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Solar Energetic Particle Anisotropies Observed by STEREO/LET

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Abstract: The Low Energy Telescopes (LETs) onboard the twin STEREO spacecraft can measure the anisotropies of energetic particles for protons through iron at energies of 1.8–12 MeV/nucleon, depending on species. A large variety of anisotropies are observed. Unidirectional beamed distributions often appear at the onset of magnetically well-connected solar energetic particle (SEP) events, while long-lasting bidirectional flows are seen within several interplanetary coronal mass ejections (ICMEs) due to either injection of particles at both footpoints of the CME or mirroring of a unidirectional beam. Several examples of a loss-cone distribution are clearly seen, in which particles with pitch angles far from the field direction are mirrored while those with smaller pitch angles are not, either because the magnetic field strength did not become large enough to turn the smaller pitch angle particles around, or more scattering occurred between the observer and the more distant mirror points of these particles. Distributions with pronounced depletions at 90° to the field, as well as those that instead have enhancements at 90° (i.e., trapped distributions) are also seen. The magnitude of the anisotropies often depends on particle energy and species, with lower energy particles typically more anisotropic than higher energy particles. We present some of the more interesting LET anisotropy observations throughout the STEREO mission to date and discuss the implications of these observations for SEP transport in the heliosphere.

Keywords: solar energetic particles, anisotropies, energetic particle transport, STEREO

1 Instrumentation

Sectored rates from the Low Energy Telescopes (LETs) onboard the twin Solar TErrestrial RElations Observatory (STEREO) spacecraft [1] provide information on particle anisotropies for elements or element groups from H through Fe. In this work, we mainly discuss protons, for which sectored rates in three energy bands of 1.8–3.6, 4–6, and 6–10 MeV are available since a commanded configuration change on 2010 November 22. The detectors of the LET instrument are arranged in two fans with viewing directions each spanning 133° of longitude in the ecliptic and ±15–20° of latitude out of the ecliptic [2]. One fan points toward the Sun and the other away, centered along the nominal Parker spiral field direction, which leaves a pair of longitudinal gaps in the field of view, each 47° wide, oriented perpendicular to the nominal magnetic field. Each detector in the instrument is segmented to allow determination of particle trajectories. Onboard the trajectory information is binned into sectored rates covering 16 different viewing directions, accumulated with a 1-minute cadence. For a sample of events, pulse-height data are also telemetered, including information on precisely which detector segments were triggered. For this relatively small sample (often <1% of the particles during periods with elevated count rates) intensities are measured in 300 viewing directions, providing greater angular resolution at the cost of greatly reduced statistical accuracy.

2 Observations and Discussion

2.1 Earlier LET Studies

A number of rather interesting periods stand out in the LET anisotropy data examined to date, several of which are discussed in our earlier works and are briefly summarized here.

During the large, gradual solar energetic particle (SEP) event observed at STEREO-Ahead on 2010 August 18, extremely large bidirectional anisotropies in 4–6 MeV protons were present for the first ∼17 hours of the event while the spacecraft was inside a magnetic cloud. Intensities along the field direction reached at least several hundred to nearly 1000 times greater than those perpendicular to the field [3], similar to an event observed in a magnetic cloud in 1998 by SOHO in which the parallel mean free path was calculated to be at least 10 AU [4]. Other unusual behavior in the particle anisotropies in the August 2010 event included the fact that at the trailing end of the cloud, the protons became isotropic and their spectrum hardened slightly while the He/H abundance ratio plunged by a factor of ∼4 for about 4 hours. Further details of LET observations during this event may be found in [3].

Inside of an interplanetary coronal mass ejection (ICME) flux rope near midday on 2011 March 8, a strongly bidirectional field-aligned flow with almost equal intensities in the forward and backward directions was observed at STEREO-Behind [5]. During this period the field direction was nearly perpendicular to the nominal Parker spiral direction and thus fell within the LET longitudinal viewing gap. The portion of the pitch angle distribution LET was able to observe showed intensities at directions 90° to the field that were a factor of ∼20 lower than those more nearly field-aligned. Similar 90° depletions that have been
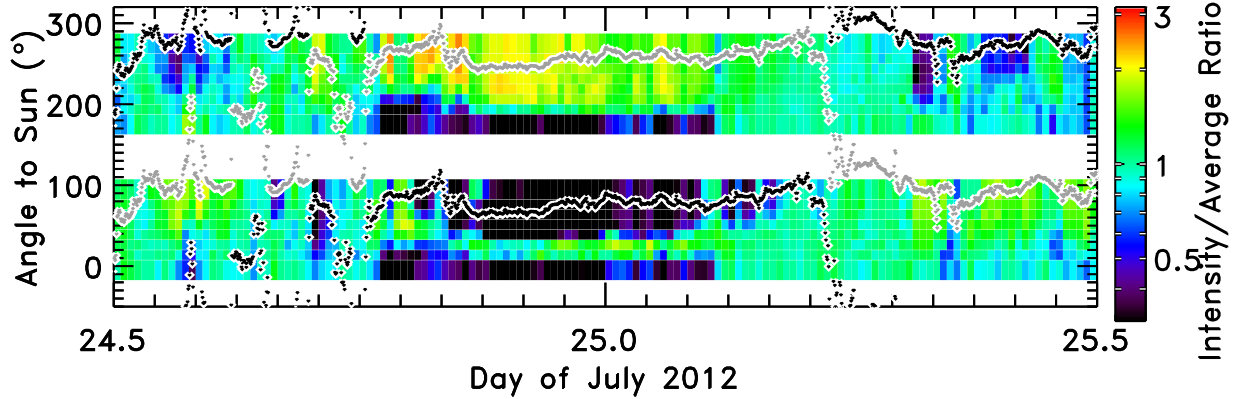
Figure 1: Relative intensity spectrogram of 4–6 MeV protons in each of 16 sectors from LET-Behind during the 2012 July 24–25 event. Shown are intensities in the in-ecliptic longitudinal viewing directions, with directions parallel (*black*) and antiparallel (*gray*) to the magnetic field longitudes superposed.

observed in solar wind suprathermal electrons are thought to arise from mirroring of an outward-going beam on an open field line at a magnetic field enhancement beyond the spacecraft [6]. Features such as these in energetic ion anisotropies have been used to infer the presence of reflecting boundaries in particle reservoirs [7].

An unusual particle distribution was observed at LET-Behind on 2012 January 19 [5]. A field-aligned beam was flanked on each side by a secondary beam separated from the main beam by a valley at 90° pitch angle, resulting in a pitch angle distribution exhibiting a loss cone as is commonly seen in the magnetosphere. Evidently the particles encountered an enhanced magnetic field bottleneck somewhere beyond the spacecraft [8] that caused particles with large pitch angles to be mirrored, while the field strengths were not great enough to turn around the particles with the smallest pitch angles, or perhaps scattering conditions changed substantially before these particles reached their more distant mirror points. In this example the width and depth of the loss cone was energy dependent, with the loss cone for the lower energy protons shallower and possibly narrower than for the higher energy protons. This is presumably due to greater scattering of the lower energy particles, since mirroring itself is independent of energy (assuming the field changes adiabatically). With further analysis and modeling, we may be able to disentangle the effects of scattering and mirroring in this event.

2.2 The 2012 July 24 Loss Cone

In the present work we present a more dramatic example of a loss-cone distribution observed at LET-Behind on 2012 July 24. This was associated with a flare, fast CME, a very large SEP event seen at the Ahead spacecraft, with proton intensities that would have ranked it as one of the largest on record if it had been directed towards Earth [9], and an unusual, particle-mediated blast wave observed in-situ at speeds exceeding 2000 km/s [10]. Here we discuss observations at the Behind spacecraft, however, which was 124° of heliolongitude westward from Ahead, where particle intensities were ∼100 times lower.

As is seen in figure 1, an anisotropic beam of 4–6 MeV protons appeared in the LET-Behind fan facing away from the Sun from ∼18:00 UT on July 24 until almost 03:00 UT on July 25. That is, energetic protons were streaming *towards* the Sun at this time. Comparison with data available
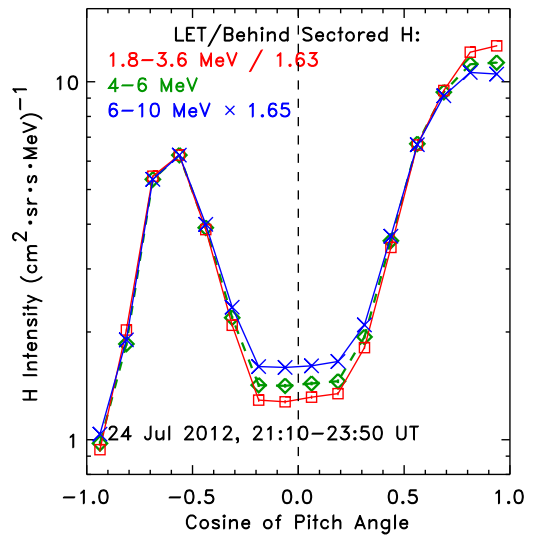

Figure 2: Pitch angle distributions, with intensities scaled as indicated, for protons in three energy bands from LET on STEREO-Behind during the loss-cone distribution of 2012 July 24.

at `http://stereo.cesr.fr` from the Solar Wind Electron Analyzer (SWEA) on STEREO confirms that the solar wind suprathermal electron strahl and LET energetic proton flows were in opposite directions and therefore that the protons were flowing from a location farther from the Sun than the spacecraft. Although STEREO-Behind did not observe any sign of a shock, the blast wave that passed STEREO-Ahead late on 23 July [10] would have been radially well beyond 1 AU by this time, and modeling indicates that the Behind spacecraft was magnetically connected to the shock after it passed [11], which was presumably the source of these particles.

Note that the edge of the beam distribution (i.e., at ∼190°–200°) in figure 1 appears similar to the narrow strip of enhanced intensities 180° away, while intensities along the field in the fan facing towards the Sun are at a relative minimum. This is a loss-cone distribution, as is more evident in the pitch angle plot shown in figure 2. If μ is the cosine of the pitch angle, then an incident beam is at $\mu = 1$. On the opposite side of the plot, the large pitch angle part
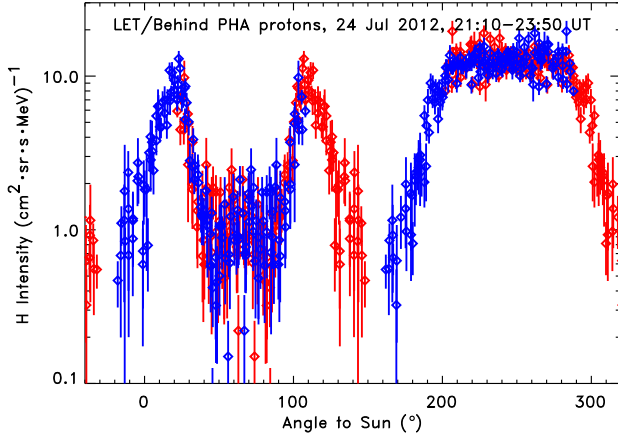
Figure 3: LET ~1.8–12 MeV proton intensities at STEREO-Behind derived from the telemetered pulse-height event data plotted versus viewing direction in the ecliptic. Actual data observed in the 300 viewing directions are shown (*blue*), along with data points estimated by assuming symmetry and reflecting the measured data about 65° and 245° (*red*) to illustrate the likely full distribution.

Figure 4: Enlarged view of the data from figure 3, with calculated shapes of loss cones of various widths superposed (see text).

of the distribution is mirrored, but at $\mu = -1$ there is a pronounced deficit of particles. Sectored protons in all three energy bands are shown (normalized as indicated), and in this example the shape of the loss cone is essentially independent of energy, unlike what was observed in the 2012 January 19 event [5]. The amplitude of the incident beam, however, shows a systematic dependence on energy, with the lower energies exhibiting a larger amplitude, narrower beam than the higher energies. We observe a similar pattern in nearly all the anisotropic periods we have studied in detail, and work is in progress to fit these distributions and extract quantitative data on the dependence of their shapes on particle energy and rigidity. Qualitatively, however, such behavior seems to be in agreement with expectations, as calculated anisotropies generally appear to be larger at smaller energies [12] due to pitch angle scattering.

Features in the pitch angle distribution in figure 2 are rather sharp, but the pitch angle bins are fairly broad. To better quantify the shape of the distribution, we examine the finer angular resolution pulse-height data in figure 3. For this figure, the intensities are plotted versus the 300 in-ecliptic longitudinal viewing directions relative to the Sun, rather than the pitch angle relative to the magnetic field. Although there is significant overlap in the fields of view among the 300 viewing cones, the improvement in angular resolution is substantial, with an average full width at half maximum of 5.3° of longitude for the pulse-height data compared with 12.2° for the sectored rates. Blue points in figure 3 are as actually measured, while red points are estimated assuming the observed features are symmetric. The beam edges at ~10° and ~190° are very similar in shape and intensity, but a steep-sided notch is cut out of the center of the distribution in the sunward-facing direction (centered at ~65°).

The results of a Monte Carlo calculation in which the pitch angle of each particle in an isotropic distribution incident upon the LET detector was calculated using the measured, 1-minute averaged magnetic field direction are shown in figure 4. To generate the red, black and blue dis-
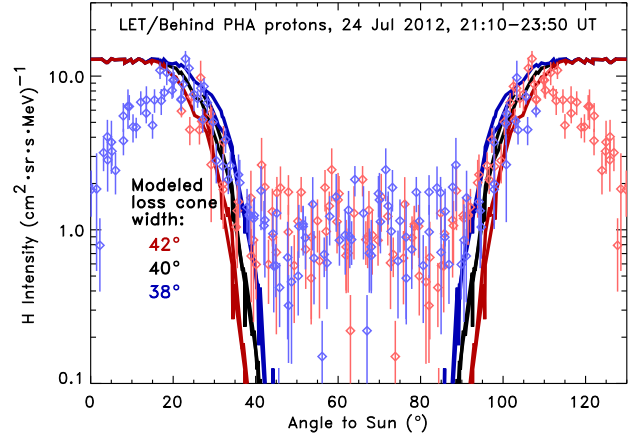
tributions, all particles in the calculation within 42°, 40°, and 38°, respectively, of the field were removed. Although the calculated loss cone is much emptier than actually observed, the shape of the edges is very similar to what is seen in the data, indicating that the measurements are consistent with a perfectly sharp loss cone convolved with the angular response of the instrument and the ~10° variation of the field direction during the time of the observation.

The width of the loss cone appears to be within a few degrees of 40°. As discussed, for example, in [13], conservation of the first adiabatic invariant implies that $\sin^2(\alpha_{\rm loss}) = B_{\rm bk}/B_{\rm mir}$, where $\alpha_{\rm loss}$ is the pitch angle of the loss-cone boundary, $B_{\rm bk}$ is the background magnetic field strength, and $B_{\rm mir}$ is the field strength at the magnetic mirror point. The ambient field strength was ~9 nT, therefore a 40° loss cone means that the field strength reached ~22 nT at the mirror point, somewhere sunward of the spacecraft. The field generally becomes stronger closer to the Sun, and an undisturbed Parker spiral field would have reached this strength ~0.4 AU from Behind. However, a loss cone would not appear in a field of this configuration, because beyond that distance the field would grow even stronger and cause the smaller pitch angle particles to also mirror. Instead, there must have been a constriction in the field, probably closer to the spacecraft, beyond which there was a region of reduced field strength and more scattering. The WSA-ENLIL-Cone model that confirmed the inward flow direction of the particles [11], when combined with SEPMOD, is also capable of predicting pitch angle distributions [14, 15]. It would be interesting to compare the results of this model with our data to see whether it predicts the observed loss cone and, if so, determine what it tells us about the location and nature of the field configuration responsible for the partial mirroring.

2.3 A Trapped Distribution

A very unusual pitch angle distribution was observed in some of the most recent STEREO/LET data that we have examined. As shown in figure 5, an anisotropy of moderate amplitude, with a peak-to-valley ratio of about a factor of 2–3, was observed at STEREO-Behind throughout all of 2013 May 5 and parts of the adjoining days. The peculiar aspect of this distribution is that instead of being aligned with the field direction, the peak intensities appear
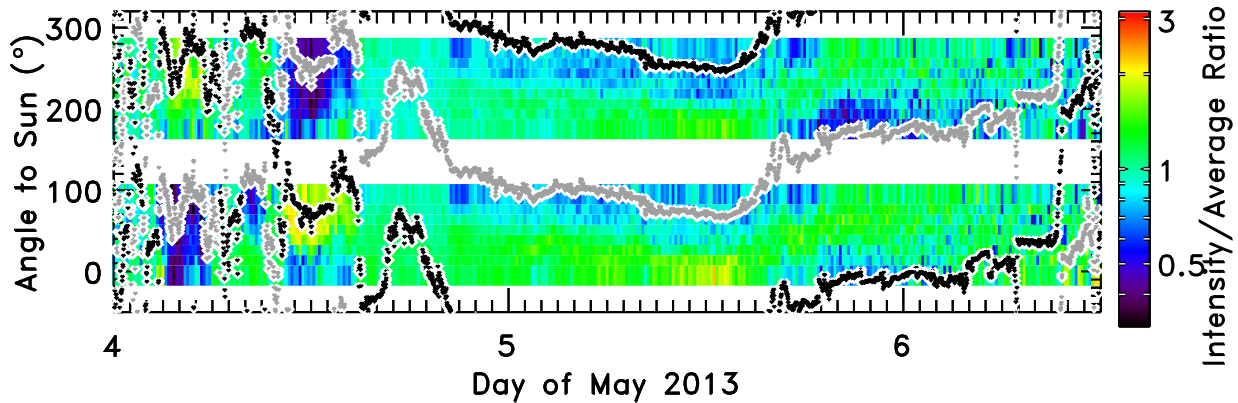
Figure 5: Relative intensity spectrogram of 4–6 MeV protons as in figure 1 with superposed magnetic field directions for a period at LET-Behind in May 2013. Note that peak particle intensities were at 90° to the field throughout all of 5 May.

at 90° to the field longitude, characteristic of a magnetically trapped distribution. (It should be noted that the magnetometer data used here were obtained from the near-real-time "beacon" data and should therefore be regarded as preliminary, however the field direction is not expected to be greatly different in the final, verified data release.) Although such trapped distributions have been reported in interplanetary space in the inner heliosphere before, they are apparently rather uncommon (see, e.g., [16] and references therein). It may be that these distributions arise from particles bouncing between two magnetic mirror points, with particles having small pitch angles escaping through loss cones at both ends [17].

3 Future Work

In addition to the proton anisotropies discussed here, most of these events were intense enough to allow LET to measure statistically meaningful He pitch angle distributions. While we are still working on obtaining quantitative information from fits to these distributions, it appears that often the He distributions are narrower than those of protons at the same energy per nucleon (although this may be variable from event to event). However, for a given species, the distributions tend to be broader at higher energies (e.g., figure 2). That is, the widths of the distributions seem to scale directly with velocity, v, but inversely with particle rigidity, R. Theoretical studies show that the pitch angle diffusion coefficient $D_{\mu\mu}$ scales for different particles as vR^{q-2}, where q is the index of the magnetic power spectrum [12]. This expression will scale directly with v but inversely with R as long as $q < 2$, and the value of q may vary from event to event. Quantitative analysis of the LET anisotropy data and comparison with magnetic power spectra and models should help to reveal insights into energetic particle transport in these interesting SEP events.

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