3D Reconstruction of Density Enhancements Behind Interplanetary Shocks from Solar Mass Ejection Imager White-Light Observations

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Abstract. The Solar Mass Ejection Imager (SMEI) observes the increased brightness from the density enhancements behind interplanetary shocks that are also observed *in situ* near the Earth. We use the University of California, San Diego (UCSD) time-dependent three-dimensional (3D) reconstruction technique to map the extents of these density enhancements. Here, we examine shock-density enhancements associated with several well-known interplanetary coronal mass ejections (ICMEs) including those on 30 May 2003 and on 21 January 2005. We compare these densities with reconstructed velocities from the Solar-Terrestrial Environment Laboratory (STELab) interplanetary scintillation (IPS) observations for the 30 May 2003 ICME, and show the shock is present at the front edge of the reconstructed high speed solar wind. The SMEI analyses certify that the brightness enhancements observed behind shocks identified and measured *in situ* near Earth are a direct response to the plasma density enhancements that follow the shocked plasma.

Keywords: Interplanetary Coronal Mass Ejections (ICMEs), Interplanetary Shocks, Solar Wind, Three-Dimensional Heliospheric Density and Velocity Reconstructions
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INTRODUCTION

The Solar Mass Ejection Imager (SMEI) instrument on board the Coriolis spacecraft is well into its sixth year in its 102-minute polar terminator orbit, returning 0.1% photometric-quality data covering nearly the entire sky [1, 2]. Before launch the University of California, San Diego (UCSD) group developed an image analysis technique that, as much as possible, retained the long-term brightness variation and individual-data-frame resolution of the instrument. SMEI sky maps are produced from a composite of 4-second exposure 3º × 60º images from each of three cameras. When the sidereal and zodiacal backgrounds are subtracted, the sky maps provide Thomson-scattering data with minimal stray light as close as 20º elongation to the Sun and out to 180º. Data outages occur in the SMEI camera closest to the Sun when a shutter closes to prevent the CCD camera from saturating in direct sunlight. All cameras fail to obtain good data when the moon is in or within a few degrees of their fields of view.

To reduce long-term brightness variations, a zodiacal-light model derived from the SMEI data [3] has been removed from the sky maps. At each sky location, a long-term Gaussian filter as a function of time provides a base spanning several hundred orbits (about 2 weeks). This long-term base is fit to time-series observations at sidereal locations selected to be free of nearby bright stars. These locations have also had the main contributions removed due to high-energy particle hits and auroral light. The data analysis technique accomplishes this by comparing the redundant images occurring at a given sky location, by recognizing times when high-energy particles hit covered (dark current) CCD pixels, and by removing bad spots in the orbit where these effects occur [4 - 7].

This data base is used in a three-dimensional (3D) tomographic analysis of heliospheric structures, which includes both the interplanetary counterparts of coronal mass ejections (ICMEs) and longer-term heliospheric density structures such as the extensions of coronal streamers. The UCSD 3D-reconstruction program is a least-squares iterative tomography routine

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first developed by B.V. Jackson and colleagues in a time-dependent version [4, 7-9] to use with interplanetary scintillation (IPS) data. This program iterates in three dimensions – longitude, latitude, and time – to generate the time-dependent source-surface boundary for a kinematic solar wind model that provides 3D volumes over time that match the observations. An earlier version of this same iterative reconstruction analysis is "corotating" in that it reconstructs the source-surface boundary for a kinematic solar wind model in just two-dimensions – longitude and latitude [10, 11]. SMEI images and views of the 3D analyses are on the Web for the bulk of the SMEI data at: http://smei.ucsd.edu/.

Changes in IPS intensity arise from 150-km size density inhomogeneities in the interplanetary medium. Signals from point radio sources form an intensity interference pattern on the ground that moves across the surface of the Earth at solar wind speeds as the solar wind density inhomogeneities move outward from the Sun. The motion of this pattern past a radio array determines both the level of scintillation, and by correlating this pattern from one radio array to another, its velocity. The variation of this pattern and its velocity relative to the observer is translated to a measurement along each radio source line of sight. Analyses of these observations have long been used to determine the extent and outward solar motion of heliospheric structure [12, 13]. Observations from the Solar-Terrestrial Environment Laboratory (STELab) have also reconstructed the shapes of CMEs/ICMEs using a technique different from that at UCSD [14, 15]. The STELab IPS analyses [16] can be found at: http://ips.ucsd.edu/.

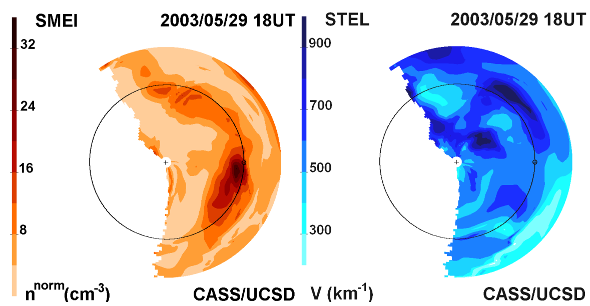
With SMEI calibrated to a ~4% absolute brightness [7], we have shown that SMEI long term variations in brightness can accurately reproduce density peaks at Earth over a large portion of a Carrington rotation and for a slow-speed ICME [4]. Here, we explore the extent to which this 3D-reconstruction technique reproduces the particle flux observed following large ICME shocks. A new higher-resolution version of our 3D-reconstruction program allows measurement of shorter density enhancements. This remote-sensing analysis ascertains how extensive and continuous shock density enhancements are. In addition, it relates these shock density enhancements to the underlying high-speed wind measured near ICMEs, and determines whether mass flux observed remotely differs from that measured *in situ*. As in other interactions, ICME shocks might electrically charge or otherwise influence interplanetary dust, and thus sweep some of the smaller dust grains outward near the location of the shock. The present work, as with Helios data in [17] is intended to determine whether this occurs to a significant extent.

3D SHOCK DENSITY MEASUREMENT

30 May 2003 ICME

A succession of halo CMEs was observed by the C2 Large Angle Spectrograph Coronagraph (LASCO) [18] on 27-28 May 2003, each in turn having a faster plane-of-the-sky speed. On 29 May 2003 an ICME shock was detected by the Charge, Element, Isotope Analysis System (CELIAS) Proton Monitor [19] Shockspotter routine beginning at about 18:35 UT; this was followed by a large density enhancement that lasted for over a day. We use this well-studied event (see Jackson *et al*. [4]) as one example of the analyses discussed in this article. Although this event does not have a large associated shock velocity enhancement, the same large density response is measured by each of the *in-situ* monitors near Earth: CELIAS, the Wind Solar Wind Experiment (SWE) [20], and the Advanced Composition Explorer (ACE) Solar Wind Electron Proton Alpha Monitor (SWEPAM) [21] to within ~10% of the Wind SWE. In this article we use Wind SWE measurements exclusively for comparison with analysis results from the SMEI spacecraft.

Figure 1 shows 2D ecliptic cuts through the 3D-reconstructed volumes at 18:00 UT 29 May for this



(a) (b)

FIGURE 1. Inner heliosphere density and velocity ecliptic cuts of 3D-reconstructed material during the 30 May 2003 ICME. Densities are in protons cm^{-3}, normalized to 1 AU, by removal of an r^{-2} fall-off. The Sun is in the center of the image, the Earth is marked (⊕) and its orbit is marked as an ellipse. White areas within the volume indicate locations where no reconstruction was possible because too few lines of sight cross for density structures to be reconstructed. **(a)** The density enhancement at 18:00 UT on 29/05 showing the enhancement behind the shock that is primarily to the East of Earth at this time. **(b)** The velocity showing a sharp boundary exists between the slower outward-moving solar wind and the faster outflows associated with the CME. There is little evidence of an extensive shock sheath surrounding the high CME density or in front of the fast velocity in these ecliptic cuts.

ICME. It shows that the density enhancement of this composite of halo events went primarily to the East of Earth while the associated higher-speed wind went primarily West. The density in hourly-averaged SWE data increases to over 35 protons cm^{-3} behind this small shock, lasts for about 18 hours, and reaches outflow speeds above 800 km s^{-1} (Figure 2a). This density increase and speed indicate a total particle flux past the spacecraft of 7.4×10^{13} protons cm^{-2} measured above an ambient base. A comparable result can be obtained as displayed in Figure 1a, or in the radial column displayed in Figure 2b, by measuring a column of mass along the Sun-Earth line and summing this over the radial extent of the material passage, which in this case extends for about 0.50 AU. This radial extent indicates a proton flux past Earth that lasts about one day at 800 km s^{-1}, and for comparison with the above *in-situ* measurements gives a flux of 7.2×10^{13} protons cm^{-2} above the ambient resulting from the SMEI analysis.

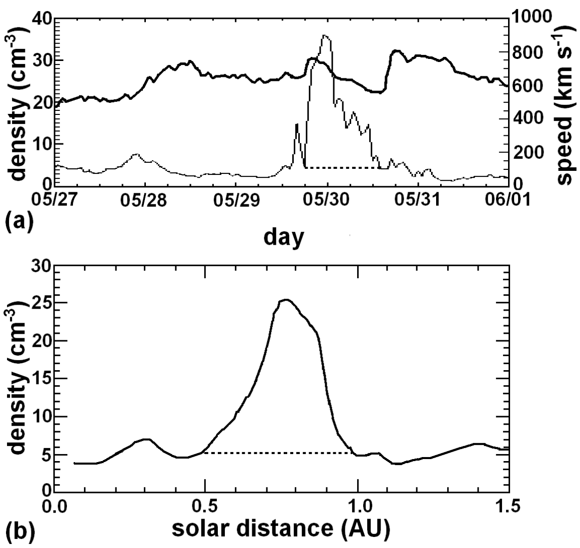


FIGURE 2. The enhancement for the 30 May 2003 ICME. The “ambient” density base is marked by a dotted line. **(a)** Hourly-averaged *in-situ* density and velocity (thick line) measured by Wind SWE over the 30 May 2003 ICME interval. **(b)** 18:00 UT 29 May radial-density plot that includes Earth obtained from the SMEI 3D reconstruction (also plotted in Figure 1a). An r^{-2} radial fall-off has been removed.

21 January 2005 ICME Shock

The 21 January 2005 ICME shock-density enhancement that began at 16:50 UT was associated with a very fast CME that was seen in LASCO and SMEI images to move outward to the solar Northwest beginning on about 06:00 UT 20 January 2005. Figures 3a and 3b give respectively ecliptic and meridional cuts through the volumetric 3D reconstruction for this event. Figure 3c shows the *in-situ* density and velocity measured at the Wind spacecraft and this is compared with the radial density determined by the SMEI analysis. The density increase and speed during the shock from Wind SWE observations indicates a flux of 4.5×10^{13} protons cm^{-2}. The radial cut at Earth provides a flux of 4.7×10^{13} protons cm^{-2}.

CONCLUSIONS

We derive the particle flux associated with the density enhancements behind shocks for the 30 May 2003 and the 21 January 2005 ICME using SMEI 3D-reconstructions and Wind SWE *in-situ* measurements. We find a very good agreement between the proton fluxes as measured *in situ* and those inferred from the remotely-sensed 3D-reconstructed shock-density enhancements. Here, Thomson-scattering brightness (from electrons) is related to proton density by assuming a 10% Helium abundance (and thus an overabundance of electrons of 20% in the solar wind during the ICME passage). Solar wind Helium abundance is known to vary during ICME passage and can potentially cause a remote-sensing error in comparison with proton density of up to half the electron number from the Helium abundance. Thus, the remote-sensing results from the SMEI 3D reconstructions could have systematic error of at least this amount or about 10% of the total measured flux. However, there are far greater uncertainties in *in-situ* measurements obtained by each spacecraft. For the 21 January 2005 ICME the three different spacecraft near Earth give fluxes behind the shock of 2.6, 4.5, and 6.6×10^{13} protons cm^{-2} respectively from ACE, Wind SWE, and CELIAS. Although the good agreement between the two measurements we have chosen to include here implies that little if any dust is observed to have been swept up by the interplanetary shocks for the events we have measured, the very large differences between the *in-situ* monitors makes it difficult to conclude whether this is generally true.

However, a more interesting aspect of these shocks, as reconstructed from SMEI observations, is the location and continuity of the density enhancements behind them. The shock front for the 21 January 2005 ICME is separated by such a great distance from the main outward-flowing mass of the ICME, that this mass is not observed in either the meridional or ecliptic cuts of Figure 3a and 3b. SMEI does reconstruct this ICME mass, but it moves outward to the solar Northwest at >90º in angle from where the shock is observed at Earth. For the 21 January 2005 shock, Earth is on the very periphery of

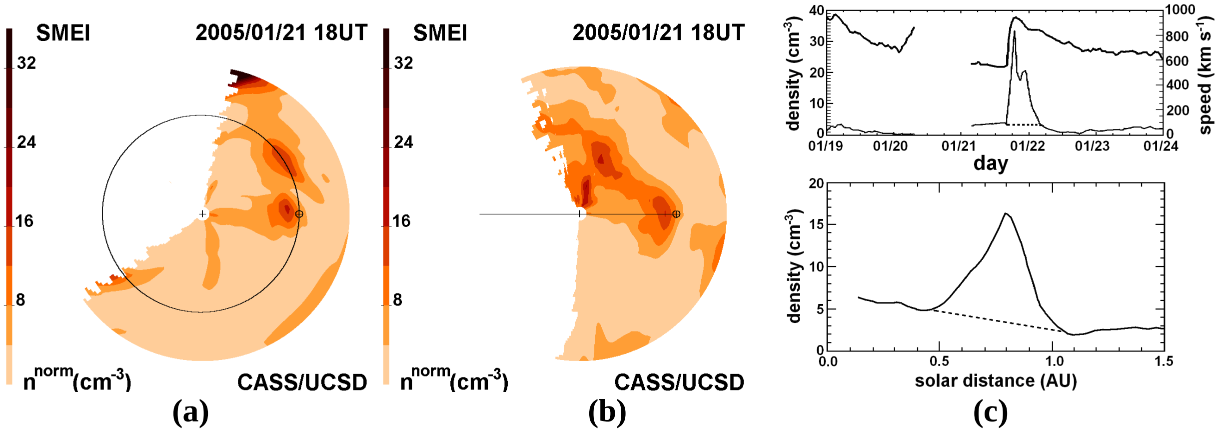


FIGURE 3. (a) and **(b)** Ecliptic and meridional cuts of the density enhancements associated with the 21 January 2005 ICME. **(c)** Wind SWE density, and speed measurements (top) and the enhancement as measured along the radial from the 3D-reconstructed SMEI density (bottom). The dashed line indicates the assumed "ambient" base.

the shock-density enhancement. Furthermore, these 3D-reconstructed density enhancements do not form a continuous front of dense material. For all the ICMEs studied to date, the shock-density enhancements are discontinuous along the extent of the shock front.

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