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Observations of the December 2006 solar energetic particle events with the Low Energy Telescope (LET) on STEREO

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Abstract: NASA's Solar-Terrestrial Relations Observatory (STEREO) was launched in October 2006 carrying an advanced payload of imaging and *in situ* instrumentation designed to study coronal mass ejections and associated solar energetic particle (SEP) events and interplanetary effects. Included in the payload is a Low Energy Telescope (LET) designed to measure SEP composition, energy spectra, and anisotropies. This paper describes the LET sensor and measurements of the large solar eruptions of December 2006. These unexpected events fortunately provided opportunities to test the LET hardware and software and to cross-calibrate the LETs and several near-Earth instruments.

Introduction

NASA's twin STEREO spacecraft (named Ahead and Behind) each include four solar energetic particle (SEP) sensors (part of the IMPACT investigation [1]) that measure the composition and energy spectra of energetic ions with $1 \leq Z \leq 28$ from ~0.05 to ~100 MeV/nuc, as well as electrons. These include the Low Energy Telescope (LET), which measures ion composition from ~3 to ~30 MeV/nuc [2], and the High Energy Telescope (HET), which extends these measurements to ~100 MeV/nuc [3]. The LET and HET sensors were first powered up in space in mid-November of 2006. In early December, a sudden outburst of solar activity included four X-class flares and associated solar energetic particle (SEP) events. These events provided an excellent opportunity to test and optimize the on-board particle identification systems of LET and HET, and to cross-calibrate the response of STEREO sensors with near-Earth instruments.

In this paper we report results on the composition and energy spectra of the December 2006 SEP events, which were surprisingly large given the proximity to solar minimum (see Figure 1). This paper also discusses the particle identification approach used by LET to measure energetic particle composition and energy spectra onboard, and it describes LET data products available to the community.

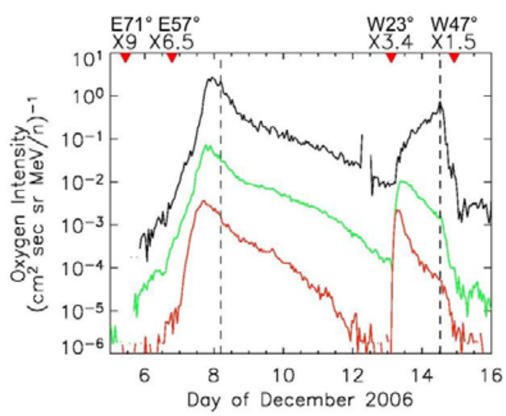

Figure 1: Oxygen intensity in 3 energy intervals during early December, 2006. The 3 MeV/nuc data are from LET; the 11 and 30 MeV/nuc data are from ACE/SIS. Occurrences of X-class flares and interplanetary shocks are indicated.

The Low Energy Telescope

Ion detection in LET is performed by an array of silicon solid-state detectors shown schematically in Figure 2 (see [2] for details). Each of the 2-cm^2 L1 devices is nominally 25 µm thick and has 3 segments. The 10.2 cm^2, rectangular 50-µm-thick L2 detectors have 10 segments, and the 15.6 cm^2, 1-mm-thick L3 devices have 2 segments. Valid events require a coincidence between L1 and L2, giving two 133° x 29° fan-shaped fields of view with the front fan centered on the average Parker spiral direction. The geometry factor of 4 $cm^2 sr$ includes 300 separate L1L2 combinations sorted onboard into 16 sectors.

The L1, L2 and L3 segments are analyzed by custom low-power Pulse Height Analysis System Integrated Circuits (PHASICs) developed at Caltech. There are 16 channels per PHASIC with a dynamic range of 5,000 to 10,000, depending on the input capacitance.

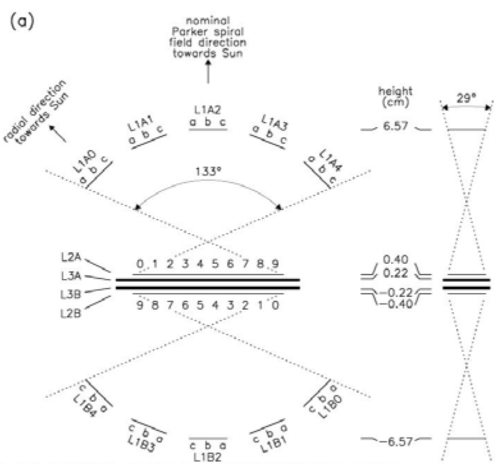

Figure 2: Schematic of the LET telescope

Particles that stop in L2, L3, and the 2nd L3 detector are fed to a Minimum Instruction Set Computer (MISC) that includes an on-board particle identification system based on ΔE vs. residual-energy matrices for Range 2 (L1-L2), Range 3 (L2-L3), or Range 4 (L3A-L3B). The individual pulse-heights are corrected for angle-of-incidence and detector thickness and then compared with species bands that depend on Range. The energy/nuc of an ion is determined by summing the energy deposits of the triggered detectors and dividing by the mass of the most abundant isotope. The 16 species are sorted into ~10 energy/nuc bins (see Figure 3).

In addition to data from the on-board particle identification system, which can process ~1000 events/sec, pulse-height data for ~4 events/sec are transmitted by telemetry. These data are useful for checking and optimizing the on-board system and also for identifying additional rare species. A charge histogram for Range-3 pulse-height data from the Behind spacecraft is shown in Figure 4.

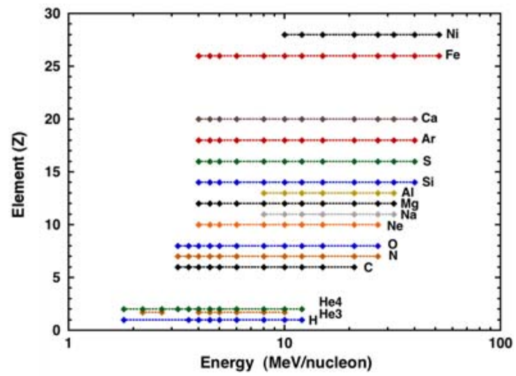

Figure 3: Species vs. energy/nuc bins identified on-board in LET.

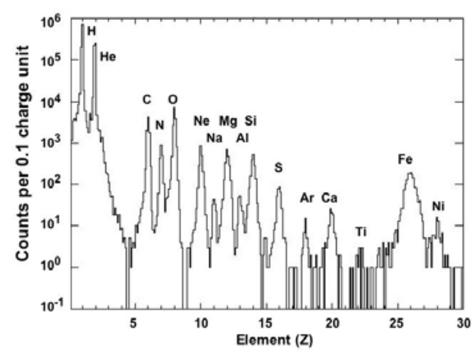

Figure 4: Charge histogram of LET/Behind Range-3 events from Nov. – Dec. 2006.

The December 2006 SEP Events

Although the particle intensities started increasing soon after the start of the Dec. 5 X-ray flare, it is likely that the Dec 6 particle injection was the larger of the two because the intensity appears to increase more rapidly after the onset of this event, which was also better connected to Earth. The composition of these events was somewhat Fe-poor (see Figure 5). At the onset of the Dec. 13

event the Fe/O ratio suddenly increased by ~x50 and then gradually decayed away. The event averaged 4-27 MeV/nuc Fe/O ratios were 0.092 for the Dec. 5-6 event and 0.55 for the Dec. 13 event. This behavior is typical of events originating in the eastern and western hemispheres [4], and Cohen et al. [5] discuss their relevance to recent models of Fe-rich SEP events.

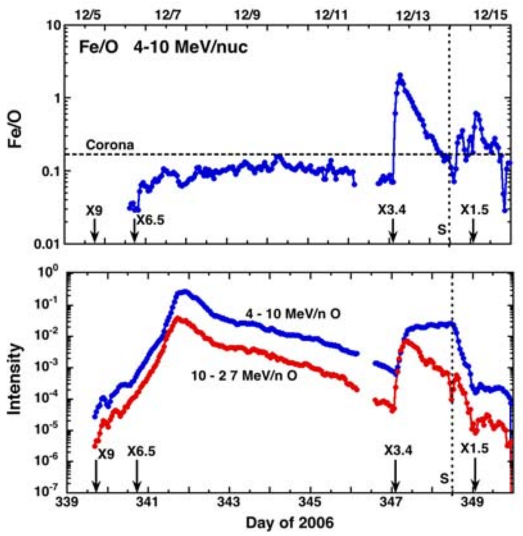

Figure 5: The Dec. 5-6 events are Fe-poor relative to the corona (dashed line), while the Dec. 13 event is Fe-rich.

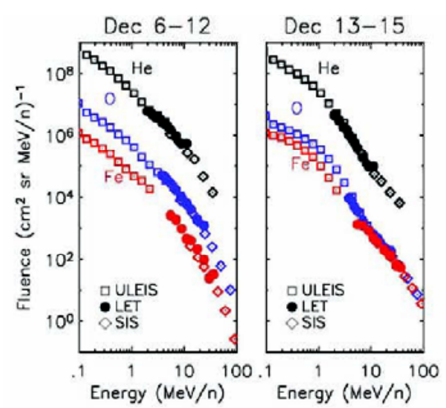

Figure 6: Fluence spectra for He, O and Fe from ACE/ULEIS, LET, and ACE/SIS.

Comparison with Other Spacecraft Data

The December SEP events provided an unexpected opportunity to cross-calibrate the response of the two LET instruments (which agree well), and to compare LET data with data from other near-Earth instruments. In Figure 6 the He, O, and Fe data from LET agree well with data from ACE/ULEIS and ACE/SIS. Similar agreement is found for other species identified onboard [5]. The spectral shape of all three species is the same if they are shifted in energy by an amount depending on the charge to mass ratio (Q/M) of the species (see, e.g., [6]).

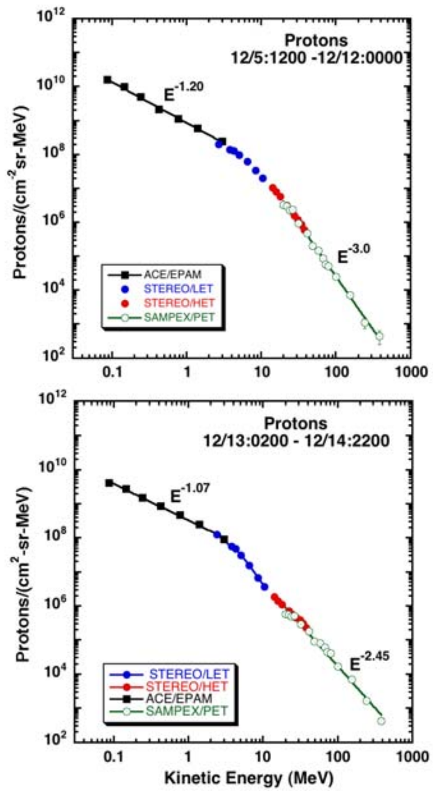

Figure 7: Fluence spectra of protons measured in the two largest December 2006 SEP events by ACE, STEREO, and SAMPEX instruments. Spectra from GOES-11 (not shown) also agree over the region from 5 to 100 MeV.

Both December events had reasonably hard proton spectra that could be measured up to ~400 MeV. Figure 7 shows proton fluence spectra based on data from ACE/EPAM, LET, HET and

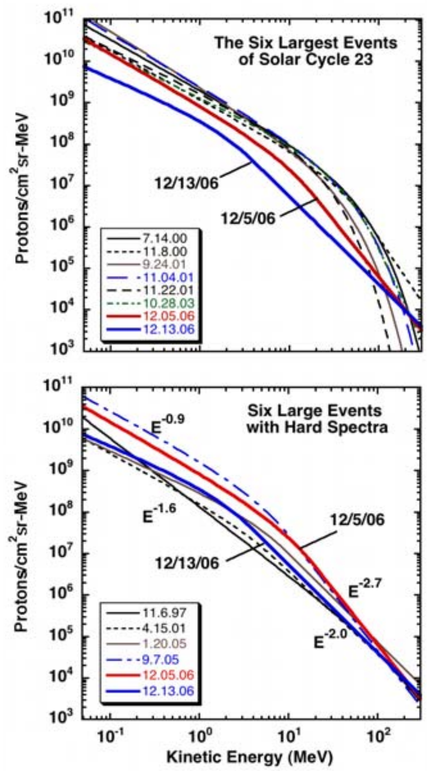

Figure 8: Spectra from the December events are compared with those of the six largest events of solar cycle 23 (top) and with four other events with hard energy spectra (bottom).

SAMPEX/PET. Note the excellent agreement among the instruments. Tylka et al. [7] suggested that hard spectra such as these result from acceleration at quasi-perpendicular shocks. It is of interest to compare the December 2006 events with others from solar cycle 23. Figure 8 compares spectral fits to the December events with those from the six largest events of solar cycle 23 (based on >30 MeV proton fluences from GOES) and also with four other events with hard energy spectra. The Dec. 5 and Dec 13 events come out to be the 11th and 15th largest on the cycle 23 list. The six largest events all have spectra that roll over in similar fashion beyond ~50 MeV, as in the 10/28/03 event [8]. The two Dec. 2006 events are more like the Jan. 20, 2005 event [9].

Summary

The December 2006 events provided the opportunity to thoroughly test the LET hardware and software, including the on-board particle identification system. Both LETs are performing beyond their design requirements. Figure 3 illustrates the species and energy bins that should routinely be available to the community as Level-1 data products, in addition to a comprehensive selection of real-time Beacon data [2].

These two SEP events also provided the unexpected opportunity to cross-calibrate the LETs and HETs with each other (Figure 7) and with other instruments in near-Earth orbit on ACE, GOES, and SAMPEX. The excellent agreement in Figures 6 and 7 demonstrates that the combination of STEREO and near-Earth spacecraft will provide reliable 3-point measurements of the longitudinal distributions of SEP events that can be integrated with other *in situ* and imaging data provided by STEREO.

Acknowledgements

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