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RADIO SIGNATURES OF CORONAL MASS EJECTION INTERACTION: CORONAL MASS EJECTION CANNIBALISM?

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ABSTRACT

We report the first detection at long radio wavelengths of interaction between coronal mass ejections (CMEs) in the interplanetary medium. The radio signature is in the form of intense continuum-like radio emission following an interplanetary type II burst. At the time of the radio enhancement, coronagraphic images show a fast CME overtaking a slow CME. We interpret the radio enhancement as a consequence of shock strengthening when the shock ahead of the fast CME plows through the core of the preceding slow CME. The duration of the radio enhancement is consistent with the transit time of the CME-driven shock through the core of the slow CME. As a consequence of the interaction, the core of the slow CME changed its trajectory significantly. Based on the emission characteristics of the radio enhancement, we estimate the density of the core of the slow CME to be ~4×10^4 cm^{-3}. The CME interaction has important implications for space weather prediction based on halo CMEs: some of the false alarms could be accounted for by CME interactions. The observed CME interaction could also explain some of the complex ejecta at 1 AU, which have unusual composition.

Subject headings: solar-terrestrial relations — Sun: corona — Sun: coronal mass ejections (CMEs) — Sun: flares — Sun: prominences — Sun: radio radiation

1. INTRODUCTION

Long-wavelength radio emission in the decameter-hectometric (DH) wavelengths (21–280 m or 1–14 MHz in frequency) has proven to be an important diagnostic for understanding very energetic coronal mass ejections (CMEs) propagating into the outer corona and interplanetary (IP) medium (Kaiser et al. 1998; Gopalswamy et al. 1999; Reiner & Kaiser 1999). The DH type II bursts have been to shown to be due to CMEs that are faster and wider than the average CMEs (Gopalswamy et al. 2000). Observations in DH wavelengths have confirmed a number of previous results from kilometric observations and provided new insights on the IP propagation of CMEs. In this letter, we report on a new spectral feature: a remarkable sudden enhancement in type II radio emission at very low frequencies. We identify this new spectral feature with the interaction between a fast and a slow CME in the IP medium at a distance of more than 10 $R_\odot$ from the Sun center. We also discuss the origin of the enhanced radio emission and the implications of CME interaction for the understanding of CME propagation.

2. OBSERVATIONS

On 2000 June 10 the Radio and Plasma Wave Experiment (WAVES) on board the *Wind* spacecraft (Bougeret et al. 1995) detected an unusual feature at the low-frequency end of a narrowband type II burst recorded in the dynamic spectrum of the high-frequency radio receiver known as RAD2. RAD2 operates in the frequency range 1.075–13.825 MHz, a new radio window open since the launch of the *Wind* spacecraft in 1994 November. The corresponding wavelength range is referred to as the DH regime (Gopalswamy et al. 2000). Figure 1 shows the dynamic spectrum of the event from 16:30 to 19:30 UT on 2000 January 10. The event was marked by intense type III–like bursts (the intense vertical features during 16:55–17:30 UT) followed by an extremely narrowband type II burst (the thin slanted feature) with no obvious fundamental-harmonic structure. The type II burst starts at ~17:12 UT at 10 MHz and drifts down to 2.5 MHz at ~18:05 UT. At 18:12 UT, a sudden broadband radio enhancement followed the type II burst and lasted until 18:48 UT. The enhancement also showed a fundamental-harmonic structure, with a much weaker harmonic. The fundamental component had a central frequency of about 2 MHz with no frequency drift.

Since all the DH type II bursts are associated with CMEs (Gopalswamy et al. 2000, 2001), we examined the white-light images of the corona obtained by the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*) mission. The DH type II burst was indeed associated with a fast CME that had a plane of the sky speed of 1095 km s^{-1} measured at a position angle of 300°. The CME originated from the northwest quadrant of the Sun and was associated with an intense flare (M5.2) from Active Region 9026 (N22°, W38°) starting at 16:37 UT. The real speed could be as high as 1780 km s^{-1} if one takes into account the projection effect. The event was also associated with a metric type II burst observed between 16:55 and 17:18 UT. The CME was first observed in the field of view of the inner coronagraph (C2) of LASCO at 17:08 UT, above the west limb, consistent with the solar source.

The radio enhancement occurred about 1 hr after the appearance of the CME in the LASCO/C2 field of view, so we examined for unusual features in the coronagraphic images around the time of the radio enhancement. There was indeed a slow CME moving northward in projection. The slow CME

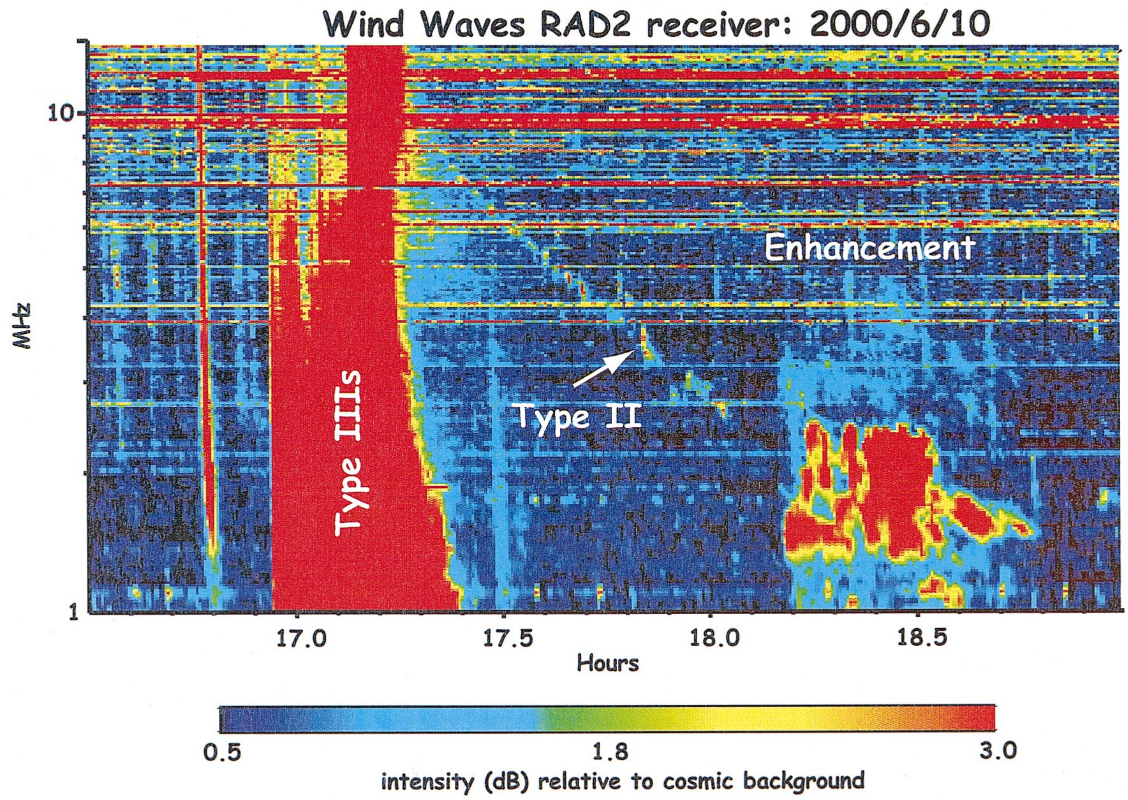

FIG. 1.—*Wind*/WAVES dynamic spectrum in the 1–14 MHz range obtained by the RAD2 receiver. The vertical features are type III–like bursts due to electron beams escaping from the shock along open field lines. The thin slanted feature is the type II burst. The enhancement in question is the bright emission between 18:12 and 18:48 UT. A faint harmonic emission can be seen above the bright emission.

had started much earlier, first appearing in the C2 field of view at 05:30 UT. The LASCO images in Figure 2 show the progression of the two CMEs as the fast CME (CME2) approaches the slow one (CME1). The slow CME was not spectacular and was relatively narrow. However, it had a bright core (see the 14:08 UT image), which seems to have originated from the filament eruption at N52°, E29° (Solar-Geophysical Data, 2000 June). The 17:30 UT image shows that the span of the fast CME extends beyond the central position angle of the slow CME. In the 18:18 UT image, we can see that the fast CME has overtaken the core of the slow CME. In the 21:18 UT image, the fast CME has moved beyond the core of CME1, altering the trajectory of the latter significantly.

Comparing the timings of the events in Figures 1 and 2, we can see that the radio enhancement corresponds exactly to the time of the interaction between the two CMEs. There was no other feature in the LASCO field of view that could be considered as an alternative source of radio enhancement. Therefore, we are confident that the radio enhancement is a direct consequence of the interaction between the two CMEs.

3. ANALYSIS AND INTERPRETATION

In order to study the dynamics of the CME interaction, we have plotted the height-time history of the two CMEs in the top panel of Figure 3. For the fast CME (CME2), the height-time history corresponds to a position angle (P.A.) of 0°, the central P.A. of the slow CME. Along this P.A., the fast-CME speed was 660 km s^{-1} with a deceleration of ~10.6 m s^{-2}, although its maximum speed was 1095 km s^{-1} at P.A. = 300° (with a similar deceleration). The leading edge of the slow CME (CME1) could be measured only until about 17:30, which gives an average speed of 290 km s^{-1} with an acceleration of 6.7 m s^{-2}. The core of CME1 showed significant change in trajectory at the time of interaction: the acceleration increased from 2.25 m s^{-2} to 2.9 m s^{-2} (by ~30%). The average speed of the core also doubled between the preinteraction and postinteraction intervals. The duration of the type II enhancement is shown by two vertical dotted lines corresponding to the interval 18:12–18:48 UT.

Another dramatic display of the CME interaction can be seen in the bottom panel of Figure 3, where we have plotted the position angle of the core of CME1. Early on, the core was moving slightly westward, starting from P.A. = 5° and reaching P.A. = −4° (356°) just before the interaction. It was then deflected eastward when the fast CME collided with it and ended up at P.A. = 9°. The sharp change in P.A. occurs during the period of radio enhancement and beyond (see also the LASCO/C3 images in Fig. 2).

Since the fast and slow CMEs originated from N22°, W38° and N52°, E29°, respectively, we can infer the separation between the two CMEs as 67° in longitude and 30° in latitude. This is also consistent with the separation (60° in P.A.) between the central position angles of the two CMEs (0° for the slow CME and 300° for the fast). Note that this separation is smaller than the width of the fast CME (192°). Based on the solar sources, we would expect the slow CME to be closer to the plane of the sky than the fast CME, but the size of the fast CME is large enough to cause a physical overlap between the two.

What is the origin of the radio enhancement? Note that the

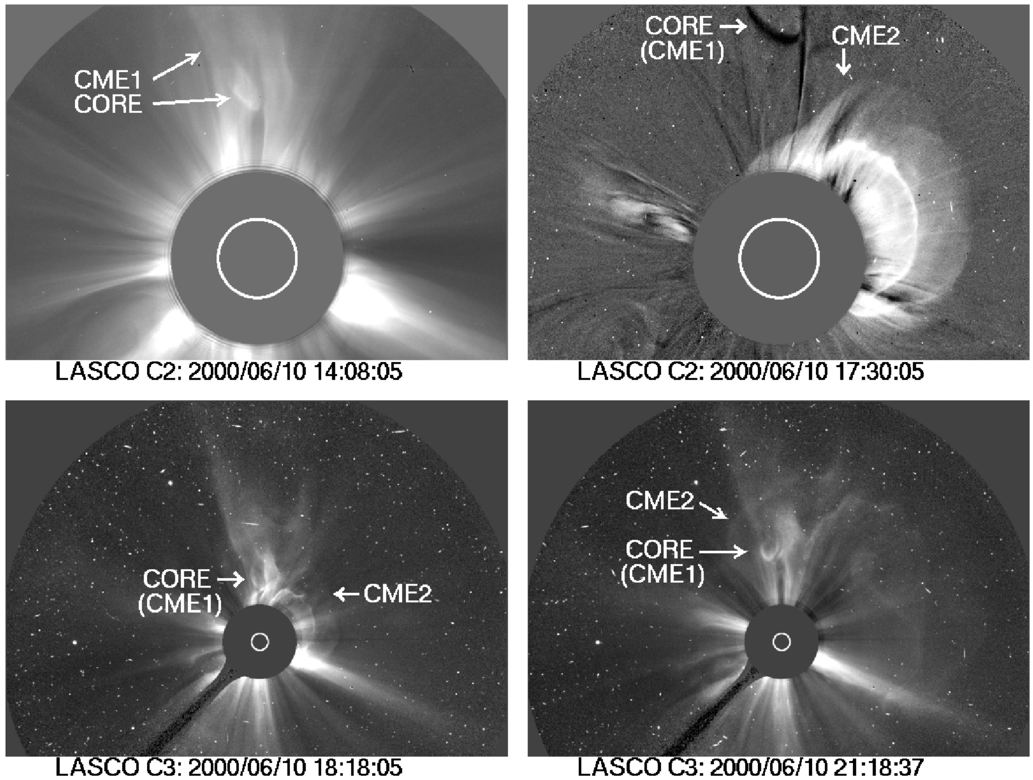

FIG. 2.—Series of *SOHO*/LASCO images showing the fast CME approaching the core of the slow CME. *Top left:* Slow CME (CME1) with its core in the LASCO C2 image at 14:08 UT. *Top right:* Fast CME (CME2) with its frontal structure and bright prominence core in the LASCO/C2 image at 17:30 UT. Note that the span of the fast CME extends beyond the central position angle of the slow CME. The top right panel is a difference image between the 17:30 and 17:08 UT images, so the core of CME1 appears as a dark feature. *Bottom left:* LASCO/C3 image at 18:18 UT obtained at the time of the radio enhancement. *Bottom right:* LASCO/C3 image at 21:18 UT showing that the core of CME1 is pushed to the left by CME2.

radio enhancement occurred at the low-frequency end of the DH type II burst, when the fast CME caught up with the slow one. We interpret the radio enhancement as a consequence of the propagation of the shock ahead of the fast CME through the core of the slow CME, thereby increasing the shock strength and accelerating electrons. The shock strengthens when it propagates through a region of low Alfvén speed. In the present event, the core of the slow CME has higher density and hence lower Alfvén speed. The magnetic field in the prominence core is expected to be higher than the ambient medium but might have diminished considerably because of expansion, so the net effect is to reduce the Alfvén speed in the core to a value less than that in the ambient medium. The central frequency of the fundamental component of the radio enhancement is ∼2 MHz. If the preceding type II burst was due to emission at the second harmonic of the plasma frequency (expected for close-to-limb events), then the ambient plasma frequency was ∼1 MHz, corresponding to an ambient electron density of $\sim 10^4$ cm^{-3}. Since the plasma frequency in the core is twice that of the ambient, the core electron density must be around 4×10^4 cm^{-3}.

The overall radial extent of the slow-CME core was $\sim 1.5\ R_\odot$. If the shock ahead of the fast CME had a speed close to the CME speed, then one would expect the shock to approach the slow-CME core with a speed of ∼550 km s^{-1} (speed of the fast CME along P.A. $= 360°$ minus the speed of the core of the slow CME). If the shock thickness was small compared to the size of the core, the expected transit time is ∼32 minutes, consistent with the duration of the radio enhancement, 36 minutes.

Some caveats to the above interpretation are in order. The shock driven by the fast CME is expected to be all around the CME with highest speed at the nose and lower speeds at the flanks. The CME interaction occurs in the northern flank of the shock. We do not know from which part of the shock the type II burst originated because the radio observations do not have positional information. However, we do know that the radio enhancement is from the location of CME interaction. In this sense, the radio enhancement and type II burst correspond to the same shock, maybe at different locations. One can think of other mechanisms such as gyrosynchrotron emission due to energetic particles trapped in the core of CME2 from the fast shock. However, the radio enhancement has a fundamental-harmonic structure, which points to a plasma emission mechanism. One can also think about electron acceleration due to reconnection during the interaction period if the magnetic field geometry is appropriate.

4. DISCUSSION

It is important to note that the CME spans have to overlap and their trajectories need to intersect in order to realize an interaction within the range of the IP medium accessible to the WAVES RAD2 receiver in the DH domain. The DH domain roughly corresponds to about 3–10 $R_\odot$ for typical density distribution in the outer solar atmosphere (see, e.g., Gopalswamy et al. 2001). The DH type II bursts are indicative of shocks in the outer corona driven by fast and very wide CMEs, and therefore it is not surprising that we were able to detect CME interaction. During solar maximum when the activity is the largest, one would expect more interactions. The typical interaction scenario seems to be a slow CME followed by a fast

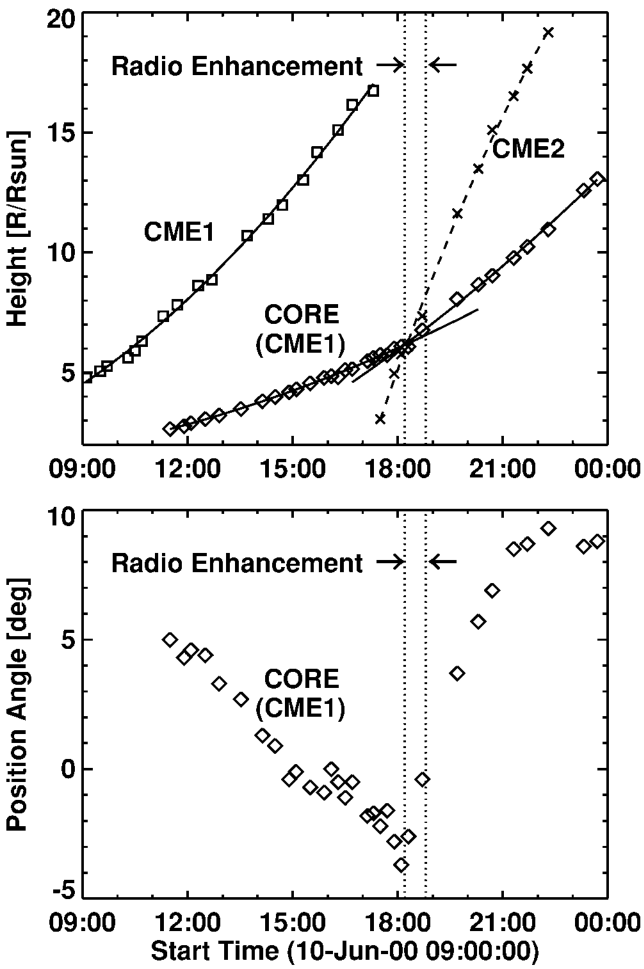

FIG. 3.—*Top:* Height-time plot of the slow and fast CMEs showing the sudden increase in the speed of the slow-CME core due to the impact of the fast CME. There is a sudden change in the speed of the slow-CME core at the time of type II burst enhancement (bracketed by the vertical dotted lines). *Bottom:* Time variation of the P.A. of the slow-CME core. Note the change in P.A. at the time of the impact, resulting in an eastward motion of the slow-CME core.

CME. Since this finding, we have identified a number of other events that show signatures of CME interaction. A detailed investigation of these events will be reported elsewhere.

CMEs are large-scale magnetic structures carrying ionized plasma. The physics of the interaction would therefore be very complex. One can speculate that the interaction between two CMEs may result in reconnection or simple piling up of the slower CME at the leading edge of the faster CME, resulting in a complex structure. Beyond the interaction region, one would expect a single CME consisting of magnetic field lines and plasma from both CMEs. We can describe this process as "CME cannibalism." The final structure and composition of the resulting CME would depend upon the nature of the interaction between the two CMEs. An analogous situation exists in the high-latitude solar wind: it is well known that high-latitude CMEs and the fast solar wind from coronal holes have similar composition (Galvin 1997). Even though the high-latitude CME originates from closed field lines and the fast solar wind originates from open field lines, they end up having similar composition, suggesting a possible interaction between the two magnetized plasma systems.

CMEs near the Sun typically consist of a frontal structure, a cavity, and a core of high-density cool material. As CMEs move away from the Sun, they expand, and hence the density decreases. Shocks ahead of the fast CMEs that catch up with slow ones might strengthen or weaken depending on the Alfvén speed in the preceding CME. In the present case, we saw that the core of the preceding CME was responsible for shock strengthening. The density of the slow CME itself (outside the core) was probably close to that of the ambient medium. When the preceding CME is also dense, one would expect appropriate changes in the radio dynamic spectrum.

5. CONCLUSIONS

We have presented evidence for interaction between CMEs in the interplanetary medium from long-wavelength radio and white-light observations. The interaction results in the enhancement of radio emission for the duration corresponding to the transit time of the fast-CME shock through the core of the preceding slow CME. The interaction severely affects the trajectory of the preceding CME core. From radio observations, we were able to determine the density of the core of the preceding CME to be $\sim 4 \times 10^4$ cm^{-3}, about 4 times greater than that of the ambient medium at a heliocentric distance of $\sim 6.5\ R_\odot$. The interaction between CMEs has important implications for space weather applications: (1) the interaction causing deflection can explain the lack of manifestations of some Earth-directed CMEs at 1 AU, and (2) it can explain composition anomalies of some CMEs at 1 AU (Gloeckler et al. 1999). This work might also help us understand the complex interplanetary ejecta reported by Burlaga et al. (2001), which consist of intervals of irregular fields and extended durations.

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