 45° would then match the MFR observations.

2. Is the direction of the CME obtained from various direction-finding techniques consistent with the observations at 1 AU? Yes, within the error bars all methods we use give a consistent picture. There seems to be a minor offset to the west when techniques are applied closer to the Sun. Concerning the latitudinal direction, TR and FM yielded results to within ±5° latitude of the solar equator, and the measurements for EF and KP were also taken within that range. This also means that STEREO-B encounters the apex or nose of the CME and not one of its “legs.”

The tools and concepts we developed allow a first comparison between three-dimensional CME directions and modeled in situ data of those ICMEs that contain MFRs or MCs. Modeling ICMEs is important in order to obtain good estimates of their orientations and impact parameters, and where the spacecraft intersects the axis (the eastern/western part of the central MFR south/north). Our results underline the need of having coronagraphs and instruments which image the heliosphere between the Sun and the Earth from a vantage view-point away from Earth so as to enhance our ability to forecast the geo-effects of CMEs.

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