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A Survey of Anisotropic Energetic Particle Flows Observed by STEREO

R. A. Leske*, C. M. S. Cohen*, B. Dotson*, R. A. Mewaldt*, A. C. Cummings*, A. W. Labrador*, E. C. Stone*, M. E. Wiedenbeck†, E. R. Christian** and T. T. von Rosenvinge**

*California Institute of Technology, Pasadena, CA 91125 USA
†Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA
**NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA

Abstract. The Low Energy Telescopes (LETs) onboard the twin STEREO spacecraft have been measuring the anisotropies of energetic particles since before the beginning of solar cycle 24. Large unidirectional anisotropies often appear at the onset of magnetically well-connected solar energetic particle (SEP) events, suggesting beamed particles with relatively little scattering. Also, long-lasting bidirectional flows are seen during the decay phase of several SEP events. Some of these instances appear to be within interplanetary coronal mass ejections (ICMEs), as indicated by characteristics such as magnetic field rotations or bidirectional suprathermal electrons. We present preliminary findings from a survey of LET proton anisotropy observations, which illustrate that bidirectional flows appear more likely to come from directions far from the nominal Parker spiral direction than do unidirectional beams, consistent with previous studies. Individual cases that show unusual intensity depletions perpendicular to the magnetic field or pitch angle distributions otherwise indicative of magnetic mirroring are presented in more detail.

Keywords: Solar energetic particles, anisotropies, STEREO
PACS: 96.50.-e, 96.50.sh, 96.50.Vg

INTRODUCTION

The Low Energy Telescopes (LETs) onboard the twin Solar TErrestrial RElations Observatory (STEREO) spacecraft can measure the anisotropies of energetic particles for elements (or element groups) from H through Fe with energies between ~4 and 12 MeV/nuc. Sectored rates are accumulated in 16 different viewing directions distributed in two fans each spanning 133° of longitude in the ecliptic and ±15–20° of latitude out of the ecliptic, one pointing toward the Sun and one away, centered along the nominal Parker spiral field direction [1]. Note that this configuration results in a pair of gaps in the field of view each 47° wide pointed perpendicular to the nominal magnetic field.

We have started to use LET data to survey how frequently anisotropies appear, under what conditions they are found, and what their characteristics are (such as magnitude, flow direction, duration, etc.). Our preliminary analysis, consistent with earlier, similar surveys by others (e.g., [2]), suggests that solar energetic particles (SEPs) are found within interplanetary coronal mass ejections (ICMEs) relatively frequently. In these cases, magnetic field directions and particle flow directions can be unusual, such as flows towards the Sun or from the east. We present brief highlights of the survey thus far and discuss two interesting cases in more detail.

OBSERVATIONS

A thorough characterization of the particle anisotropies would require knowledge of the magnetic field direction, determination of the particle pitch angle distributions relative to the field, and parameterizing the distributions, such as by fitting to obtain the first and second order anisotropies (e.g., [3]). Furthermore, one would want to compare the resulting anisotropy measurements with the plasma conditions (solar wind velocity, density, temperature, plasma beta, etc.) prevailing at the time. Although we have done this for limited time periods [4], we have not yet completed such an analysis for the entire two-spacecraft, six-year-long dataset of the STEREO mission to date. However, significant information may be obtained from a much simpler analysis, as we illustrate in Figure 1.

A good indication of the anisotropy, or at least that portion within the instrument's field of view, may be obtained from the ratio of the maximum to minimum sectored intensities. The logarithm of this ratio for 4–6 MeV protons during the years 2011.0 to 2012.6 is plotted on the horizontal axis in Figure 1a. Data from both spacecraft in all ten-minute intervals in which there were more than three counts in the minimum sector are shown. Note that there are periods in which the magnitude is quite large, often well over 100. Indeed, there was an

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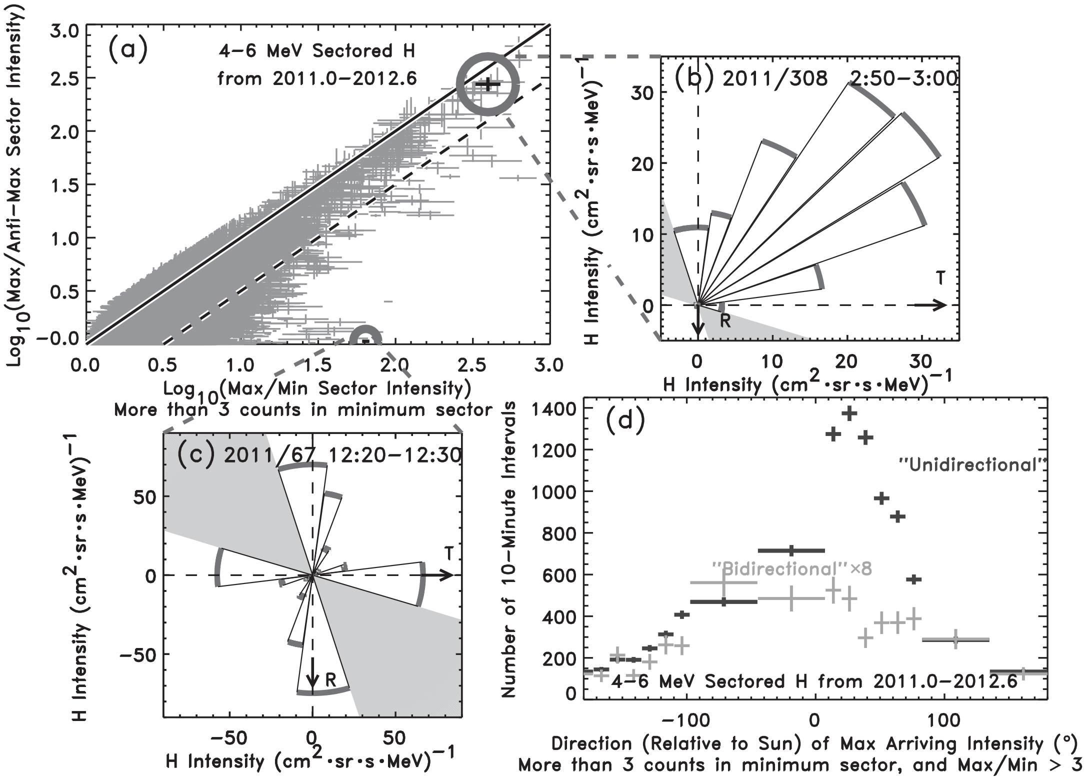

FIGURE 1. *(a)*: Comparison of the anisotropy "amplitude" (ratio of the maximum to minimum 10-minute averaged sectored intensities) with the intensity ratio of the maximum sector to the sector directly opposite the maximum for 4–6 MeV protons from STEREO/LET. *(b)*: Polar plot in RTN coordinates of an angular distribution from near the diagonal in *(a)* that is highly anisotropic but unidirectional, from STEREO-Ahead during the indicated time period. Gaps in the LET field of view are shaded here and in *(c)*. *(c)*: Example of an angular distribution from STEREO-Behind far from the diagonal in *(a)* that is strongly bidirectional. *(d)*: Directions relative to the Sun of maximum sectored intensities for anisotropic cases (Max/Min sectored intensities >3) above the dashed line in *(a)* ("unidirectional"; *black*) and below the line ("bidirectional"; *gray*).

interesting case on 18 August 2010 in which this ratio reached nearly 1000 within a magnetic cloud, which we discuss in detail in [4].

To simply characterize the shape of any particle distribution, one might wish to compare the intensities in the maximum direction with those in the opposite direction and in the directions perpendicular to the maximum, however the gaps in the LET field of view can make this difficult. Instead, on the vertical axis of Figure 1a, we show the ratio of the intensity in the maximum sector to that in the sector directly opposite the maximum sector. By definition, all points on this plot must lie on or below the diagonal; only the statistical error bars may extend above it. Purely isotropic distributions would appear at the origin, while other points near the diagonal should represent unidirectional distributions, since the minimum intensity is nearly the same as that in the direction opposite to the maximum intensity, as in the example in Figure 1b. Points far below the diagonal are strong candidates for bidirectional distributions, with a minimum intensity very different from that in the direction opposite to the maximum intensity. An arbitrary demarcation between events near and far from the diagonal is shown by the dashed line in Figure 1a. In the example in Figure 1c, the intensity opposite the maximum intensity is nearly the same as the maximum, while the minimum intensity is ∼60 times lower, and the distribution is strongly bidirectional (gaps in LET's longitudinal field of view are shaded; see Figure 2 for more about this period).

In Figures 1b and 1c, note that the unidirectional example is aligned with the nominal Parker spiral field direction (-R, +T in the RTN coordinates used), while flows in the bidirectional case are nearly perpendicular to the nominal direction. In a survey of SEP anisotropies, Richardson & Cane [2] found that flow directions in 30% of SEP event onsets observed in ICMEs came from east of the Sun, while in >90% of the events observed outside of ICMEs the flow directions were near the Parker spiral direction. We have not yet examined each period to determine the presence of ICMEs, but we find in Figure 1d that in cases with significant anisotropies (with the maximum sectored intensity more than 3 times the mini-

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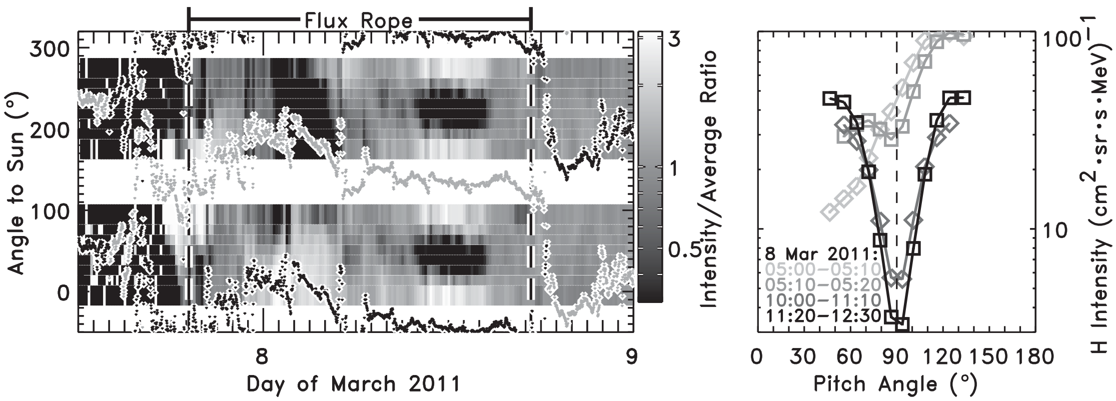

FIGURE 2. *Left panel*: Intensity ratios of 4–6 MeV protons in each of 16 sectors to the sector-averaged intensity from LET-Behind during the 8 March 2011 period. Superposed are the directions both parallel (*black*) and antiparallel (*gray*) to the magnetic field longitudes, and start and end times of a flux rope are indicated. The grayscale saturates at ratios of ∼0.3 and 3, but proton anisotropies were at times much larger than this. *Right panel*: Evolution of the 4–6 MeV proton pitch angle distributions during the strong 90° depletion near midday on 8 March.

mum) the maximum intensity in the "unidirectional" periods (above the dashed line in Figure 1a) strongly favors directions near nominal, while in "bidirectional" periods (below the dashed line) flows towards the Sun from the east are relatively more common. If bidirectional flows preferentially occur in ICMEs, these results may be qualitatively consistent with [2].

Several rather interesting periods stand out in the LET anisotropies examined to date. We present two of them here in Figures 2 and 3.

For several hours near midday on 8 March 2011, a strongly bidirectional field-aligned flow with almost equal intensities in the forward and backward directions, and coming from a direction nearly perpendicular to the nominal Parker spiral direction, was observed at STEREO-Behind (Figure 2). A polar plot of the directional intensities during one 10-minute interval during this event was shown as Figure 1c. An ICME was observed during this period (`http://www-ssc.igpp.ucla.edu/~jlan/STEREO/Level3/STEREO_Level3_ICME.pdf`), and the bidirectional proton streaming took place inside the ICME flux rope, as indicated in Figure 2.

Using the field direction obtained from STEREO/MAG, we derived the evolution of the pitch angle distribution during the event, as shown in the right panel of Figure 2. Note the sudden appearance (within a single 10-minute interval) of the dip at 90° and the extreme symmetry of the beams aligned and anti-aligned with the field once the depletion is fully developed. Although this might arise from bidirectional streaming on a closed field line, mirroring of an outward-going beam on an open field line at a magnetic field enhancement beyond the spacecraft, as proposed to account for observed 90° depletions in solar wind suprathermal electrons [5, 6], might also be responsible. Similar 90° depletions in energetic ion anisotropies have been used to infer the presence of reflecting boundaries in particle reservoirs [7].

A more peculiar particle distribution, illustrated in the spectrogram in Figure 3, was observed at LET-Behind on 19 January 2012. A field-aligned beam appeared shortly after 21:00 UT flanked on each side by a secondary beam separated from the main beam by a valley at 90° pitch angle. Other features in the anisotropies around this time (not shown) include a 16-hour period two days earlier when the energetic protons were flowing unidirectionally but from nearly due east of the Sun; examination of the plasma parameters indicate that this occurred within an ICME flux rope that passed the spacecraft from ∼11:00 UT on 17 January until ∼09:00 UT on 18 January. Another example of unidirectional flow inside a flux rope appears in Figure 2. Even suprathermal electrons are often not bidirectional throughout an entire flux rope, and may flow unidirectionally when one end of the rope is disconnected from the Sun [8].

Proton pitch angle distributions at three energies are shown in the right panel of Figure 3. The depletion opposite the beam (at 180°) is evident, and is reminiscent of loss cones commonly seen in the magnetosphere. This might be expected if the particles encountered an enhanced magnetic field bottleneck somewhere beyond the spacecraft [9] and particles with large pitch angles were mirrored. The field strengths were not great enough to turn around the particles with the smallest pitch angles, or perhaps scattering conditions changed substantially before the particles with the smallest pitch angles reached their more distant mirror points. The width and depth of the loss cone appears to be energy dependent, with the loss cone for the lower energy protons shallower and possibly narrower than for the higher energy protons.

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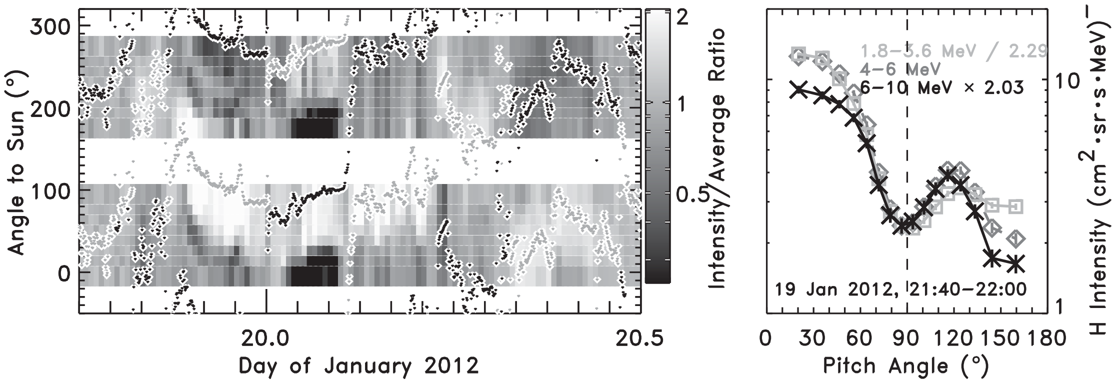

FIGURE 3. *Left panel*: Similar to *left panel* in Figure 2, but for a period in January 2012 at STEREO-Behind. *Right panel*: Pitch angle distributions, scaled as indicated, for protons in three energy bands during the "loss cone" distribution on 19 January 2012.

This is presumably due to greater scattering of the lower energy particles, since mirroring itself is independent of energy. With further analysis, we may be able to estimate the energy dependence (and by including helium data, perhaps the rigidity dependence) of the scattering mean free paths for this time period.

DISCUSSION

STEREO/LET sectored rates constitute a rich set of SEP particle anisotropy measurements at MeV energies for studying particle transport and probing scattering conditions. In our early examination of the data, we find that bidirectional flows are less likely to be aligned near the Parker spiral than unidirectional flows, similar to the findings of earlier surveys [2]. Simple inspection of LET anisotropy browse plots and comparison with tentative LET SEP event lists (`http://www.srl.caltech.edu/STEREO/Level1/LET_public.html`) shows that in about half of all SEP onsets in 2011, proton flows were initially unidirectional from near the Parker spiral direction. Similar comparison with ICME lists (`http://www-ssc.igpp.ucla.edu/~jlan/STEREO/Level3/STEREO_Level3_ICME.pdf`) shows that in 20 out of 32 ICMEs with MeV protons present in 2011, flows were sunward or bidirectional. This suggests that observed SEP flow directions may often be affected by intervening ICMEs.

In exploring the dataset we have encountered several interesting individual cases. Some of the more interesting distributions are the ones that apparently result from mirroring, as shown in Figures 2 and 3, as these can serve as probes of heliospheric transport conditions and magnetic field topology far from the spacecraft. Following the reasoning of Tan *et al.* [10], conservation of the first adiabatic invariant implies that $\sin^2(\alpha_{\mathrm{loss}}) = B_{\mathrm{bk}}/B_{\mathrm{mir}}$, where α_{loss} is the pitch angle of the loss cone boundary, B_{bk} is the background magnetic field strength, and B_{mir} is the field strength at the mirror point. For the case of the 19 January 2012 loss cone, if the particles mirrored at the shock that passed Behind at 02:00 UT on 19 January, and if the field strength did not decrease, then using the measured values of $B_{\mathrm{bk}} \sim 8.5\mathrm{nT}$ and $B_{\mathrm{mir}} \sim 17\mathrm{nT}$, we find that the width of the loss cone should be ~45°. The loss cone in Figure 3 seems to be more like 50–60° wide, which suggests the field strength at the shock decreased after passing the spacecraft. Additional analysis of the scattering and mirroring in this event, as well as in a similar loss cone distribution observed on 24–25 July 2012, will be the subject of a future study.

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REFERENCES

1. R. A. Mewaldt, *et al.*, *Space Sci. Rev.* **136**, 285–362 (2008).
2. I. G. Richardson and H. V. Cane, *JGR* **101**, 27521–27532 (1996).
3. D. Lario, *et al.*, *JGR* **113**, A03105 (2008).
4. R. A. Leske, *et al.*, *Solar Physics* **281**, 301–318 (2012).
5. J. T. Gosling, *et al.*, *GRL* **28**, 4155–4158 (2001).
6. R. M. Skoug, *et al.*, *JGR* **111**, A01101 (2006).
7. L. C. Tan, *et al.*, *ApJ* **750**, 146 (2012).
8. D. E. Larson, *et al.*, *GRL* **24**, 1911–1914 (1997).
9. J. W. Bieber, *et al.*, *ApJ* **567**, 622–634 (2002).
10. L. C. Tan, *et al.*, *ApJ* **701**, 1753–1764 (2009).

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