

Insights Into Particle Transport Obtained from Solar Energetic Particle Anisotropies

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Solar energetic particle (SEP) pitch-angle distributions are shaped by the competing effects of magnetic focusing and scattering as the particles travel through interplanetary space. Therefore, measurements of SEP anisotropies provide insight into particle transport and can probe interplanetary conditions at remote locations from the observer. The Low Energy Telescopes (LETs) onboard the twin STEREO spacecraft measure pitch-angle distributions for protons and heavier ions at energies of about 2-12 MeV/nucleon. Using these instruments, we have observed a wide variety of SEP anisotropies, such as bidirectional flows within interplanetary coronal mass ejections, sunward-flowing particles when the spacecraft was magnetically connected to the back side of a distant shock, and loss-cone distributions in which particles with large pitch angles magnetically mirror at an interplanetary field enhancement that is too weak to reflect particles with the smallest pitch angles. One of the more puzzling observations is unusual oscillations on a timescale of several minutes in the width of a beamed distribution at the onset of the very large 23 July 2012 SEP event. We report LET anisotropy observations at both STEREO spacecraft during the extreme event of 23 July 2012, in which a large range of anisotropies were observed at various times during the event, and discuss their implications for SEP transport.

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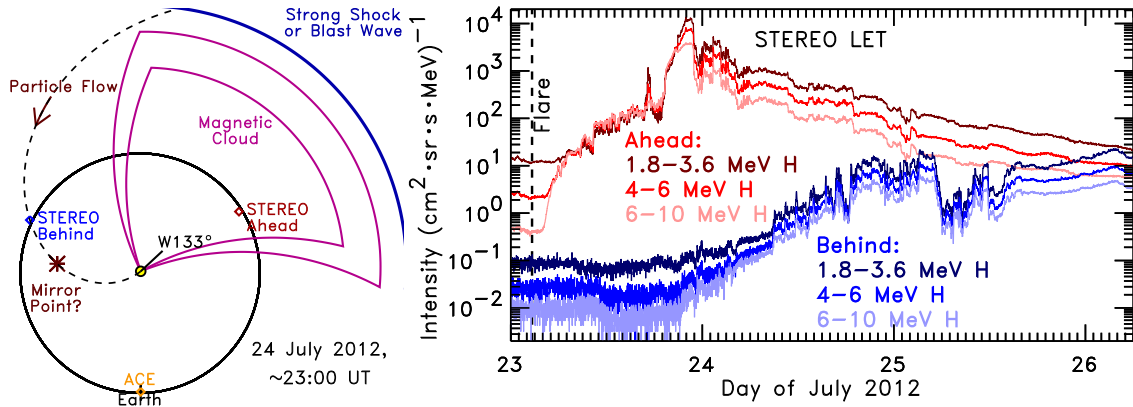


Figure 1: *Left:* Positions in the ecliptic of Earth and both STEREO spacecraft on 24 July 2012, relative to the approximate location of a strong shock or blast wave driven by a magnetic cloud that erupted the previous day from an active region near W133°. STEREO-Behind is shown connected to the back side of the shock by a nominal field line for a 400 km/s solar wind speed (*dashed line*), however the actual field configuration was far more complicated (see text). The radial spacing of features at the longitude of STEREO-Ahead is approximately correct, but the extent and shape of these features away from this longitude are somewhat speculative and meant for illustration purposes only. *Right:* Time profiles at 1-minute resolution for omnidirectional H rates in three energy bands from LET on STEREO-Ahead (*red*) and Behind (*blue*) during the July 2012 SEP event.

1. Instrumentation

Data for this study were collected by the Low Energy Telescopes (LETs) [1] onboard the Solar TERrestrial Relations Observatory (STEREO) spacecraft [2], which measure the composition, spectra, and time variations of solar energetic particles (SEPs) from H through Ni at energies of about 2–50 MeV/nucleon. The LET instrument consists of an array of silicon solid-state detectors arranged in two back-to-back fans viewing a range of longitudes in the ecliptic plane, each with a total field of view spanning 133° of longitude and ± 15 – 20° of latitude. The fans point 45° and -135° from the Sun (along the nominal Parker spiral field direction), therefore particles in a pair of 47° -wide longitudinal gaps perpendicular to the nominal magnetic field cannot be observed. Each detector is segmented to obtain particle trajectory information, and sector rates in 16 different longitudinal viewing directions are accumulated onboard for 10 different element and energy bands with angular bins $\sim 12^\circ$ wide. During very high count rate periods, the angular coverage for H and He is deliberately restricted to reduce electronic deadtime, but heavier elements are still observable over the entire field of view.

2. Observations

The largest SEP event detected so far in solar cycle 24 was observed by STEREO-Ahead on 23 July 2012 [3, 4, 5]. As shown in Figure 1, this event originated from an active region over the limb from Earth at $\sim W133^\circ$ (or near central meridian from the vantage point of Ahead) and was associated with an x-ray flare having an estimated magnitude of M8.2 to X2.5 [6]. At STEREO-Ahead the event included an unusual, particle-mediated blast wave observed in situ at

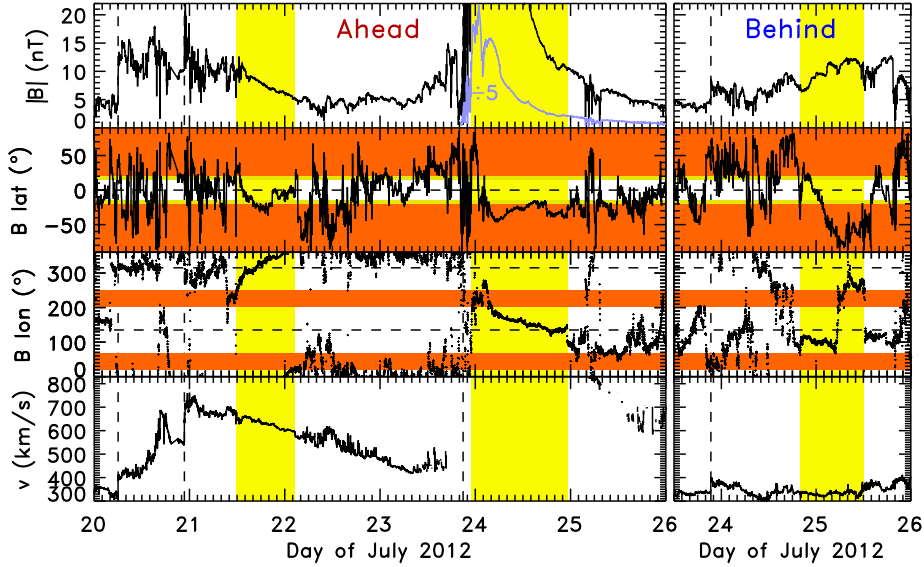


Figure 2: Magnetic field magnitude and direction (in RTN coordinates) from STEREO/MAG and solar wind speed from STEREO/PLASTIC at Ahead (*left*) and Behind (*right*). Shocks and ICMEs from http://www-ssc.igpp.ucla.edu/forms/stereo/stereo_level_3.html are shown as *vertical dashed lines* and *yellow shaded regions*, respectively. *Orange shaded regions* indicate directions outside the LET field of view. On 24 July at Ahead the field magnitude is also shown reduced by a factor of 5, and the solar wind proton speed is unavailable throughout most of the day.

speeds exceeding 2000 km/s [3]. Only a minor shock was encountered at STEREO-Behind (Figure 2), 124° of heliolongitude westward from Ahead (Figure 1). Despite the fact that the arrival time of the shock at Behind was nearly the same as that of the very much larger one at Ahead, it is not clear whether this was the same shock or associated instead with one of several other coronal mass ejections (CMEs) during this period [5]. The ICME at Behind, however, had the opposite chirality from that observed at Ahead, and therefore was unrelated [Y. Liu, private communication]. Proton intensities at Ahead were comparable to the highest recorded near Earth since 1972 [4], but while particles were detected at Behind, their intensities were almost 1000 times lower (Figure 1) as the source was beyond the east limb from this perspective. As discussed below, interesting features were seen in the particle anisotropies at both STEREO spacecraft at various times during this event.

An overview of the anisotropies observed by LET during the 2012 July event is shown by the relative intensity spectrograms in Figure 3. Two broad bands, one spanning -20° to 110° from the Sun and the other 160° to 290° , illustrate particles arriving in the fan pointed 45° and -135° from the Sun, respectively, with each fan comprising 8 sectors. (The white gap between the bands, as well as angles not included on the plot, represent the coverage gaps in ecliptic longitude.) For comparison, the variation in the magnetic field longitude with time measured by STEREO/MAG [7] is also shown. Data plotted for Behind (*bottom panel*) are sectorized rates for 4–6 MeV H, while we instead use 4–6 MeV/nucleon CNO sectorized rates for Ahead (*top panel*) since angular coverage for H and He was limited throughout much of the event due to the high count rates.

The most striking feature in Figure 3 at Behind may be seen between $\sim 19:00$ on 24 July and $\sim 02:00$ on 25 July. Note that the peak intensity at this time appeared in the fan viewing away from

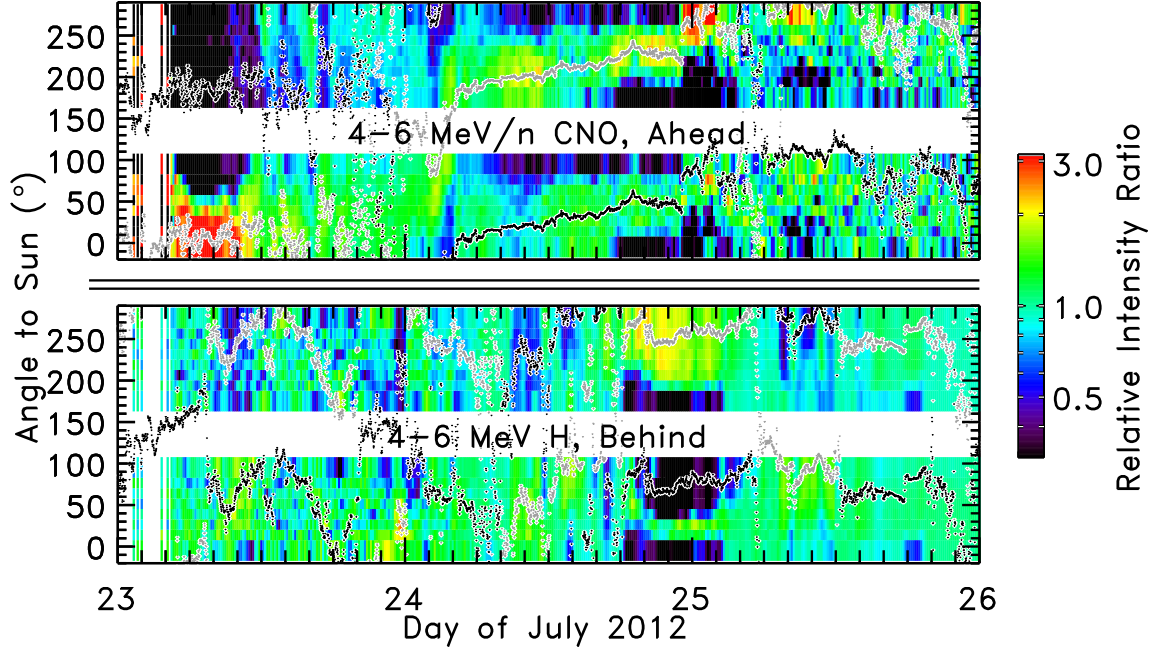


Figure 3: Relative intensities in each of the 16 LET sectors in the in-ecliptic longitudinal viewing directions, for 4–6 MeV/nucleon carbon through oxygen at STEREO-Ahead (*top*) and 4–6 MeV protons at Behind (*bottom*) during the July 2012 SEP event. Directions parallel (*black*) and antiparallel (*gray*) to the magnetic field longitudes are superposed. The color scale saturates at ratios of ~ 0.3 and 3, but at times the relative intensity ratios were significantly larger (see Figures 4 and 5); colors at all angles would be identical at the value of 1.0 during periods of complete isotropy.

the Sun, that is, the particles were flowing along the field line towards the Sun. Comparison with the solar wind suprathermal electron strahl (which indicates the direction of the field line pointing outward from the Sun [8]) as measured by the Solar Wind Electron Analyzer (SWEA) on STEREO [9] confirms that the electron strahl and LET energetic proton flows were in opposite directions [10] and therefore that the protons were flowing from a location opposite that of the Sun. As illustrated in Figure 1 and suggested by modeling [11], Behind may have been magnetically connected to the back side of the shock, which would be a likely source of these particles. However, it has also been reported that the spacecraft was inside an interplanetary coronal mass ejection (ICME) at this time (see Figure 2). In any case, the particle intensities along the field direction in the fan facing towards the Sun were at a relative minimum during this period, while there was a narrow strip of higher intensities 180° away from the edge of the incoming beam. This is a loss-cone distribution, which occurs when an incident particle distribution undergoes partial mirroring at an enhanced magnetic field bottleneck [12]. Particles with large pitch angles are reflected, but those with smaller pitch angles pass through the constriction if the field strength is not great enough to turn them around. We have previously described this particular loss-cone distribution in more detail elsewhere [10, 13].

At the Ahead spacecraft, throughout most of 24 July (after the shock passage at 20:55 on 23 July), the spacecraft was inside an ICME [5] as indicated in Figure 2. The particle flow was bidirectional at this time (Figure 3), as is often observed in such structures [14], but intensities were higher in the direction facing away from the Sun, suggesting a shorter path to the particle source in

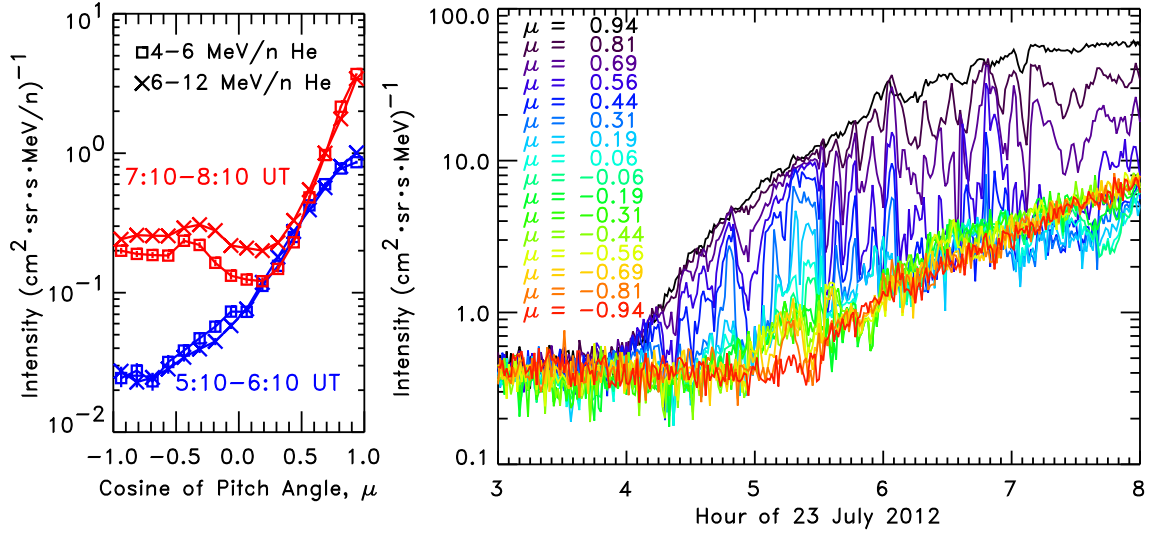


Figure 4: *Left:* Hourly-averaged pitch-angle distributions for He in two energy bands in LET at STEREO-Ahead earlier (blue) and later (red) during the onset of the 23 July 2012 event. The distribution appeared narrower later in the event. *Right:* Time profiles at 1-minute resolution for 6–10 MeV sector H in each of 16 pitch-angle bins from LET on STEREO-Ahead at the onset of the 23 July 2012 particle event.

this direction.

Late on 25 July, anisotropies had subsided at both Ahead and Behind (Figure 3). At about this time, proton intensities were nearly the same at both spacecraft (Figure 1), nearly three days after the event onset, suggesting that the particles had isotropized throughout the quasi-trapped, expanding region behind the shock, as is often seen in large SEP events [15].

At the event onset at Ahead, the ions were strongly anisotropic for the first 6 hours. After 08:39 on 23 July, particle intensities at Ahead became large enough that angular coverage was restricted for H and He, but prior to this their pitch-angle distributions were exponential (Figure 4) and formed a field-aligned, unidirectional beam flowing outwards from the Sun. Curiously, however, the width of the beam appeared to become narrower as the event progressed, at least when examined over longer (~ 1 hour) timescales. To study this in more detail, in Figure 4 we show intensities in each of 16 bins in μ (where μ is the cosine of the pitch angle) vs. time using 1-minute time resolution. In the outward-flowing, field-aligned direction ($\mu=0.94$), particle intensities rose rather smoothly over 4 hours. The intensity rise was also smooth in the opposite direction ($\mu=-0.94$), as particles streamed back along the field after an initial delay of ~ 1.5 hours. At particle velocities of ~ 0.11 – $0.14c$, this delay corresponds to an outward travel distance of ~ 0.7 AU, suggesting they may have reflected or scattered off the shock that passed Ahead late on 20 July or the ICME of 21 July (see Figure 2). However, for intermediate values of μ that were not field-aligned, the time profiles were not smooth and the intensities varied tremendously, by factors of 5 or so on timescales of ~ 10 – 15 minutes.

The rapid time variability of the pitch-angle distributions is directly shown by the selection of 1-minute samples in Figure 5. Here it becomes clearer how longer time averages as in Figure 4 might suggest that the beam narrowed with time. Instead, earlier in the event the beam width fluctuated repeatedly by $>25^\circ$ in a matter of minutes, while it was much steadier later in the event.

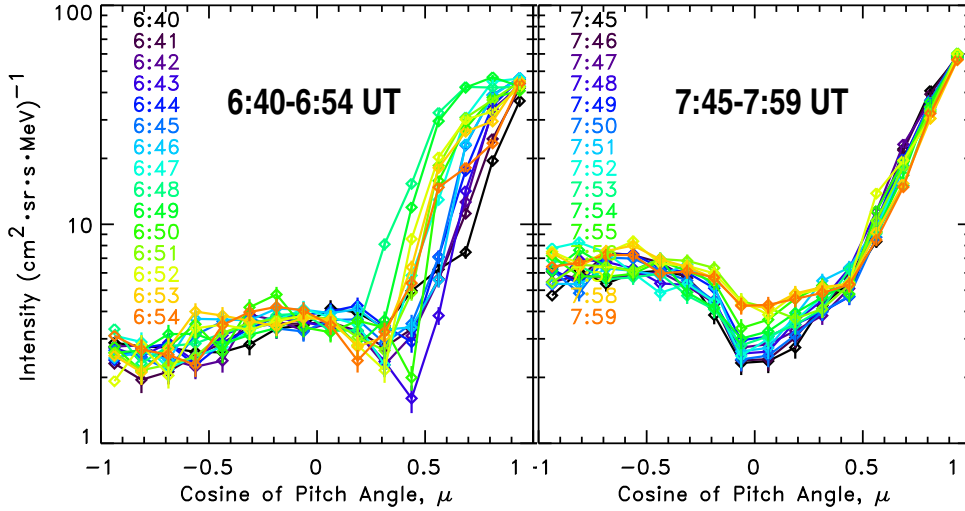


Figure 5: Sample one-minute averaged pitch-angle distributions for 6–10 MeV H in LET at STEREO-Ahead on 23 July 2012 at the times indicated.

Interestingly, even while the width was variable, the slope of the distribution seemed relatively constant, while the peak, field-aligned intensities seemed truncated or suppressed.

3. Discussion

Anisotropy measurements can be used to probe heliospheric conditions remote from the observing spacecraft. Within the 23 July event, from two vantage points, we have observed inward-flowing particles, a loss-cone distribution, bidirectional streaming, and a peculiar beam-width oscillation, as described above, which can be used to help understand how the particles become distributed throughout the inner heliosphere.

We have discussed the pronounced loss-cone distribution observed at Behind during the July 2012 event in previous papers [10, 13]. The width of a loss cone depends on the field strength at the observer and at the mirror point [16, 17], which allows estimation of interplanetary conditions far from the observer. Note that even if the spacecraft was inside of an ICME at this time, the very existence of the loss cone indicates that particles were injected into only one of the ICME legs, with partial mirroring occurring in the other. The fact that the mirror point seems to be located closer to the Sun than the spacecraft requires some explanation. A loss cone would not appear sunward of the spacecraft in an undisturbed Parker spiral field, since eventually the field strength would grow large enough to mirror even the smallest pitch angles. Beyond the magnetic constriction the field must once again have become weaker and allowed the smaller pitch-angle particles through, or scattering must have become more significant. Perhaps interactions of the magnetic cloud with other coronal mass ejections or solar wind streams might have produced the required conditions. Comparison of the anisotropy observations with the results of modeling packages such as the combined WSA-ENLIL-Cone-SEPMOD [18, 19] that can predict particle pitch-angle distributions may prove useful.

The oscillations in beam width at the onset of the event at Ahead are puzzling, and to our knowledge such behavior has not been reported before in other events. Note that the field was

nearly radial for more than a day, from midday on 22 July until the shock arrival late on 23 July (Figure 2), and radial fields appear to be conducive to the propagation of ion cyclotron waves due to reduced refraction and Landau damping in this geometry [20]. Indeed, intermittent and short ion cyclotron waves were observed during the beam-width oscillation period, but they did not appear unusual [L. Jian, private communication]. Later in the day however, from $\sim 19:40$ – $20:15$, shortly before the arrival of the extreme shock, several small flux ropes with some high frequency magnetic field fluctuations were observed, which is rare [L. Jian, private communication]. If these high frequency fluctuations had been present ~ 13 – 16 hours earlier when we observed the beam-width oscillations, and if they traveled at the ambient solar wind speed (~ 800 km/s at 20:00 [3, 5]), they would have been located ~ 0.27 AU sunward of the spacecraft at 06:00, and 10 MeV protons would have passed through them only ~ 15 minutes before we observed them. More work is needed to determine if the interaction of the particles with these field fluctuations might have produced the unusual anisotropy behavior. Meanwhile, however, it is worth noting that by midday on 23 July particle intensities leveled off within a factor of ~ 2 of the streaming limit (Figure 1), which is caused by the scattering of particles by self-generated waves [21]. Although intensities were ~ 10 times lower during the oscillations, the restricted range of variability in the field-aligned intensities (Figure 5) might be related to an early phase in the development of the streaming limit.

Acknowledgments

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