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The Solar Energetic Particle Event of 16 August 2001: ∼400 MeV Protons Following an Eruption at ∼W180

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A fast (∼1500 km s^{-1}) full-halo coronal mass ejection (CME) was observed late on 15 August 2001 by the white-light coronagraph on SOHO, and was followed within an hour by an intense 400 MeV proton event at 1 AU. The absence of significant front side activity at the inferred launch time of the CME indicates a source region on the far side of the Sun. The most promising active region to produce a major CME on 15-16 August was AR 9557, located near the far side disk center. Supporting evidence for this extreme back side CME origin is provided by helioseismology analysis of Michelson Doppler Imager (MDI) data and from analysis of the trajectories of low-frequency (< 1 MHz) radio bursts observed by experiments on Ulysses and Wind. Extreme ultra-violet Imaging Telescope (EIT) images reveal the onset of activity at the west limb of the Sun, suggesting the arrival of a wave front near the time that the first solar energetic particles (SEPs) to arrive at Earth were injected into space. We interpret these observations in terms of widespread acceleration of SEPs at a coronal shock wave that is manifested by a Wind/WAVES decametric/hectometric (DH) type II radio burst.

1. Introduction

Prompt SEP events that originate in solar eruptions well removed from the nominal ∼W60 footpoint of the interplanetary magnetic field (IMF) spiral to Earth provide an opportunity to probe the means by which solar particles become rapidly distributed in solar longitude. Generally such "fast propagation" of particles is attributed to a coronal shock [1], but recently Cane and Erickson [2] have suggested cross-field transport of particles as an alternative. In this paper we study the > 400 MeV proton event of 16 August 2001 that appears to have originated in an eruptive flare located at ∼W180, i.e., on the exact opposite side of the Sun from Earth.

Previous examples of prompt high-energy SEP events from behind the limb sources, including ground level events (indicating > 500 MeV protons), have been reported by several authors (e.g., 28 January 1967, ∼W155, [3]; 1 September 1971, ∼W120, [4]; 16 February 1984, ∼W130, [5]). In those cases, the association was largely made on the basis of flare histories (while on the visible disk) of candidate back side active regions. In the present study, we use such evidence to support a back side association for the 16 August 2001 event but also employ the modern tools of helioseismology and low-frequency radio tracing that allow us to look through and behind the Sun, respectively. We then investigate the nature of acceleration/propagation in this unusual event using: (1) SEP anisotropy, composition, and charge state measurements from Wind, ACE, and SAMPEX; and (2) a comparison of SEP injection timing with wave effects observed by EIT on SOHO and with radio bursts observed with the low-frequency radio experiments on Wind and Ulysses.

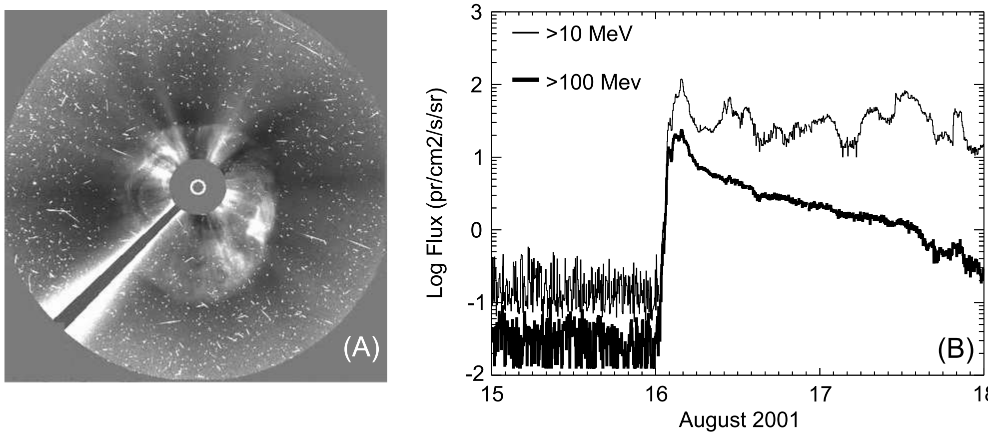

Figure 1. (a) SOHO/LASCO C3 back side CME on 16 August 2001, 0142 UT. (b) Associated GOES SEP event.

2. Event Overview

A CME with speed $\sim$1500 km s^{-1} was first observed off the southwest limb of the Sun at 2354 UT on 15 August at a height of 3.38 $R_\odot$ from Sun center. By 0142 UT on 16 August, the CME had formed a symmetric (in the east-west direction) halo about the Sun (Figure 1a). A height-time plot assuming constant deceleration (-32 m s^{-2}) indicates a disk center launch time of 2335 UT. There was no significant ($>$ C1) GOES 1-8 Å activity near this time, suggesting a back side CME source. The GOES and IMP-8 spacecraft recorded a prompt proton event extending beyond $\sim$400 MeV (Figure 1b).

3. Location of Parent Eruption

EIT images of the visible disk near the inferred 2335 UT CME launch time reveal no candidate CME source. Based on flare productivity, magnetic evolution, and latitude, AR 9557 (Carrington longitude $\sim$290; S20) was the most likely back side region to have produced the CME. When AR 9557 returned to the visible disk on 20 August as AR 9591 ($\sim$295; S20), it was the only region associated with M-class flares from 20-25 August. Extrapolating the positions of the last visible disk M-class flare from 9557 (on 7 August) and the first such flare from 9591 (24 August), yields a range of longitudes from $\sim$W180-W195 for the region on 15-16 August.

The east-west symmetry of the halo CME observed by the SOHO coronagraph (Figure 1) is consistent with a CME having its source in the southern solar hemisphere near back side central meridian. Similar symmetry is displayed in an EIT image at 0025 UT showing dimming around the entire limb, most pronounced in the south. For both coronagraph and EIT images, the first manifestations of this event were in the southwest and the east-west symmetry only became apparent in later frames.

Helioseismology allows us to construct images of the back side of the Sun on 15-16 August from SOHO MDI observations of the visible disk. In these images, AR 9557, located between $\sim$W180-200, is the largest invisible-disk region and exhibits flux emergence near the time of the halo CME.

Low frequency radio emission in this event was observed by both Wind and Ulysses. Spectra of the bursts as observed at Wind are shown in Figure 2(a). The absence of significant high frequency ($>$ 1 MHz) emission in the WAVES detector at the time of the inferred CME launch at 2335 UT is consistent with an occulted flare

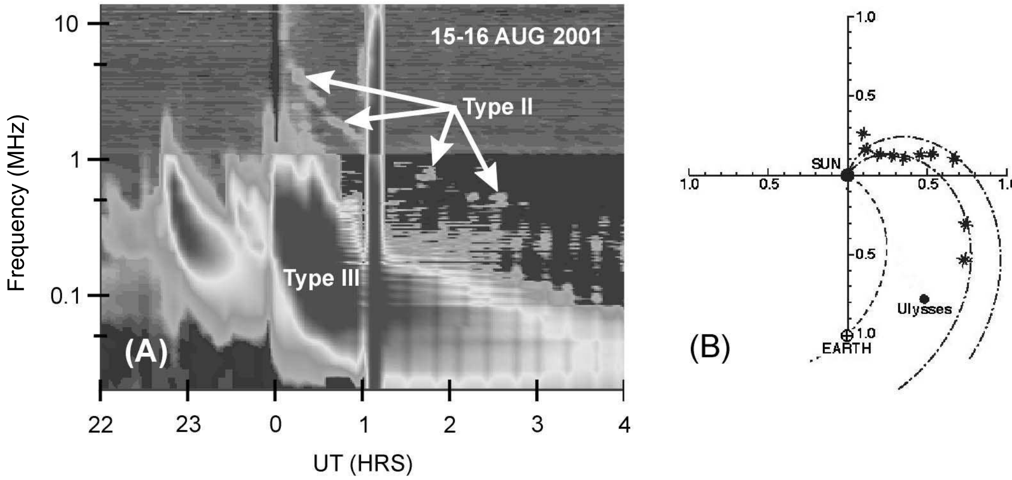

Figure 2. (a) Wind/WAVES radio data showing a DH type II burst and associated type III emission on 15-16 August 2001. (b) Trajectory of the centroid of type III emission from 0000-0040 UT on 16 August.

(impulsive phase) emission source. Wind is in Earth orbit while Ulysses was located ∼1.65 AU above the ecliptic plane at a heliocentric latitude of ∼64° and an angle ∼34° west of the Earth-Sun line. The Wind and Ulysses data can be used to triangulate the position of the centroid (below 1 MHz) of the strong radio burst from 0000-0040 UT as it drifts to lower frequencies. The Parker spiral fit (dot-dashed curves) to the radio source locations (stars) derived for this burst suggests a solar origin of ∼W150 (Figure 2(b)). This magnetic spiral, corresponding to a relatively low solar wind speed of ∼250 km s^{-1}, might result from an apparent (westward) shift of the radio source centroids at lower frequencies due to proximity effects as the large radio source nears the spacecraft. Much, if not all, of the low frequency radio emission during this period appears to be emanating from the type II shock identified in Figure 2(a).

4. SEP Acceleration and Transport

At the onset of the SEP event, angular distributions from Wind/EPACT show that ∼3 MeV/nuc H, He, and O ions have a "front-to-back" intensity ratio of ∼6. The preferred direction of arrival was outward from the Sun, centered on the field line to Earth. The event-integrated Fe/O (based on measurements from Wind and ACE), increases at the lowest energies until it reaches the coronal value at ∼1 MeV, above which energy it remains relatively constant. Measurements from the MAST experiment on SAMPEX give an oxygen charge state ∼6, indicating a source in a 1-2 MK coronal plasma [6].

We obtained three estimates for the time of SEP injection: (1) For a nominal 1.2 AU path length, the observed relativistic electron onsets imply a departure time from the Sun of 0011 UT ± 3 min; (2) an onset-dispersion analysis (onset time vs. inverse beta plot) using measurements of only the most energetic electrons and protons yields a solar release time of 0005 UT ± 4 min (path length = 1.8 ± 0.3 AU); and (3) an onset dispersion analysis that includes alphas and slower protons gives an injection time at the Sun of 0000 UT ± 3 min (2.1 ± 0.1 AU). To accommodate the uncertainty, we take the range of injection times to be two sigma beyond the extremities obtained by the three methods, i.e., from 2354-0017 UT. The corresponding range of times for comparison with electromagnetic emissions observed at 1 AU is 0002-0025 UT.

What was happening on the Sun at the time that the first arriving particles were injected onto the field line connected to Earth? The first indication of activity at the limb due to the back side eruption can be seen in an EIT difference image at 2348 UT where dimming occurs in the southwest. By 0000 UT, the dimming is visible at the west limb and the dimming in the southwest has intensified. By 0025 UT, the dimming has become prominent around the entire Sun. The dimming above the limb between 2348-0000 UT implies that an EIT wave had propagated outward from the inferred CME launch site, with an average speed of $\sim$400-800 km s^{-1}.

The WAVES radio data in Figure 2 show a fundamental component of a DH type II burst starting at $\sim$0010 UT at $\sim$5 MHz. Extrapolating the frequency-time drift of the type II yields an initiation time $\sim$2330 UT. The type II onset at $\sim$0010 UT may be due to deoccultation or it may result from decreasing Alfven speed in the corona (e.g., [7]). The radio emission arising at lower frequencies than the type II burst during the inferred 0002-0025 UT injection time is type III emission caused by electrons propagating on open field lines. Because of their temporal association with the shock, these radio bursts would be referred to as SA (shock-accelerated) events. Given: (1) the onset of particle injection near the onset of the DH type II (and the type III emission which appears to emanate from the slow-drift burst); (2) the continuation of the DH shock through the peak of the high-energy SEP event at $\sim$0230 UT; and (3) the essentially coronal (rather than flare) values of both the Fe/O ratio and O charge state of the SEP event, it is natural to attribute the energetic protons to the shock.

Based on the above observations, we propose the following picture for this extreme propagation event: As the CME propagates outward it drives a disturbance/shock (manifested by the EIT dimming at the limb) that encompasses the invisible hemisphere and wraps around to the front side of the Sun where it intercepts the Earth IMF spiral sometime between 0002-0025 UT, giving shock-accelerated SEPs access to Earth.

5. Discussion

We have presented evidence that: (1) $>$ 400 MeV protons were injected onto the spiral field line connected to Earth within $\sim$40 minutes of a solar eruption at $\sim$W180; and (2) that the energetic protons observed near Earth were accelerated and injected onto the IMF line to Earth by a coronal shock wave.

Our near disk center back side location for the 15-16 August 2001 SEP event is supported by associations of prompt energetic SEP events with front side eastern hemisphere eruptions, e.g., 7 October 1981 (E83), that are located at longitudinal distances from the footpoint to Earth's IMF spiral comparable to that observed in this case. Other cases of injection of high-energy SEPs in conjunction with large-scale propagating solar disturbances have been reported previously (e.g., [4, 8]).

References

[1] D.V. Reames, Space Sci. Rev. 90, 413 (1999).
[2] H.V. Cane and W.C Erickson, J. Geophys. Res. 108, Issue A5, pp. SSH 8-1.
[3] H.W. Dodson and E.R. Hedeman, Solar Phys. 9, 278 (1969).
[4] E.W. Cliver, Solar Phys. 75, 341 (1982).
[5] H. Debrunner et al., J. Geophys. Res. 93, 7206 (1988).
[6] A.W. Labrador et al., Proc. 28th Int. Cosmic Ray Conf., 6, 3269 (2003).
[7] S.A. Knock and I.H. Cairns, J. Geophys. Res., 110, Issue A1, cite ID A01101 (2005).
[8] Cliver, E.W., et al., Proc. 24th Int. Cocmic Ray Conf., 4, 257 (1995).