Tracking a major interplanetary disturbance with SMEI

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[1] We present the first clear observations of an Earth-directed interplanetary disturbance tracked by the Solar Mass Ejection Imager (SMEI). We find that this event can be related to two halo CMEs seen at the Sun about 2 days earlier, and which merged in transit to 1 AU. The disturbance was seen about 16 hours before it reached Earth, and caused a severe geomagnetic storm at the time which would have been predicted had SMEI been operating as a real-time monitor. It is concluded that SMEI is capable of giving many hours advance warning of the possible arrival of interplanetary disturbances. *INDEX TERMS:* 2194 Interplanetary Physics: Instruments and techniques; 2788 Magnetospheric Physics: Storms and substorms; 7513 Solar Physics, Astrophysics, and Astronomy: Coronal mass ejections. **Citation:** Tappin, S. J., et al. (2004), Tracking a major interplanetary disturbance with SMEI, *Geophys. Res. Lett.*, *31*, L02802, doi:10.1029/2003GL018766.

1. Introduction

[2] The Solar Mass Ejection Imager (SMEI) [*Eyles et al.*, 2004] was designed to observe interplanetary disturbances propagating from the Sun, and to demonstrate the feasibility of using such observations as a tool for space weather forecasting.

[3] SMEI was launched on the US Department of Defense Space Test Program Coriolis satellite on 6 January 2003. This satellite is in a circular polar orbit at an altitude of about 840 km. The orbit is maintained over the terminator.

[4] The instrument consists of 3 CCD cameras each observing a strip of sky approximately $60^\circ \times 3^\circ$ through a baffle which minimizes stray light. The cameras are arranged on the spacecraft such that in the course of an orbit almost the full 4π sr of the sky other than small regions close to the Sun and in the anti-solar direction is observed. Interplanetary disturbances are detected by looking for variations in the intensity of the Thomson-scattered light caused by the density enhancements and depletions of the disturbances. This technique has been previously demonstrated by Jackson and collaborators [*Jackson et al.*, 1985; *Jackson and Leinert*, 1985] using the zodiacal light photometers on the two Helios spacecraft.

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[5] Although the methods of subtracting stars and zodiacal light and of eliminating satellite tracks and particle interactions in the CCDs are as yet at an early stage of development, it is still possible to detect heliospheric plasma by subtracting a pre-event background image.

[6] In this letter we describe how a major disturbance was tracked from 0.6 to 1 AU. We also show that the properties of this disturbance are confirmed by measurements from other sources, but that the SMEI observations are able to add information not obtainable from any other source.

2. The Observations

[7] Each of the 3 SMEI cameras captures an image of its $60^\circ \times 3^\circ$ field of view every 4 seconds. These CCD images are transmitted back to Earth where they are assembled to produce all-sky maps of the brightness in white light of the sky. These maps, which are the primary data product from SMEI, have a resolution of approximately 1° in an Aitoff-Hammer equal-area projection, currently these are not converted to physical units but are in instrument analog-digital converter units (ADU). A given point in the sky takes about one minute to cross the field of view of a SMEI camera, and the 1° pixels in the Aitoff maps are larger than the bins in the original CCD images; consequently each pixel in the final maps is the average of many input values. Hence we are able to detect features with a brightness less than the digitization unit of the SMEI cameras.

[8] Almost all remote sensing methods of determining heliospheric structure require the removal of some form of background to reveal the disturbances. Since we do not yet have an absolute background to use for SMEI, we must rely on the slow variation of the backgrounds compared with that of travelling disturbances and use an average of several pre-event orbits as a background.

[9] In the background-subtracted images from the orbit starting at 0445 UT on 29 May through to the end of the day, a structure can clearly be seen as a bright arc moving outwards in the region to the north of the Sun (Figure 1). The precise extent of the event in position angle is difficult to determine as the regions of the maps at low ecliptic latitude are strongly affected by energetic particle interactions with the CCDs as the spacecraft moves though the polar cap regions, and also by auroral light. It is however clear that the arc of enhanced scattering extends into the regions where the data are adversely affected by energetic particles. In a movie of the event, the arc of enhanced scattering can be seen to extend around at least 150° of sky, and probably forms a complete halo. In the images from the 1959–2141 UT (to the Northwest) and 2141–2322 UT (to the South-East) orbits it is possible to see a general

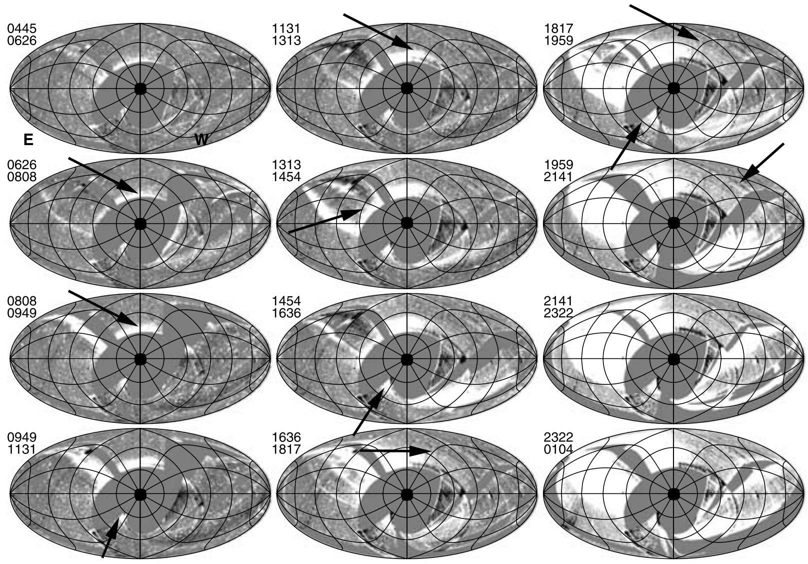

Figure 1. All-sky Aitoff images of the May 29 interplanetary transient. Each image represents one orbit (the start and end times in UT are in the upper left, all the images are from 29 May). The coordinates are solar ecliptic coordinates, so the Sun is at the center of each image (indicated by a black dot), the equator of the map is the ecliptic plane, the north ecliptic pole is at the top of each map, and the anti-solar direction is at the extreme left and right ends of the equator. The grid is at intervals of 30° in elongation and position angle. A background image derived from 10 orbits prior to these observations has been subtracted from the images. The range from black to white is from −2 to +2 digitization units of the SMEI cameras. Areas of uniform mid-grey are regions of missing data; these data gaps are due to the presence of bright objects (Sun, Moon, Venus. . .) in the field of view or to very high energetic particle fluxes. The arrows indicate the locations of parts of the loop in selected orbits. The large diffuse bright regions to the NE and SW in the later images are believed to be due to aurorae above the spacecraft.

enhancement of scattering from the region beyond 90° elongation as the disturbance passes beyond the Earth.

[10] From the northern region, it is possible to derive a height-time relation (Figure 2). If we ignore the first point which clearly lies below the trend of the rest, this gives a speed of 960 km/s (assuming that the disturbance is large enough for the sky-plane speed to be a true measure of the radial velocity), and a projected launch from the Sun early on 28 May. The inferred arrival at Earth would be 2100 UT on 29 May, with an uncertainty of about 1 hour.

[11] Clearly to establish the validity of these observations, we must be able to relate them to other, more familiar, measurements.

[12] Solar X-rays are monitored by the GOES detectors, while in the corona our best source of information is from the LASCO coronagraphs on SOHO which are able to trace CMEs out to $30R_\odot$ (0.14 AU). The GOES monitors recorded X-ray flares of class X1.3 and X3.6 from a region just southwest of the disk center, with peaks at 2307 UT on 27 May and 0027 UT on 28 May. The LASCO coronagraphs observed two halo CMEs late on 27 and early on 28 May (Figure 3). These were comparatively weak events but were strongest in the North where they had sky-plane speeds around 675 km/s with the second being slightly faster so we expect them to have interacted before they reached the SMEI field of view (Figure 4). Since most large X-ray flares are associated with CMEs, it seems probable that these observations represent the same activity. To reach Earth at 2100 UT as inferred from the SMEI observations this requires a propagation speed of 925 km/s, which is in

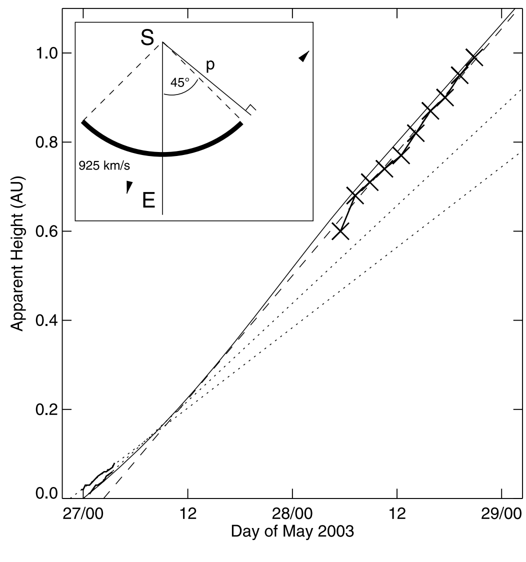

Figure 2. The height-time evolution of the May 29 SMEI event. The y-axis is the perpendicular distance (p) from the line of sight intersecting the leading edge of the disturbance to the Sun (i.e., the sine of the elongation angle). The dashed line shows the extrapolation back to the Sun. The height-time profiles of the LASCO CME fronts (Figure 3) are also shown, and their extrapolations are shown as dotted lines. The light solid curve is the apparent height-time curve calculated for a structure extending to 45° from the Sun-Earth line and travelling at 925 km/s; this is shown schematically in the inset.

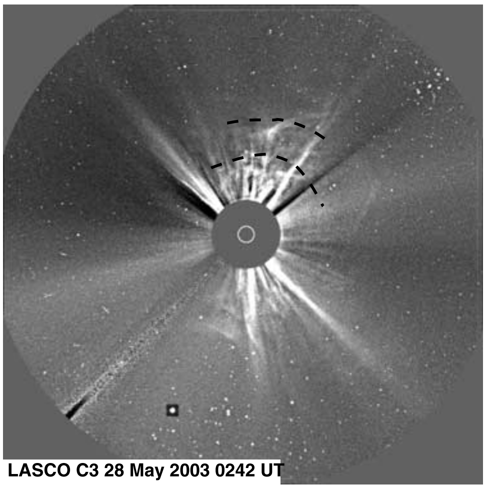

Figure 3. A LASCO C3 image taken at 0242 UT on 28 May, showing the complex of halo CMEs believed to be the early stages of the disturbance observed by SMEI. This image is an edge-enhanced ratio of the original image to a model of the "quiet" corona, black and white represent 10% excursions in the observed intensity. The dashed curves indicate the approximate locations of the fronts of the 2 structures. The small circle within the occulting disk indicates the size and location of the Sun. (The feature cutting across the indicated outer front is part of another loop, nearer to the sky plane).

reasonable agreement with the 960 km/s measured. These CMEs and flares were the only plausible sources of this disturbance. Within the accuracy of our determinations, this launch time is consistent with that deduced from the SMEI data. The apparent discrepancy of speeds is not a problem as the sky-plane speed of a halo CME measured from LASCO is always a lower limit on the actual speed of the CME. In the case of an Earth-directed CME extending to 45° away (as in the schematic shown in the inset Figure 2) from the Sun-Earth line, the apparent speed close to the Sun will be reduced by a factor of $\sqrt{2}$, which is approximately what we see. The linearity of the height-time plot after the first point

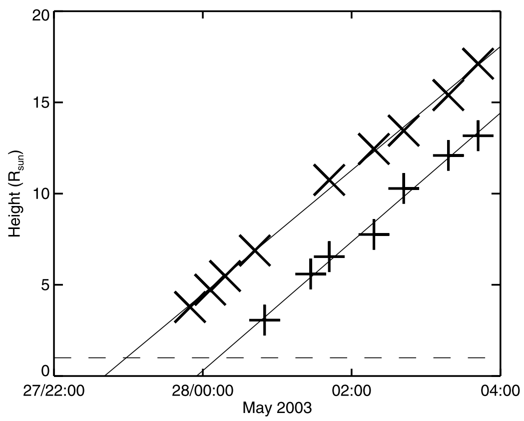

Figure 4. The height-time curves for the double halo CME seen by LASCO C2 and C3 which we believe to be the same disturbance as that seen by SMEI.

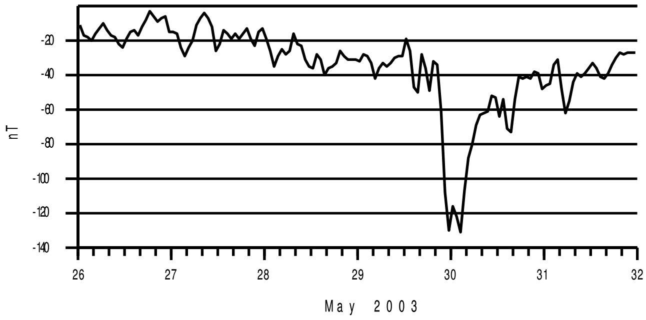

Figure 5. The Kyoto provisional Dst indices for 26–31 May 2003.

requires that the transient must extend more than 30° from the Sun-Earth line.

[13] LASCO also saw several CMEs which may have been Earth-directed on the afternoon of 26 May and which may have been the source of the disturbance that arrived about 1200. At or near the Earth, we have geomagnetic indices and measurements from ACE, which is in a halo orbit at L1. The geomagnetic indices Dst, *kp* and *ap* are used to indicate disturbed magnetic conditions. The Kyoto provisional Dst indices for May 2003 (Figure 5) show a very strong dip starting between 2100 and 2200 UT on 29th and reaching a peak at −130 nT between 2300 and 2400 UT and −131 nT from 0300–0400 on 30th, in agreement with the arrival time deduced from the SMEI measurements. This was the first excursion of Dst below −100 nT in 2003. The *ap* and *kp* indices also showed severe storm activity, but from around 1200 UT. The highest *kp* values were 8+ for 1800–2100 UT and 2100–2400 UT, after which activity declined.

[14] ACE, which is at L1, should see plasma structures about half an hour prior to their arrival at Earth. At 1155 UT a weak interplanetary shock reached ACE, we believe that this was related to an earlier partial halo CME seen by LASCO from about 1800 UT on 26 May. At this time the IMF became significantly southward-pointing which accounts for the geoeffectiveness of this otherwise weak feature. Since this event had only a small density increase it probably lay below the threshold for detection by SMEI in its current state. There was a much stronger shock and density enhancement at 1830 UT (Figure 6) which probably corresponds to the feature seen by SMEI. However during this event the IMF turned northwards thus effectively terminating the geomagnetic activity early on 30 May.

[15] In addition, it should be noted that aurorae were seen as far South as Wisconsin, Normandy and Switzerland on the night this disturbance hit Earth.

3. Discussion

[16] The primary purpose of SMEI is to demonstrate the feasibility of using remote sensing of interplanetary disturbances by their scattered light for forecasting their arrival at Earth. In this case we see that a disturbance which caused the strongest geomagnetic activity of the first half of 2003 was seen about 16 hours prior to its arrival at Earth.

[17] In terms of heliospheric coverage, this was very close to a worst-case scenario as the orbit of Coriolis is

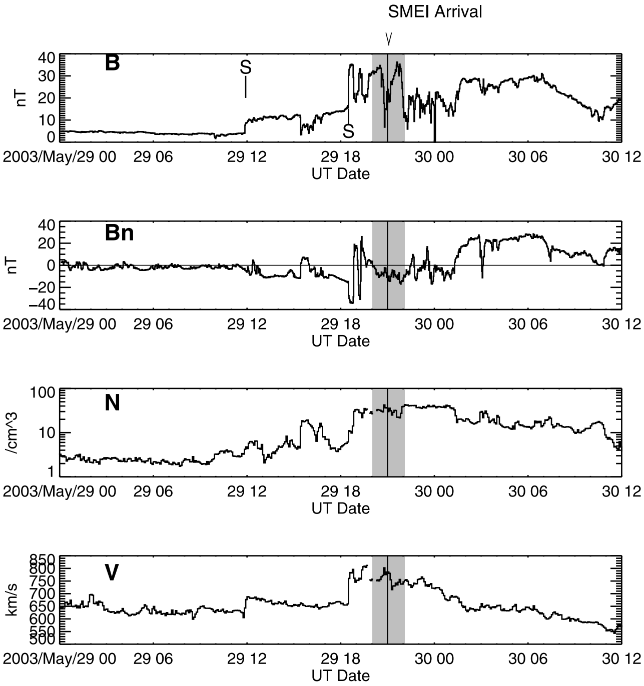

Figure 6. Magnetic field and plasma measurements from ACE. The "S" s indicate the times of the interplanetary shocks at ACE. The grey band indicates the estimated range in time of arrival inferred from SMEI.

such that at this time of year the sunward camera of SMEI spends much of the orbit with its shutter closed. This restricts our field of view north of the Sun to the region outside about 35° elongation. In addition the data processing used in this analysis was still in a preliminary form with many background contributions not yet subtracted (rather we have relied on their slow variation by using a pre-event average image as a background).

[18] A careful examination of the actual values in the running difference images shows that the peak enhancement was about 2 ADU. This compares with typical levels in the raw images of tens or hundreds of units for the backgrounds due to zodiacal light and faint stars, with the brighter stars showing levels well above 1000 ADU. The fluctuations in the region outside the leading edge of the disturbance were about 0.5 ADU and of a much smaller angular scale than the disturbance.

[19] The speed inferred from the motion through the SMEI field and that obtained from the transit from the putative source to the sudden commencement are in agreement to the precision with which we have been able to estimate them. This supports the idea that the speed was constant throughout the transit from the Sun to 1 AU. In comparison with many of the events detected by interplanetary scintillation measurements during the 1980 solar maximum period, this was a very fast event [e.g., *Tappin et al.*, 1983; *Tappin*, 1987]. Since the propagation speed was much greater than the speed of the ambient solar wind, the disturbance might have been expected to decelerate. The fact that it does not do so implies that the disturbance must have continued to be driven from below to overcome the decelerating forces from the slower solar wind ahead of it.

4. Conclusions

[20] The fact that the SMEI observations correlate well with observations both at the Sun and the Earth, as well as the similarity of form of this disturbance to that seen in the past in the same region of space by IPS, strongly suggest that SMEI can measure and track transient interplanetary disturbances.

[21] These observations show that the SMEI instrument is capable of providing at least several hours warning of the impending arrival of a major disturbance at Earth. With improved data processing techniques we would expect to be able to extend this to more typical (i.e., fainter and slower) interplanetary disturbances. While density and speed alone are not sufficient to make a complete prediction of geo-effectiveness, they are the only parameters that can be sensed sufficiently far into interplanetary space to give a warning many hours, or even 1–3 days for slower events, ahead of potential storms. The ability of SMEI to track disturbances and make accurate predictions of if and when they will hit Earth has not previously been available and should be of great value in space weather forecasting.

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