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Evidence for multiple ejecta: April 7–11, 1997, ISTP Sun-Earth connection event

D. Berdichevsky[1,4], J.-L. Bougeret[2], J.-P. Delaboudinière[3], N. Fox[1,4], M. Kaiser[4], R. Lepping[4], D. Michels[5], S. Plunkett[6], D. Reames[4], M. Reiner[1,4], I. Richardson[4,7], G. Rostoker[8], J. Steinberg[9], B. Thompson[4,10], and T. von Rosenvinge[4]

Abstract. Evidence is presented that the enhanced geomagnetic activity, on April 10-11, 1997, was caused by one of two ejecta that left the Sun at ≈14 UT on April 7. This ejecta was not directly detected at the Earth. The evidence for this interpretation is based on WIND spacecraft observations in the solar wind (SW). It is consistent with: (i) measured velocities of the coronal mass ejections from the SOHO coronagraph; (ii) the initial propagation speed of the shock generated in this event, estimation from type II radio burst observations from the WAVES instrument on WIND, and (iii) the time profile of energetic ions observed by EPACT on WIND. This locally unobserved ejecta (moving at 600 to 700 $\mathrm{km s^{-1}}$) generated a fast shock which accelerated ions to several tens of MeV/amu. The inferred passage of the first ejecta close to Earth (on April 10 to 11) is based on the observation of an interplanetary shock (IS) ahead of a field and plasma compressional region where the draping of the SW flow and possibly the changes in the direction of the IMF are consistent with a location northward of a faster ejecta. This ejecta was responsible for disturbed SW conditions including approximately ten hours of southward orientation of the interplanetary magnetic field (IMF) and a ram pressure many times above normal. The slower moving ejecta was directed toward Earth and was observed with WIND from about 0550 until 1500 UT on April 11. It had a strong northward IMF and produced density enhancements which elevated the ram pressure to more than four times above normal.

1. Introduction

Coronal mass ejections (CME) are massive emissions of material from local or extended regions of the solar corona caused by sudden magnetic field reconfigurations in the atmosphere of the Sun [e.g., *Gosling et al., 1974; Webb and Hundhausen, 1987*]. The Sun is currently in an interval of reduced activity (solar minimum) between approximately eleven year periods of highly increased activity (solar maxima); the last solar maximum occurred in 1990-91. Nevertheless occasional activity does occur.

On April 7, 1997, the LASCO/SOHO instrument [*Brueckner et al,* 1995] of the International Solar Terrestrial Physics (ISTP) program [*Acuña et al.,* 1995] observed a CME with a halo configuration suggesting that it was directed toward Earth. The WAVES/WIND instrument [*Bougeret et al.,* 1995] observed faint type II radio bursts which traced the progression of a shock wave through the higher corona. There were varying predictions of the time of arrival of the ejecta at Earth, the consensus being that it would arrive no later than 00 UT, April 10. This event may be related to the failure of about 20% of the communications satellite TEMPO-2 power supply on April 11th (*Space-News, May 5-11,* 1997). The SW disturbances resulted in above normal ram pressure and IMF intensities causing major geomagnetic activity.

The SW observations to be discussed here were obtained in the vicinity of the Earth (≈1 AU) by plasma and magnetic field instruments on WIND [*Ogilvie et al.,* 1995; *Lepping et al.,* 1995]. At 1 AU, a typical ejecta (the manifestation of the CME immersed in the ambient SW) has properties such as low plasma β (≈ 0.03 to 0.3), unusually high alpha to proton ratios, low proton temperatures and bi-directional flows consisting of energetic electrons and ions [*Zwickl et al,* 1983; *Gosling,* 1990]. An important subset of ejecta are the interplanetary magnetic clouds (IMC) [*Klein and Burlaga,* 1982; *Marubashi,* 1986], which are large flux ropes identified by their large IMF rotation over time scales of the order of a day.

2. Solar and SW observations

2.1 Solar activity near the April 7, 1997 event onset

A C6.8 solar flare (observed by the thermal X-ray instrument on the GOES-9 satellite) occurred in NOAA AR 8027 (24 to 33° South, and 11 to 31° East of disk center) on April 7, 1997, beginning at 1350 UT and peaking at 1407 UT. Soft X-ray emissions from the flare were also detected by the Yohkoh satellite, together with adjacent emission decrease or "dimming" event [*Sterling and Hudson,* 1997] which is a common signature of a CME. From 1359 to 1411 UT, multiple type III radio bursts were observed by the WAVES instrument on the WIND spacecraft (Figure 1).

These radio emissions are generated by highly energetic relativistic electrons, accelerated by the solar flare, propagating through the interplanetary medium.

One of the first observations of a class of large-scale coronal transients believed to be the coronal manifestations of Moreton waves [*Moreton,* 1960] was made by EIT/SOHO

[1]Hughes-STX Corporation, Greenbelt, MD 20770.
[2]DESPA/URA CNRS 264, Observatoire de Paris-Meudon, France.
[3]Inst. d'Astrophysique Spatiale, Université Paris XI, Orsay, France.
[4]NASA/Goddard Space Flight Center, Greenbelt, MD 20771.
[5]Naval Research Laboratory, Washington, DC 20375.
[6]USRA, Naval Research Laboratory, Washington, DC 20735.
[7]Dept. of Astron., University of Maryland College Park, MD 20742.
[8]Canadian Network for Space Res. & Dept. of Phys., U. of Alberta.
[9]Center for Space Research, MIT, Cambridge, MA 02139.
[10]Space Applications Corporation, Greenbelt, MD 20770.

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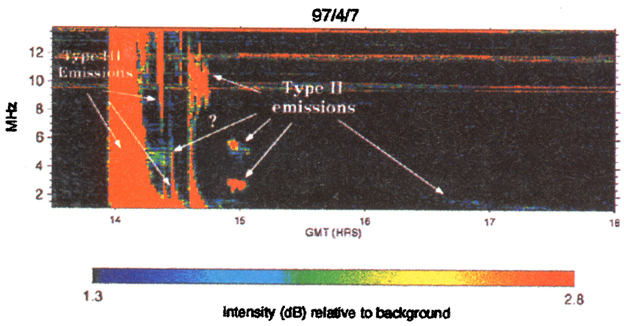

Figure 1. WIND/WAVES Type III and II radio bursts on April 7, 1997. Frequencies are plotted as a function of time and the color indicates the intensity of the radio emission (scale at the bottom of the figure). (GMT ≡ UT)

(Extreme Ultraviolet Imaging Telescope, [*Delaboudinière et al.,* 1995]) during this period. The wave observed by EIT appeared to propagate away from the flare over the entire visible surface of the Sun (Figure 2), at initial speeds of ~ 400 kms^{-1}.

The LASCO/SOHO C2 coronagraph [*Michels et al.,* 1997] observed a CME beginning at 1427 UT on April 7, 1997, as an expanding arcade of loops in the southeast direction (bottom left corner in Figure 3). This CME had a speed of ≈ 800 kms^{-1}, and probably originated from the same flare region AR 8027. This event may have destabilized nearby field configurations toward the center of the solar disk [*Howard et al., this issue*], triggering a CME extending all around the Sun (i.e. a "true halo event" [*Howard et al., 1982*]), clearly seen in the LASCO/SOHO coronagraph at 1500 UT (Figure 3). At a projected height above 3R_s (solar radius R_s ≈ 700,000 km) radial speeds of approximately 700, 500, and 450 kms^{-1} were measured in the south-west, north-west, and north-east directions, respectively [*Howard et al., this issue*]. This asymmetry in the expansion speed may mirror an asymmetric nature of the ejecta (perhaps the presence of multiple ejecta), or indicate that the ejecta was not directed exactly toward the Earth. The presence in the high corona of the shock driven by the CME was inferred from faint type II radio bursts detected intermittently by the WAVES/WIND instrument between 1436 and 1730 UT in the frequency range from 10 to 1 MHz (Figure 1) as the radio source moved away from the Sun. These radio observations, corresponding to estimated heliocentric distances from ≈ 3 to 15 R_s, are in the same range as the white light coronagraph images so that direct comparisons can be made. The estimated speeds obtained from the heights of the radio emissions range from 650 to 750 kms^{-1} and may be consistent with the halo CME. It is also possible, however, that these radio emissions were associated with the arcade-like southeast-directed CME or the Moreton wave.

In summary the solar observations suggest that multiple ejecta, or a complex structure, were propagating from the active region or nearby regions closer to the center of the solar disk, at velocities of 600 to 800 kms^{-1}, approximately radially toward the Earth. Assuming radial expansion away from the location of the solar event we might expect these structures to have been directed to the East of Earth and about 20° South of the solar equator (14° South of the Earth). Assuming constant velocity, the time of arrival of the event at Earth was predicted to be between 5 UT on April 9 and 3 UT on April 10.

Other signatures of the solar event were observed near Earth. The WIND energetic particle instruments EPACT/LEMT [*von Rosenvinge et al.,* 1995] observed an enhancement in the 2 MeV ion intensity starting about 1700 UT on April 7, two hours after the CME event (see Figure 4). Allowing two to three hours transport time for the particles from the Sun to the IMF lines well-connected to the Earth, the time of this surge is consistent with an event time of 1400 - 1500 UT. Observations from the Goddard particle experiment on IMP-8 show this enhancement extending to ≈ 70 MeV. Hence this was a more energetic event than the Jan. 6-11, 1997 Sun-Earth connection event, when almost no shock-energized particles (SEP) were observed.

2.2 Near-Earth Observations (April 7 to 12, 1997)

The SEP observations in Figure 4 provide a link between the solar phenomena on April 7 and solar wind structures observed ~3 days later [*Cane et al.,* 1988; *Reames et al.,* 1996]. The ion intensity remained enhanced on April 7-10 as accelerated particles streamed ahead of the CME-associated shock which arrived at WIND at 1255 UT on April 10, several hours later than predicted. The association between the particle enhancement and the shock, including a brief intensity increase at shock passage, suggests that the shock was related to one of

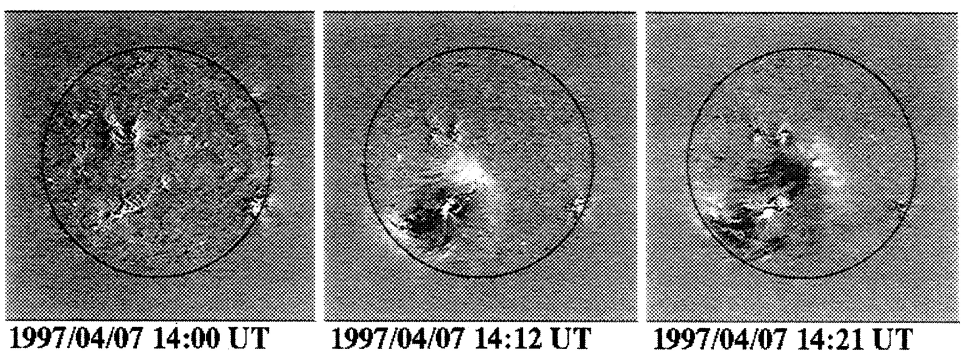

Figure 2. "Running difference" images showing the evolution of the "Moreton" coronal wave in the EIT 195 Å images. The first panel is the difference between images at 1400 and 1328 UT. Subsequent panels show the difference between an image and the previous one. The darker regions represents the wave location in the earlier panel. The circle = 1 R_s.

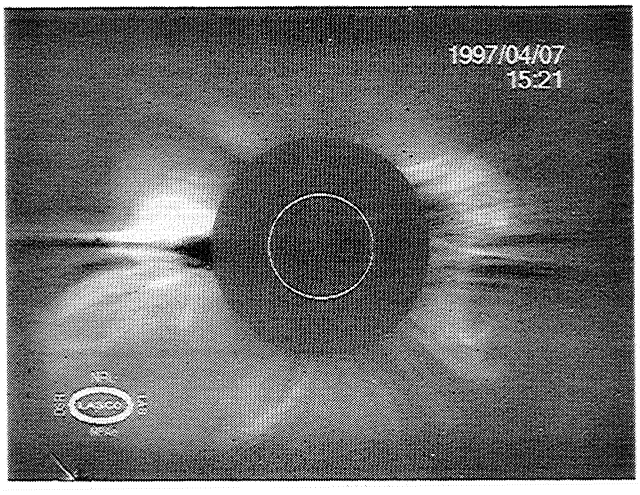

Figure 3. The halo coronal mass ejection (CME) on April 7, coincidental with an arcade type CME in the southeast flank of the Sun, based on density difference from corona observations at 1521 UT and the quiet corona at 1405 UT.

the halo-type CMEs on April 7. Thus it was not a corotating interplanetary shock (IS) lying ahead of the period of increasing SW speed following the shock. (See Figure 5 where WIND SW parameters for April 10-11 are shown.)

SW conditions during the ~ day and a half following the shock were complex and typified by a fluctuating, enhanced, ram pressure (top panel of Figure 5). Several structures can be identified in the first region (from the IS) to the start of the ejecta). At 1912 UT on April 10, a ~20 nT field intensity spike occurred at the center of a smooth change in the solar wind flow from above 5° northward to nearly 5° southward. Although there was an abrupt south-north change in the IMF direction at the spike, the larger-scale field changed around this time from predominantly northward to southward. From 0550 to ~1500 UT on April 11, a structure containing an intense magnetic field and low proton temperature such that the plasma $\beta \leq 0.1$, an enhanced plasma alpha to proton ratio, and a decrease in the SEP intensity (Figure 4) is evident. We interpret this structure as an ejecta but one lacking the rotation in the magnetic field direction characteristic of an IMC. Following the ejecta is a region of enhanced pressure and field intensity in which the alpha/proton ratio is generally lower than in the ejecta. This was evidently an interaction region formed ahead of the high-speed stream present late on April 11. A reverse IS at 2052 UT most likely marked the trailing edge of this interaction region.

A simple interpretation of the observations is that the shock on April 10 was generated ahead of the ejecta observed on April 11. However, there is evidence that this may not be the case. The short-duration region of enhanced plasma pressure immediately following the shock was clearly separated from the region of enhanced pressure generated ahead of the ejecta (top panel, Figure 5). Had the ejecta generated the shock, we might have expected a high-pressure region to extend out ahead of the ejecta to the shock. We also note the unusual changes in the magnetic field intensity and direction, and solar wind flow angle, in the region between the shock and ejecta. Based on the LASCO observations of a fast, arcade-like

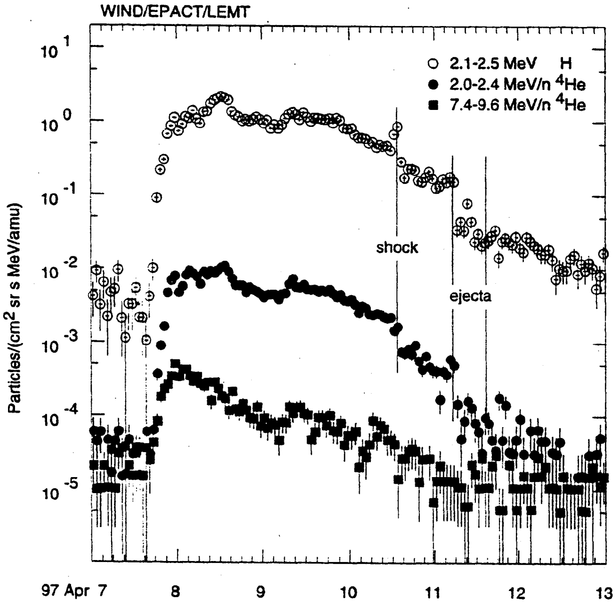

Figure 4. Time profile of the shock-energized particles (SEP) intensities (three channels), from April 7 to 13, 1997.

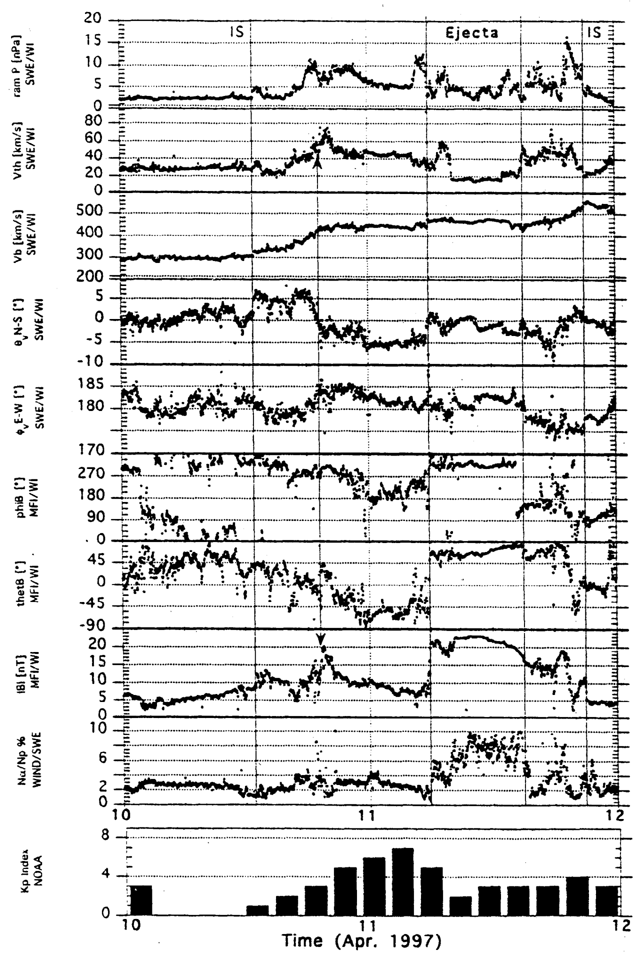

Figure 5. From top to bottom the panels show: the SW proton (1) ram pressure ($\approx m_p v_x^2$), (2) thermal velocity, (3) bulk velocity, (4) flow-direction away from the ecliptic, and (5) in the ecliptic; direction of the IMF (6) in the ecliptic, (7) out of the ecliptic, and (8) magnitude |B|, (9) the ratio of SW alpha to proton densities, and (10) the three-hour Kp index of global geomagnetic activity. Vertical arrows on April 10, mark a possible travelling compressional structure, at 1912 UT in the SW. ISs, and ejecta boundaries are indicated with vertical lines.

southeastern CME as well as a halo-type CME with an asymetric velocity distribution, which indicate that more than one ejecta may have been created in the April 7 event, we make the alternative proposal that the signatures at Earth were caused by two ejecta, of which only the second encountered the Earth, producing the clear ejecta signatures observed on April 11. We suggest that the first (i.e., faster) ejecta passed south of the Earth (based on the solar event location in the southern hemisphere) and that only the northern flank of the shock it generated was detected at Earth. The SW signatures following the shock suggest that WIND may have entered a region of field lines draped around this ejecta analogous to the draping of lobe field lines around plasmoids observed in the geomagnetic tail (so-called "traveling compression regions", e.g., *Slavin et al.*, [1989]). In particular, there is (1) a brief, spike-like enhancement of the magnetic field accompanied by plasma heating which may correspond to the region of maximum field compression close to the widest part of the ejecta and indicating the closest approach of the ejecta to WIND; (2) a predominantly northward field before the field spike followed by a predominantly southward field, consistent with draping of the sunward-directed IMF over the northern surface of the ejecta, and (3) a northward plasma flow which turned to southward at the field spike, consistent with the northward displacement of the solar wind by the approaching ejecta and a corresponding southward flow as the ejecta passed by. These SW conditions were highly efficient to generate magnetospheric activity between 1912 UT (April 10) and 0420 UT (April 11) (see bottom panel, Figure 5).

3. Conclusions and Closing Remarks

Our interpretation of this event centers on the idea that there were two related ejecta from the Sun. The first was faster and propagated from the Sun in a path south/south-east of the Earth. Its origin was either the arcade-like southeast CME or part of the halo-type CME. The Earth did not encounter this ejecta but was influenced by the associated disturbances in the SW. These disturbances were (a) the IS detected at Earth at 1255 UT on April 10, which produced SEP and possibly generated type II radio bursts when closer to the Sun, and (b) the prominent pressure structure around 1912 UT April 10, traveling away from the Sun, including (i) an enhanced IMF intensity and heating of ions, (ii) draped SW flow, and (iii) possibly, a change in the predominant orientation of the IMF. The observed ejecta, on the other hand, had to be a part of the halo type CME and was directed toward the Earth. The measured velocity of this second ejecta was 470 kms^{-1}. This is consistent with the departure time from about 2 R_s above the Sun on April 7, 1500 UT and its arrival to Earth on April 11, 0550 UT with a slight de-acceleration of about 10% from its initial speed at the Sun. The IMF in the April 11, 1997 ejecta pointed north during the entire time of its passage, (i.e., it was not an IMC). Both IMF and ram pressure were well above normal during the passage of the April 11, 1997 ejecta.

We believe that the April 7-11, 1997 Sun-Earth connection event has great significance to the investigation of space weather. Based on this case; it is possible that complex events containing a halo CME can occur, at the Sun, and then have the potential for producing disturbed SW conditions ≈ 3 days later, capable of generating strong geomagnetic activity. The need for a better, permanent coverage of the interplanetary medium from Sun to Earth is highlighted by the arguments presented here on the existence of the first ejecta. There are many uncertainties, however, concerning this ejecta. For example, its nature, i.e. velocity of propagation at 1 AU (estimated to be 600 to 700 kms^{-1}), IMF strength, and plasma composition, as well as its precise connection to the observed ejecta will probably remain a mystery.

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D. Berdichevsky, N. Fox, M. Kaiser, R. Lepping, M. Reiner, M.C. 690, NASA/GSFC,Greenbelt, MD 20771 (e-mail: berdi@istp1.gsfc.nasa.gov, nfox@pop600.gsfc.nasa.gov, u3mlk@lepvax.gsfc.nasa.gov, rpl@leprpl1.gsfc.nasa. gov, reiner@urap.gsfc.nasa. gov),

J.-L. Bougeret, DESPA/URA CNRS 264, Observatoire de Paris-Meudon, Meudon, France (e-mail: bougeret@obspm.fr),

J.-P Delaboudinière, Inst. d' Astrophisique Spatiale, Université Paris XI, Orsay, France (e-mail: boudine@deneb.ias.fr),

D. Reames, I. Richardson, T.T. von Rosenvinge, M.C. 661, NASA/GSFC, Greenbelt, MD 20771, (reames@lheavx.gsfc.nasa.gov, richardson@lheavx.gsfc.nasa.gov , rosenvinge@lheavx.gsfc.nasa.gov)

D. Michels, S. Plunkett, Naval Research Laboratory, Washington, DC 20735 (e-mail: michels@lasco11.nascom.nasa. gov, plunkett@kreutz.nascom.nasa.gov),

G. Rostoker, Can. Network for Sp. Res. and Dept. of Phys., U. of Alberta, Edmonton, Alberta, Canada (e-mail: rostoker@space.ualberta. ca)

J. Steinberg, Center for Space Res., MIT, Cambridge, MA 02139 (e-mail: jts @space.mit.edu),

B. Thompson, Space Applications Corp. at NASA/GSFC, Greenbelt, MD 20771 (e-mail: thompson@eitv3.nascom.nasa.gov).

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