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Observations of Loss-Cone Pitch Angle Distributions of Solar Energetic Particles

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Abstract. Pitch angle distributions of solar energetic particles (SEPs) in interplanetary space sometimes exhibit a loss cone in which an incident beam of particles is partially mirrored; particles with large pitch angles are reflected while those with smaller pitch angles are not. Mirroring requires a magnetic field enhancement, but if the field strength is not large enough to turn around particles with the smallest pitch angles or if these particles scatter before reaching their more distant mirror points, a loss cone forms. Such distributions therefore provide information on the interplanetary environment far from the spacecraft. The Low Energy Telescopes onboard the twin STEREO spacecraft have detected loss-cone distributions in several SEP events. We present some of these and other interesting anisotropy observations, and discuss their implications for SEP transport. In particular, we find that the shapes of the pitch angle distributions generally vary with energy and species, with lower energy particles usually more anisotropic than higher energy particles. Comparison with theory may be used to determine the energy and rigidity dependences of the pitch angle diffusion coefficient.

1. Instrumentation

The Low Energy Telescopes (LETs; Mewaldt et al. 2008) onboard the Solar TErrestrial RElations Observatory (STEREO) spacecraft (Kaiser et al. 2008) measure count rates for elements or element groups from H through Fe. The LET detectors are arranged in two back-to-back fans each viewing 133° of longitude in the ecliptic and ±15–20° of latitude out of the ecliptic centered along the nominal Parker spiral field direction, which leaves a pair of 47°-wide longitudinal viewing gaps perpendicular to the nominal magnetic field. Each detector is segmented to allow particle trajectories to be determined. Directional, "sectored" rates in 16 different viewing directions are accumulated onboard, but pulse-height data are also telemetered for a relatively small sample of events, often <1% of the particles during high count-rate periods. These data specify which of the 300 different detector combinations were triggered, allowing better angular resolution but with greatly reduced statistical accuracy. Proton sectored rates in three energy bands (as of late 2010) of 1.8–3.6, 4–6, and 6–10 MeV and He sectored rates at 4–6 and 6–12 MeV/nucleon are provided; statistical precision for heavier ions is low for the events we consider here and they will not be discussed.

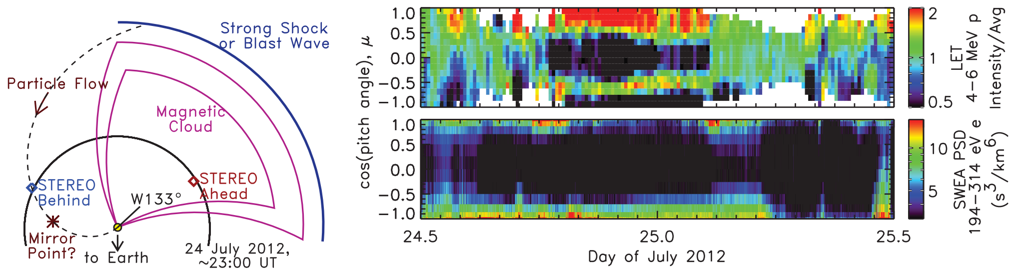

Figure 1. *Left panel:* Positions in the ecliptic of both STEREO spacecraft late on 2012 July 24, near a circle with radius of 1 AU. Also shown schematically is the location of a strong shock or blast wave driven by a magnetic cloud associated with a flare the previous day from ~W133°. A nominal field line for a solar wind speed of 400 km/s (*dashed line*) connects STEREO-Behind to the shock. The radial spacing of features at the STEREO-Ahead longitude is approximately correct, but the extent and shapes of these features away from this longitude are rather speculative and intended for illustration purposes only. *Right panel:* Pitch angle distributions of the relative intensity of 4–6 MeV protons from LET on STEREO-Behind (*top*); *white areas* are directions outside the LET field of view. The *bottom panel* shows the pitch angle distribution of the phase space density (PSD) of 194–314 eV suprathermal electrons from SWEA on STEREO.

2. Observations

On 2012 July 23, the largest solar energetic particle (SEP) event to occur so far in solar cycle 24 was observed at STEREO-Ahead (Russell et al. 2013; Mewaldt et al. 2013), associated with an estimated M8.2–X2.5 x-ray flare from an active region over the limb from Earth at ~W133° (Nitta et al. 2013). Proton intensities at Ahead would have made this event the third most intense recorded near Earth since 1972 if it had been directed towards Earth (Mewaldt et al. 2013), and it was accompanied by an unusual, particle-mediated blast wave at speeds exceeding 2000 km/s (Russell et al. 2013). At STEREO-Behind, 124° of heliolongitude westward from Ahead at the time (Figure 1), no shock was encountered and particle intensities were ~100 times lower, but as we discuss below, a dramatic example of a loss-cone distribution was observed the next day (Leske et al. 2013b). Such a distribution occurs when an incident particle distribution is partially mirrored at an enhanced magnetic field bottleneck (Bieber et al. 2002). Particles with large pitch angles are reflected, but those with smaller pitch angles pass through the bottleneck if the field strength is not great enough to turn them around.

The energetic proton pitch angle distributions at STEREO-Behind and their temporal evolution during the 2012 July event are shown in the right side of Figure 1, where they are compared with pitch angle distributions of suprathermal electron phase space densities measured by the Solar Wind Electron Analyzer (SWEA) on STEREO (Sauvaud et al. 2008) obtained from `http://stereo.cesr.fr`. From ~19:00 UT on 24 July through 02:00 UT on 25 July, the protons exhibit a loss-cone distribution, as is more clearly seen in the left panel of Figure 2. An incident beam is seen at μ=1 and the distribution is partially mirrored at negative values of μ, but with a strong depletion at μ=−1, where μ is the cosine of the pitch angle. The solar wind suprathermal electron strahl indicates the direction of the field line pointing outward from the Sun (Crooker et al. 2004), and the SWEA data show the strahl at μ=−1 at this time. Thus, the incident energetic proton beam was flowing inwards as sketched in Figure 1. The back of

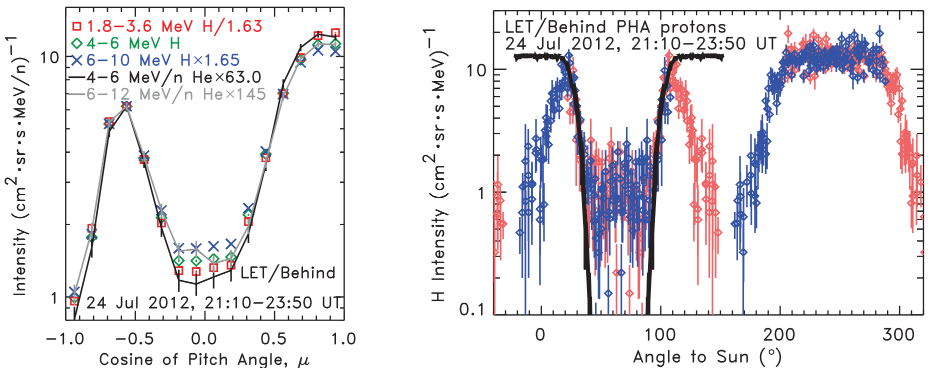

Figure 2. *Left panel:* Loss-cone pitch angle distributions, with intensities scaled as indicated, for H and He in multiple energy bands from LET on STEREO-Behind on 2012 July 24. *Right panel:* LET ~1.8–12 MeV proton intensities derived from pulse-height event data plotted versus viewing direction in the ecliptic. Measurements are shown in *blue*, while points estimated by assuming symmetry and reflecting the measured data about 65° and 245° are in *red*. The calculated shape of a 40°-wide loss cone is superposed (*black*).

the blast wave that passed STEREO-Ahead late on 23 July (Russell et al. 2013) was magnetically connected to STEREO-Behind by late on 24 July (Luhmann & Odstrcil 2013), and was probably the source of the inward-streaming particles.

The shape of the loss cone is clearer in the right panel of Figure 2, where intensities obtained from the finer angular resolution pulse-height data are shown versus the in-ecliptic longitude relative to the Sun, rather than the pitch angle relative to the magnetic field. Despite significant overlap in the fields of view among the 300 viewing cones, the improvement in angular resolution is considerable; the average full width at half maximum is 5.3° of longitude for the pulse-height data compared with 12.2° for the sectored rates. The loss cone appears as a steep-sided notch cut out of the center of the distribution in the sunward-facing direction. Superposed on the data is the calculated shape of a 40°-wide loss cone accounting for the instrumental angular resolution and

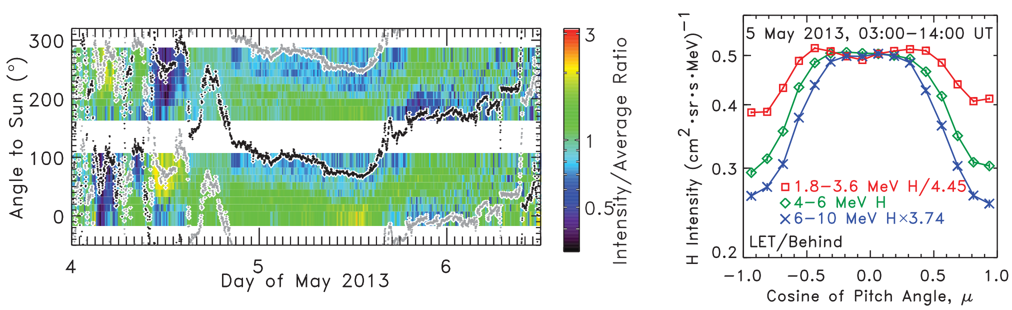

Figure 3. *Left panel:* Relative intensity spectrogram of 4–6 MeV sectored protons from LET-Behind showing particle intensities as a function of longitudinal viewing direction, with directions parallel (*black*) and antiparallel (*gray*) to the magnetic field longitudes superposed; *white bands* indicate gaps in the LET field of view. *Right panel:* Pitch angle distributions for H at three energies during this period.

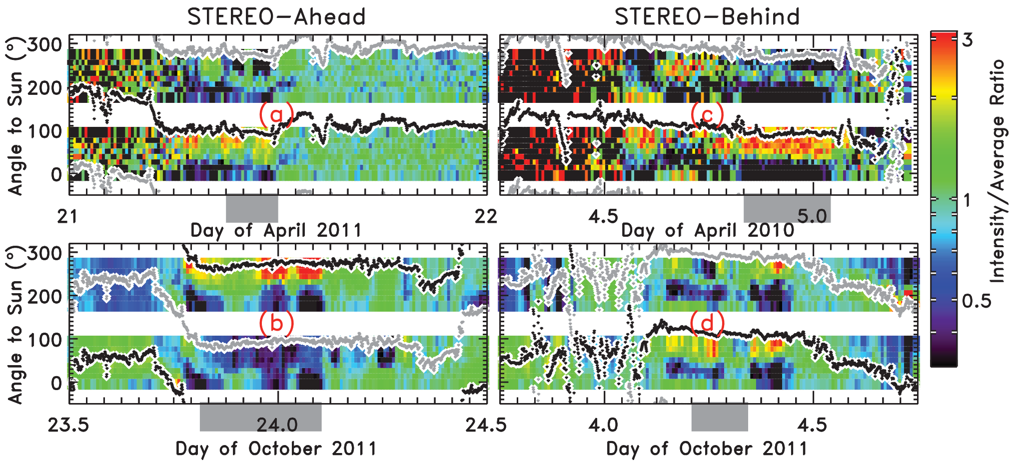

Figure 4. Relative intensity spectrograms of 4–6 MeV protons with superposed magnetic field directions as in Figure 3 for other examples of loss-cone distributions observed at LET-Ahead (*(a)* and *(b)*) and Behind (*(c)* and *(d)*). Intervals with at least intermittent loss cones are marked by *bars* under each panel.

the ~10° variation of the field direction during this time period (Leske et al. 2013b). The calculated loss cone is much emptier than actually observed, but the shapes of its edges are consistent with the data.

The pitch angle of the loss-cone boundary, α_{loss}, depends on the magnetic field strength at the mirror point, B_{mir}. From conservation of the first adiabatic invariant, it follows that $\sin^2(\alpha_{\mathrm{loss}}) = B_{\mathrm{bk}}/B_{\mathrm{mir}}$, where B_{bk} is the background magnetic field strength (e.g., Anderson et al. 1981; Tan et al. 2009). The observed background field strength was ~9 nT and the loss cone ~40° wide, so the field strength must have reached ~22 nT at the mirror point somewhere sunward of the spacecraft (Figure 1), beyond which the field was again weaker and allowed the smaller pitch angle particles through. Perhaps interactions of the magnetic cloud with other coronal mass ejections or solar wind streams might have produced such a field geometry. Modeling packages such as the combined WSA-ENLIL-Cone-SEPMOD can predict particle pitch angle distributions (Odstrcil et al. 2011; Luhmann et al. 2010). In future work we would like to compare results from such models with our data to see whether the observed loss cone is predicted and, if so, determine the location and nature of the field constriction responsible.

Figure 3 shows an unusual example of a potential loss-cone distribution. Throughout all of 2013 May 5 and beyond, the peak particle intensities at STEREO-Behind were not aligned with the field but at 90° to it, indicating a magnetically trapped population. Trapped distributions have rarely been reported in the inner heliosphere (see, e.g. Lario et al. 2008, and references therein), and might arise from particles bouncing between two magnetic mirror points, with small pitch-angle particles escaping through loss cones at both mirrors (Sarris & Krimigis 1982).

Although we have not yet studied them in detail, there are still other examples of loss-cone distributions to be found in the LET data, several of which are shown in Figure 4. The loss cones may be recognized as periods with a pronounced field-aligned anisotropy in one of the LET viewing fans, with a depletion along the field in the other fan but with a narrow enhancement at the edge of the mirrored beam. Sometimes these

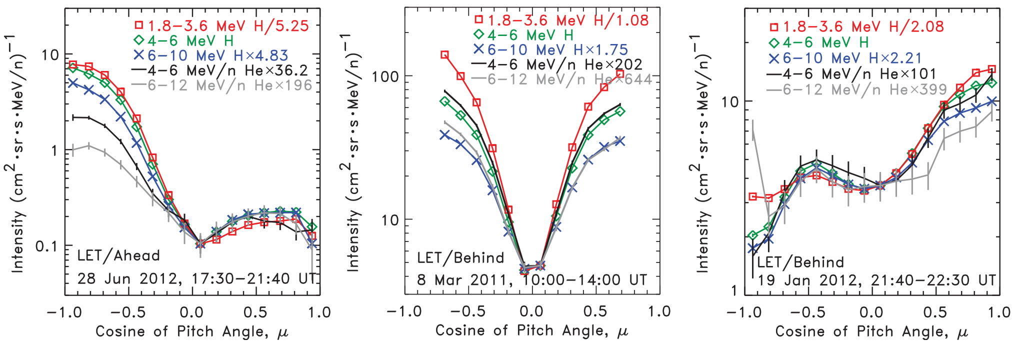

Figure 5. Pitch angle distributions of H and He from LET, scaled to illustrate differences in shapes of the distributions for the different energies and species.

features appear only intermittently, which may indicate changes in the environment at the mirror or in the spacecraft's magnetic connection to it.

3. Discussion

Further studies of these and other loss cone distributions can test global models of field strength and topology far from the spacecraft. In addition, we observe an energy dependence in the anisotropies apparently related to details of the particle transport.

The shape of the loss cone in the left panel of Figure 2 is essentially independent of energy, but the incident beam is narrower and has greater amplitude at lower energies than at higher energies for both H and He. This pattern is also evident in the examples shown in Figure 5, in the nearly unidirectional beam of 2012 June 28 (at $\mu=-1$ in the left panel), in both lobes of the 90°-depletion distribution (Leske et al. 2013a) of 2011 March 8 (middle panel), and in the incident beam of the 2012 January 19 loss cone (Leske et al. 2013a) (at $\mu=1$ in the right panel). Comparing H with He at the same energy per nucleon shows differences from event to event. In both the 2012 July 24 and 2011 March 8 periods, the pitch angle distribution for He at 4–6 MeV/nucleon was narrower than that for 4–6 MeV H, while in the 2012 January and June examples it was broader. Curiously, the energy dependence of the trapped distribution in Figure 3 is exactly opposite of that discussed above. Here the higher energy protons have narrower distributions than the lower energy particles (right panel of Figure 3); this was also seen within the 2012 January 19 loss cone (at $\mu=-1$ in the right panel of Figure 5). Apparently scattering conditions were rather unusual in this time period; further analysis and modeling are clearly needed.

It seems reasonable to suppose that particles with the same pitch angle diffusion coefficient would attain the same pitch angle distribution, and therefore that observed differences in these distributions for different species under the same interplanetary conditions may reveal the dependence of the diffusion coefficient on particle characteristics. Calculated anisotropies generally appear to be larger at lower energies (Mason et al. 2012) due to pitch angle scattering. More specifically, the pitch angle diffusion coefficient $D_{\mu\mu}$ should scale for different particles as vR^{q-2}, where v is the velocity and R the rigidity of the particles and q the index of the magnetic power spectrum (Mason et al. 2012). The observed widths of the distributions generally scale directly with v, but either directly or inversely with *R*, qualitatively as expected. We are working on obtaining quantitative information from fits to these distributions. Comparison with magnetic power spectra and models should help to provide insights into energetic particle transport in these interesting SEP events.

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