



Unusual solar energetic proton fluxes at 1 AU within an interplanetary CME

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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 occurring on December 15th was observed at the Earth just as an interplanetary CME (ICME) from a previous flare on December 13th was transiting the Earth. Although solar wind observations during this time show typical energetic proton fluxes from the prior SEP 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 unusual proton flux variations at energies ranging from ~ 3 MeV up to greater than 70 MeV. Within the Earth's magnetosphere Polar HIST also sees unusual proton flux variations at energies greater than 10 MeV while crossing open field lines in the southern polar cap. However, no such variation in the energetic proton flux is observed at the GOES 10 or GOES 11 spacecraft in geosynchronous orbit. Differential fluxes observed at GOES 12 in the 15-40 MeV energy range show some variation. However, the overall energetic particle signature within the ICME at GEO orbits remains unclear. This event illustrates the need for caution when using GEO data in detailed studies of SEP events and in interplanetary models of energetic particle transport to 1 AU.

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 topology influences observations made by interplanetary and Earth orbiting spacecraft.

In Section 2, we analyze the energy response of the Polar High Energy Space Telescope (HIST) to the December 13, 2006 SEP and cross calibrate the instrument in a high statistics mode 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 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 flares on the Sun occurred in rapid succession, spawning several CMEs and bathing the Earth in multiple solar energetic particle (SEP) events. *In situ* observations of these events were made in the solar wind with several spacecraft including ACE [1], Wind [2], and STEREO [3], and in the Earth's magnetosphere with Polar and GOES 10, 11, and 12 satellites [4] as shown in Figure 1.

The intense, high-energy SEP event on December 13, 2006 provided the opportunity to intercalibrate the Polar HIST sensor in a high-resolution mode

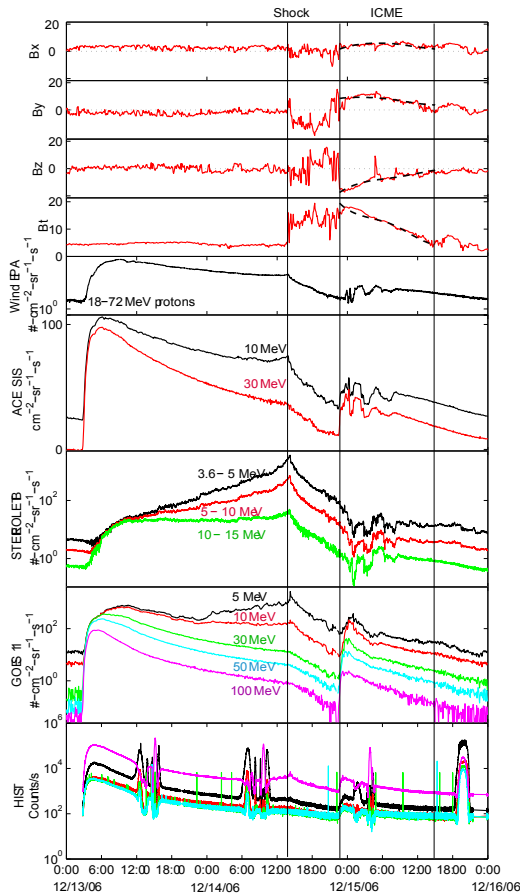


Figure 1: Time series plot of ACE magnetic field in GSE coordinates and the December 13 and 15, 2006 SEPs observed at Wind, ACE, STEREO LET B, GOES 11, and Polar HIST. Note the December 15th SEP occurs just after a shock and within an ICME marked by the vertical lines.

that allows large count rates of 10^5 particles/sec. After the SEP peaked in intensity, the decay seen by GOES 11 was exponential with a large number of protons above 100 MeV, as shown in the top 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 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 aperture, its solid angle being orders of magnitude less than 4π). Because of the relative large size of the scintillator most protons above the penetration threshold should deposit ~ 10 -50 MeV in the scintillator.

During this high resolution mode operation of HIST, the pulse-height spectrum in the plastic scintillator is digitized into 256 channels from close to the noise threshold up to 10 MeV. All pulses greater than 10 MeV in the scintillator appear in the upper channel, bin 255. The bottom panel of Figure 2 shows several bins from HIST covering the same time period as the GOES data in the top panel. The histogram data are divided into four sums of 64 bins plus the overflow bin, Bin 255. As expected, during the SEP, 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.

Analysis of December 15, 2006 SEP

During the December SEPs, 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

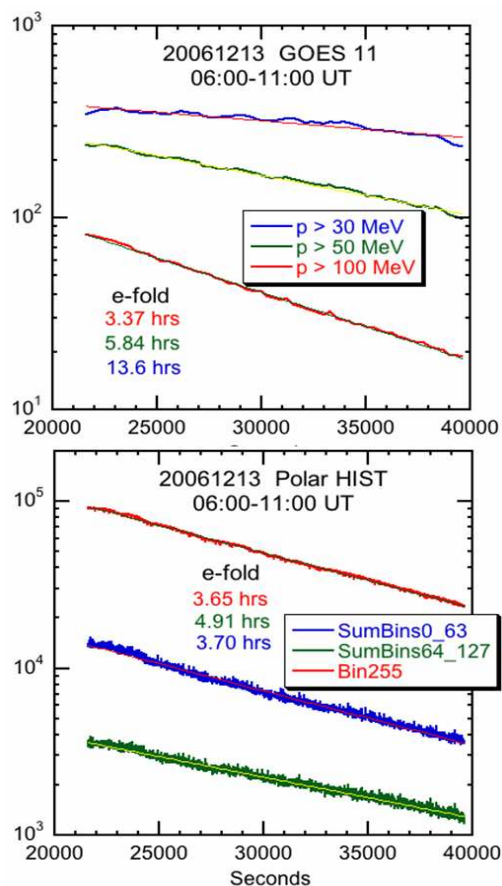


Figure 2: Energetic particle decay of the December 13, 2006 SEP as observed at GOES 11 (top panel) and Polar HIST (bottom panel). The event decay was exponential with large number of protons ≥ 100 MeV. The calibration interval shown 0600 UT 1100 UT is chosen to maximize the decay data and minimize the influence of the radiation belts. The data was truncated 1 hr prior to Polar crossing into the radiation 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 GOES 100 MeV channel with e-fold time of 3.37 hrs.

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 15, 2006 SEP event, the energetic proton flux remained elevated from December 13, 2006 SEP and 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 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). 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.

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 10 was at dusk, GOES 11 at dawn, and GOES 12 is in the subsolar region during the SEP onset, no such variation in the integral proton fluxes was observed at GOES 10 or GOES 11 (GOES 12 integral flux data was unavailable at this time.) Figure 3 shows GOES 10, 11, and 12 differential proton fluxes from ~ 1 MeV to 80 MeV energies in the three panels, respectively. Note only GOES 12 shows evidence of some short-scale variability, and only in the 15-40 MeV energy range. GOES 10 and 11 shows little, if any short-scale variability at any energy. Considering the flaring region on December 15, 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. Thus, the overall energetic

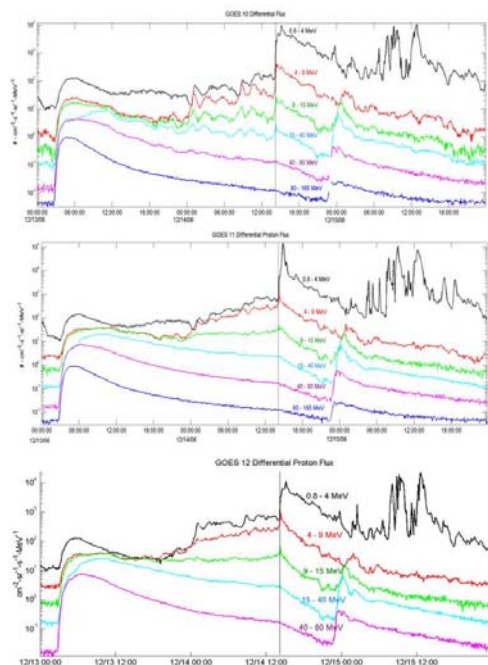


Figure 3: Differential proton flux data shown at 1 MeV to 80 MeV energies for GOES 10, 11, and 12, in the top, middle, and bottom panels, respectively. GOES 10 and 11 show little if any short-scale modulation, but the GOES 12 15-40 MeV energy band shows clear short-scale modulation.

particle signature within the ICME at GEO orbits remains unclear.

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 at both Polar and GOES. The similar e-fold time at the GOES 100 MeV channel and HIST Bin 255 enables direct comparison of the energetic proton observations at Polar and GOES for the two December SEPs. 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 PC or in the auroral oval [5]. During the SEP observed on December 14, 2006 at ~ 2300 UT, measurements from ACE, Wind, and STEREO showed 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 were coincident with the Earth crossing into the leading edge of an ICME. The unusual SEP signatures are clearly evident in the solar wind and at Polar HIST on open field lines in the Earth's magnetosphere. However, the signature observed in GEO orbit remains ambiguous with only GOES 12 near dusk observing the short-scale anisotropy. Thus caution needs to be exercised when using GOES energetic particle data in detailed studies of SEP events and in interplanetary models of energetic particle transport and anisotropy that rely heavily on GEO particle data at 1 AU.

Acknowledgements

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