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Unusual Observations during the December 2006 Solar Energetic Particle Events within an Interplanetary Coronal Mass Ejection at 1 AU

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Abstract. In mid December 2006 several flares on the Sun occurred in rapid succession, spawning several CMEs and bathing the Earth in multiple solar energetic particle (SEP) events. One such SEP event occurring on December 14 was observed at the Earth just as an interplanetary CME (ICME) from a previous flare on December 13 was transiting the Earth. Although solar wind observations during this time show typical energetic proton fluxes from the prior SEP event and IP shock driven ahead of the ICME, as the ICME passes the Earth unusual energetic particle signatures are observed. Measurements from ACE, Wind, and STEREO show proton flux variations at energies ranging from ~3 MeV up to greater than 70 MeV. Energetic electron signatures from ACE show similar variations. Within the Earth's magnetosphere Polar HIST also sees these proton flux variations at energies greater than 10 MeV while crossing open field lines in the southern polar cap. Although no such variation in the energetic proton flux is observed at the GOES 11 spacecraft in geosynchronous orbit near the subsolar region, differential fluxes observed at GOES 11 and GOES 12 in the 15-40 MeV energy range do show some variability, indicating the signature is observable near dawn and dusk.

Keywords: energetic particles, ejecta, driver gases, and magnetic clouds
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INTRODUCTION

Energetic particles serve as useful probes of the solar wind structures through which they propagate and are a primary source of the highest particle intensities observed at Earth. Analysis and modeling of solar energetic particles (SEPs) provides vital information on particle scattering and transport in the interplanetary medium. Although once believed to be accelerated in solar flares and diffusing across coronal and interplanetary magnetic fields, it is now understood that much of the energetic particle population from SEPs is accelerated at shocks driven by coronal mass ejections (CMEs). The focus of this paper is to study the solar wind structures ahead of energetic particle events to help elucidate how solar wind magnetic field topology influences observations made by interplanetary and Earth-orbiting spacecraft.

In Section 2, we briefly discuss the energy response of the Polar High Energy Space Telescope (HIST) to the December 13, 2006 SEP event and the cross calibration of the instrument relative to the GOES spacecraft response. In Section 3, we use this calibration in the analysis of the unusual signatures of the December 14, 2006 SEP event observed at

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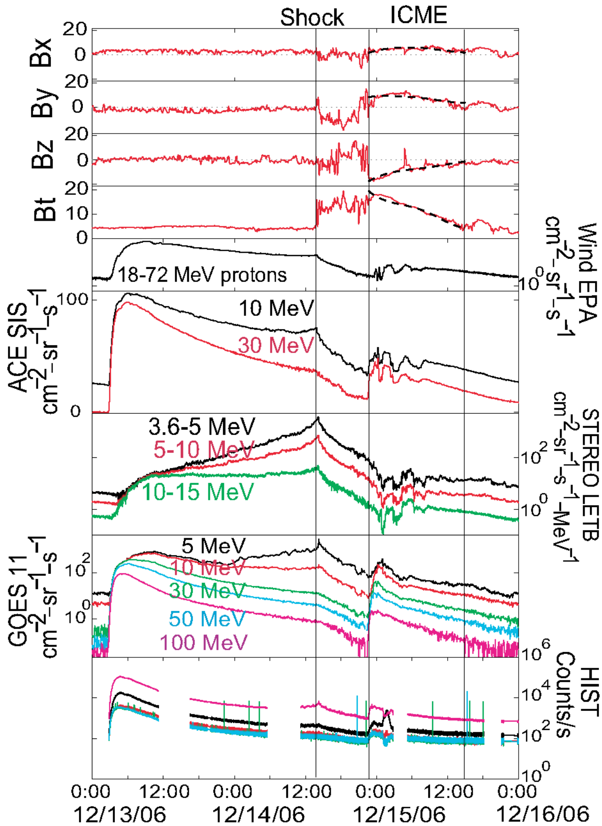

FIGURE 1. Time series plot of ACE magnetic field in GSE coordinates and the December 13 and 14, 2006 SEP events observed at Wind (integral rate), ACE (integral rate), STEREO LET B (differential rate), GOES 11 (integral rate), and Polar HIST (count rate). Note the December 14 SEP event occurs just after a shock and within an ICME (marked by the vertical lines) and exhibits a quasi-oscillatory time profile, especially at lower energies.

the ACE, Wind, STEREO, GOES, and Polar spacecraft. In Section 4, we briefly discuss the implications of our work and summarize our conclusions.

POLAR HIST CALIBRATION WITH GOES 11

In mid December 2006 several solar flares occurred with several CMEs in rapid succession, bathing the Earth in a series of solar energetic particle (SEP) events. Solar wind *in situ* observations of these events were made with several spacecraft including ACE [1], Wind [2], and STEREO [3], and in the Earth's magnetosphere with Polar [4] and GOES 10, 11, and 12 satellites [5]. Figure 1 shows such spacecraft observations for the December 13, 2006 SEP event.

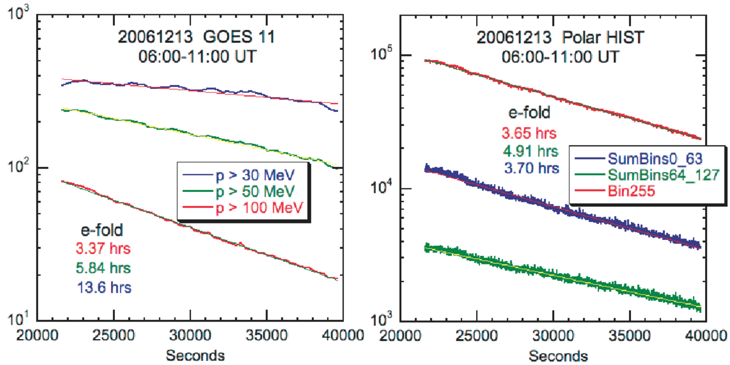

FIGURE 2. Energetic particle intensity decay of the December 13, 2006 SEP event as observed at GOES 11 (left panel) and Polar HIST (right panel). Decay was exponential with a large number of protons ≥100 MeV. The calibration interval, 0600 UT -1100 UT, is chosen to maximize the decay and minimize the influence of the radiation belts, truncated 1 hr prior to Polar crossing into the belts. HIST data are divided into 4 sums of 64 bins (bin sums [0, 63] and [64,127] are shown). All pulses larger than 10 MeV appear in overflow bin 255. The e-fold time of HIST is 3.65 hrs similar to the GOES 100 MeV channel with e-fold time of 3.37 hrs.

The intense, high-energy SEP event on December 13, 2006 provided the opportunity to intercalibrate the Polar HIST sensor in a high-resolution mode that allows large count rates of 10^5 particles/sec. After the SEP peaked in intensity at ∼0430 UT, the decay seen by GOES 11 was exponential with a large number of protons above 100 MeV, as shown in the left panel of Figure 2. This exponential decay allows the unambiguous determination of the e-fold time at both the Polar and GOES spacecraft. The time interval chosen in Figure 2 is at the beginning of the exponential decay of the solar particles to an hour before HIST data is affected by the radiation belts and prior to the onset of geomagnetic cutoff effects. The estimate for the effective threshold of the HIST scintillator protons is ∼100 MeV based upon the sensor construction and its placement in a massive spacecraft (ignoring the instrument aperature, its solid angle being orders of magnitude less than 4π-sr). Because of the relatively large size of the scintillator most protons above the penetration threshold should deposit ∼10-50 MeV.

During this high resolution mode operation of HIST, the pulse-height spectrum in the scintillator is digitized into 256 channels from close to the noise threshold up to 10 MeV. All pulses greater than 10 MeV appear in the upper channel, bin 255. The right panel of Figure 2 shows several bins from HIST covering the same time period as the GOES data in the left panel. The histogram data are divided into four sums of 64 bins plus the overflow bin, Bin 255. As expected, during the SEP event, most of the counts are in Bin 255 (i.e. the proton energy deposit exceeds 10 MeV after penetration through the spacecraft). Notice that the e-fold time of 3.65 hours fitted to the exponential decay of Polar HIST Bin 255 is similar to that of the GOES ≥100 MeV channel e-fold decay time of 3.37 hours. This similar e-fold time means the energy response in Bin 255 for the December SEP events is nearly equivalent and directly comparable to the GOES 100 MeV proton channel.

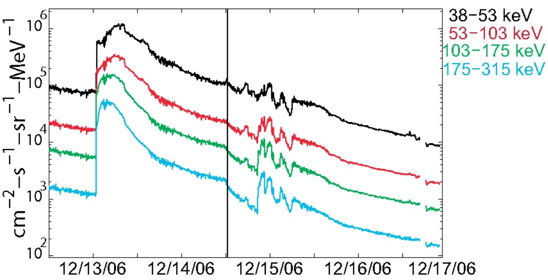

FIGURE 3. ACE EPAM differential electron flux data shown at 38 keV to 315 keV energies Note the short-scale modulation is clear at all energies.

ANALYSIS OF DECEMBER 14, 2006 SEP

During the December SEP events, ACE and Wind were on opposite sides of the Earth-Sun line and above the heliospheric neutral sheet, separated by ~100 Re along the dawn-dusk line. Both spacecraft were near the L1 Lagrangian point at ~240 Re sunward of the Earth. The newly launched STEREO spacecraft were just outside the Earth's bow shock at ~20 Re on the dawn side and on the way towards the moon to get a gravitational assist. Prior to the December 14, 2006 SEP event, the energetic proton flux remained elevated from the December 13, 2006 SEP event and the interplanetary shock driven ahead of the ICME. On December 14, 2006, a shock driven by the transiting ICME was observed at ACE and Wind at ~1355 UT. Shortly after the shock passage, the second SEP event with a harder spectrum was observed on December 14, 2006 at ~2300 UT, coincident with the Earth crossing into the leading edge of the ICME. It is during this time that measurements from ACE, Wind, and STEREO showed a similar, but unusual temporal profile in the integrated proton flux at energies ranging from ~3 MeV up to greater than 70 MeV (see Figure 1). As shown in Figure 1, the proton flux variation occurs from 0100 UT on December 15 to nearly 0900 UT during which time the flux undergoes at least three statistically significant drops in intensity that exceed the standard error of the mean. Note that these intensity variations show no energy dispersion. During this period within the Earth's magnetosphere, Polar HIST also observed proton flux variations at energies greater than 10 MeV while crossing open field lines in the Earth's southern polar cap at ~9 Re. The temporal profile of these variations was similar to those observed in the solar wind at ACE, Wind, and STEREO. Polar continued to observe these variations until it plunged into the radiation belts at ~ 0400 UT on December 15, 2006.

Figure 3 shows energetic electrons from ~40 keV to 315 keV observed by the EPAM instrument aboard ACE. The rise of the electrons due to the SEP event on December 13 is clearly seen as is the discontinuous change in slope at the shock (marked by the vertical line). Late on December 14 the injection of electrons associated with the second SEP event is observed just inside the ICME leading edge with a similar modulation as seen in the protons. Pitch angle distributions (not shown) indicate the electrons, especially

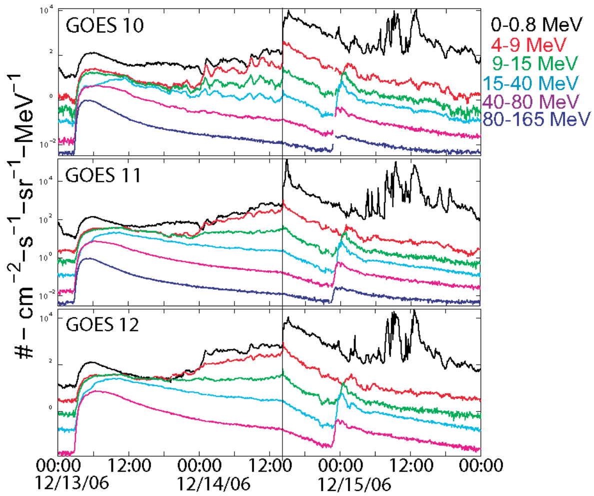

FIGURE 4. Differential proton flux data shown at 1 MeV to 80 MeV energies for GOES 10, 11, and 12, in the top, middle, and bottom panels, respectively. The GOES 12 15-40 MeV energy band shows clear short-scale modulation.

at higher energies, are bidirectionally streaming along the field during this time (E. Roelof private communication). The bidirectional streaming signature along with the dispersionless signature may indicate that the particle population is accelerated by the nearby shock and is obscuring direct observation of the particles accelerated near the Sun. Another plausible mechanism is that the shock may simply be trapping previously accelerated electrons.

The energetic proton flux observations differed substantially at GOES in geostationary orbit from those observed in the polar cap at Polar and in the upstream solar wind. Although GOES 11 was near the subsolar region during the main SEP onset, no such variation in the integral proton fluxes was observed at GOES 11 (GOES 12 integral flux data were unavailable at this time). Figure 4 shows GOES 10, 11, and 12 differential proton fluxes from $\sim$1 MeV to 80 MeV energies in the three panels, respectively. Note only GOES 12, near dusk during this time, shows strong evidence of some short-scale variability, and only in the 15-40 MeV energy range. GOES 10, near dawn, shows slight short-scale variability in the same energy range. Considering the flaring region on December 14, 2006 is near the center of the solar disk, better magnetic connectivity is expected at dawn due to nominal Parker spiral field direction. However, this is not observed.

DISCUSSION AND CONCLUSIONS

The intense, high-energy SEP event on December 13, 2006 provided the opportunity to cross-calibrate the Polar HIST sensor in a high statistics mode that allows large count rates of 10^5 particles/sec. The exponential SEP decay allowed the e-fold time to be unambiguously compared and the similarity between the e-fold time at the GOES 100 MeV channel and HIST Bin 255 indicates the energy response of HIST is ~100 MeV. Prior studies have shown the best observation periods for interplanetary studies with Polar are when Polar is on open field lines either crossing through the polar cap or in the auroral oval [6]. During the SEP event observed on December 14, 2006 at ~2300 UT, measurements from ACE, Wind, and STEREO show similar, but unusual temporal profiles in the integrated proton flux at energies ranging from ~3 MeV up to greater than 70 MeV. These unusual variations are coincident with the Earth crossing into the leading edge of an ICME and are evident in both the energetic electron and proton observations. The unusual SEP signatures also extend into the Earth's magnetosphere, made clearly evident by Polar HIST energetic proton observations as Polar crosses through open field lines in the Earth's polar cap. Signatures observed in geostationary orbit remains ambiguous with only GOES 12 near dusk observing strong short-scale variation.

There are several possible mechanisms for these unusual energetic particle signatures due to the complexity of the ambient solar wind during the SEP events. Since the SEP event on December 14 occurs just within the leading edge of the flux rope, one such mechanism is that the tangential rotations and planar structures in the ICME magnetosheath preferentially backscatter the particles sunward, away from the more coherent flux rope guiding fields causing the strange modulation observed. Preliminary numerical particle tracing through electromagnetic fields shows scattering at the sheath boundary affecting the particle trajectories similarly over the spectral range of 20-110 MeV. Another possibility is that the spacecraft are magnetically connected both to the ICME shock and the flare region during the period of unusual particle variability. Since the ICME shock is located very close at ~1/12 AU beyond Earth at SEP onset, the spacecraft could be simultaneously observing the reflected shock and flare accelerated particles, which then would result in the bidirectional streaming signature. This connectivity would also explain the observed variations in the Earth's magnetosphere preferentially near dawn and dusk and not near the subsolar region. One final mechanism consistent with the observations may be the mixing of populated and unpopulated flux tubes near the flaring region due to magnetic footpoint motion near the flare site as suggested by [7]. As the flux tubes are convected to 1 AU they become mixed causing dropouts ~0.01 AU in size, similar to the scale size of the flux modulation shown in Figure 1 and Figure 3.

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