Observations of the longitudinal spread of solar energetic particle events in solar cycle 24

C.M.S. Cohen, G.M. Mason, M.E. Wiedenbeck, D.K. Haggerty, R. Gomez-Herrero et al.

Citation: AIP Conf. Proc. **1436**, 103 (2012); doi: 10.1063/1.4723596
View online: http://dx.doi.org/10.1063/1.4723596
View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1436&Issue=1
Published by the American Institute of Physics.

Observations of the Longitudinal Spread of Solar Energetic Particle Events in Solar Cycle 24

C.M.S. Cohen[a], G.M. Mason[b], M.E. Wiedenbeck[c], D.K. Haggerty[b], R. Gomez-Herrero[d], R. Bucik[e], E. R. Christian[f], A.C. Cummings[a], A. Korth[e], A. W. Labrador[a], R.A. Leske[a], U. Mall[e], R.A. Mewaldt[a], E.C. Stone[a], and T.T. von Rosenvinge[f]

[a]California Institute of Technology, MC 290-17, Pasadena, CA 91125
[b]Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723
[c]Jet Propulsion Laboratory, California Institute of Technology, MC 169-327, Pasadena, CA 91109
[d]University of Kiel, 24118 Kiel, Germany
[e]Max-Planck-Institut für Sonnensystemforschung, 37191 Katlenburg-Lindau, Germany
[f]NASA/Goddard Space Flight Center, Code 661, Greenbelt, MD 20771

Abstract. With the twin STEREO spacecraft, significantly separated from L1-based satellites such as ACE, simultaneous multi-point measurements of solar energetic particle (SEP) events can be made for H-Fe ions from a few hundred keV/nuc to over 100 MeV/nuc and for electrons from tens to hundreds of keV. These observations allow studies of the longitudinal characteristics of SEP events to advance beyond statistical analysis of single point measurements. Although there have been few large SEP events thus far in cycle 24, there have been a number of smaller events that have been detected by more than one spacecraft. The composition of these SEP events, as indicated by the H/He and Fe/O abundance ratios, shows a dependence on longitudinal distance from the solar source in some events, at times with ratios varying by an order of magnitude. However, these variations are not organized by either the speed or width of the associated coronal mass ejections.

Keywords: Solar energetic particles, solar wind, solar composition, solar flares
PACS: 96.50.Vg, 96.60.Vg, 96.60.Q-, 96.50.Pw, 96.60.P-, 96.60.Qe

INTRODUCTION

With the launch of the twin STEREO spacecraft on 25 October 2006, our ability to measure the spatial distribution of solar energetic particle (SEP) events reached a new level. The separation of the two spacecraft from near-Earth spacecraft (increasing by 22.5 degrees/year) allows observations to be made from spatially distinct vantage points simultaneously. Not since the days of the Helios spacecraft has this been routinely possible. On board the STEREO spacecraft is a suite of SEP sensors which provides intensities of electrons from tens to hundreds of keV and H-Fe from ~0.03 to ~100 MeV/nuc [1 and Figure 18 therein]. This is similar to the energy and species coverage of the ACE SEP instruments [2]; thus combining the STEREO and ACE SEP observations yields a consistent set of measurements from three separate locations.

Physics of the Heliosphere: A 10 Year Retrospective
AIP Conf. Proc. 1436, 103-109 (2012); doi: 10.1063/1.4723596

Additionally, the STEREOs carry instrumentation which allows the solar context in which the SEP events occur to be studied in detail. The SECCHI suite [3] provides EUV and coronagraph images, and the SWAVES sensor [4] supplies information on relevant radio phenomena such as type III bursts. For remote sensing, the third vantage point is provided by the instruments on GOES, SOHO, Wind, and most recently SDO.

Combining these rich data sets allows detailed examination of the longitude dependence of many SEP event characteristics and their associated solar phenomena. Of particular interest is the variation of SEP event composition with longitude. Single spacecraft studies in solar cycle 23 revealed large SEP events highly enriched in Fe and ^{3}He [5,6], perhaps due to a direct contribution of flare material (typically exhibiting high Fe/O and ^{3}He/^{4}He ratios). In events with significant amounts of flare-accelerated particles, this component would be most evident when the observer was magnetically well connected to the flare site [7] and would result in an expected longitudinal dependence of the Fe/O abundance. Alternately, it has been suggested that the enhanced Fe results from interplanetary shocks, driven by coronal mass ejections (CMEs), accelerating remnant flare material [6,8]. The effectiveness of this would depend on the shock orientation but not the relative position of the observer, yielding no longitude dependence in the Fe/O ratio. Results from model simulations which combine the effects of direct flare contributions and reacceleration of flare material by an interplanetary shock have also shown a longitudinal dependence of the Fe/O ratio [9]. By combining STEREO and ACE composition measurements obtained during the same SEP event these scenarios can finally be tested, furthering the understanding of the origin of the Fe-enriched large SEP events.

Unfortunately, soon after STEREO was launched, solar activity declined to extremely low levels with only one SEP event exceeding the NOAA SEP event threshold (i.e., 10 MeV proton peak intensities of > 10 particles/cm^2-sr-sec) for all of 2007 through 2010. There were, however, a number of smaller events which, in spite of fairly large separations between the STEREOs and ACE, were detected by more than one spacecraft. Below we present the results of examining the compositional dependence on longitude for these multi-spacecraft SEP events.

OBSERVATIONS

In this study the electron intensities were measured by the STEREO/SEPT and ACE/EPAM sensors and the ion data were obtained from the STEREO/SIT, STEREO/LET, ACE/ULEIS, and ACE/SIS sensors. An initial selection of possible events was made by examining the 1.8-10 MeV proton rates from the STEREO/LET sensors. An accompanying electron increase and associated type III burst (from STEREO/SWAVES and Wind/WAVES) were required and subsequently used to aid in identifying the related solar activity (x-ray flares from GOES/XRS and CMEs from SOHO/LASCO and/or STEREO/SECCHI). Solar energetic particle data from the other STEREO spacecraft and ACE were then examined to determine if the same event was also observed. Over the period of January 2009 through February 2011, 22 events were identified as being observed by at least two spacecraft.

An example is shown in Figure 1. Several events are clearly seen by both STEREO-Behind and ACE, with at least one seen by all three spacecraft, in spite of their low intensities. The peak He intensities of the two events seen by ACE during days 226-233 are 2-3 orders of magnitude smaller than those of the December 2006 SEP events [10].

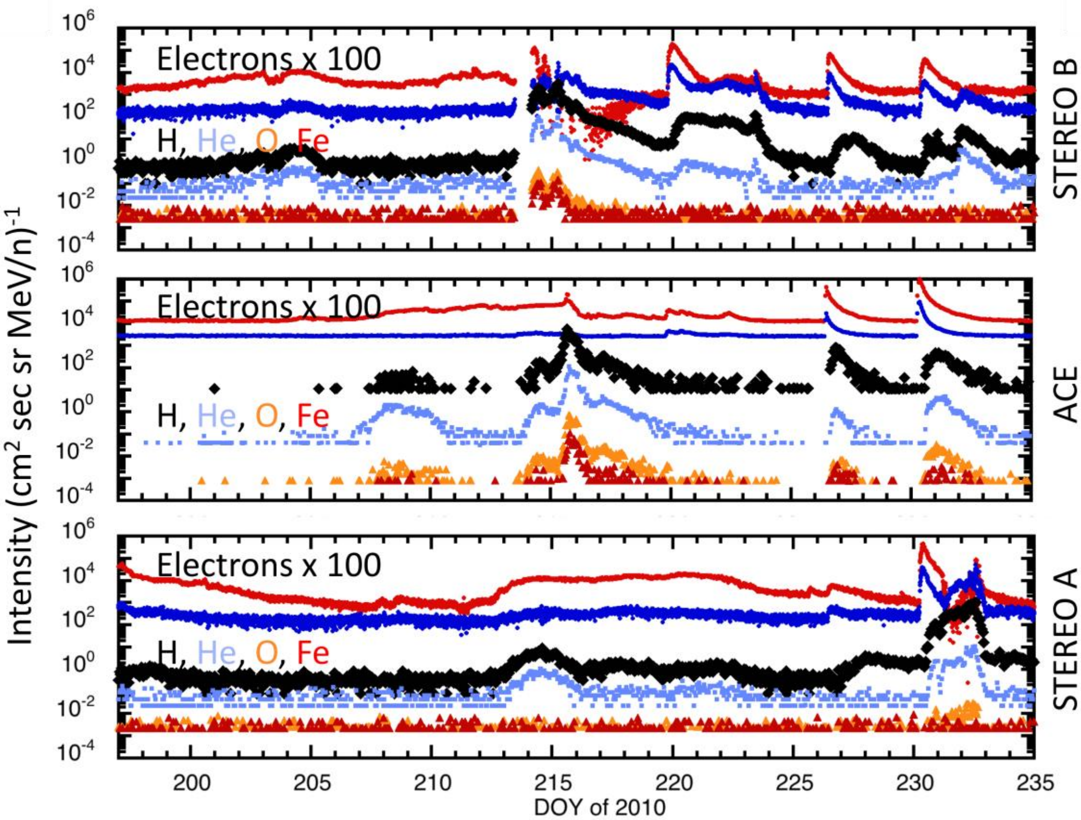

FIGURE 1. Time intensity profiles for e- (at 65 and 175 keV; red and blue traces respectively), H, He, O, and Fe (all at ~1 MeV/nuc; black, light blue, gold and red traces respectively) from STEREO-BEHIND (top panel), ACE, (middle panel), STEREO-AHEAD (bottom panel) for a 38 day time period covering 16 July to 23 August, 2010. The electron intensities have been multiplied by 100 for clarity.

A consequence of the small size of the selected events is the lack of statistically significant fluences of heavy ions above a few MeV/nuc. Thus it is not possible to derive Fe/O ratios at the energies most appropriate to investigating the origins of Fe-rich events seen in cycle 23. Although it is unclear whether similar effects will be evident at lower energies in smaller events, we have calculated Fe/O and H/He abundances at energies where most of the selected events had accurate measurements. The event integrated spectra were calculated by combining the measurements from the SIT and LET instruments on STEREO and ULEIS and SIS instruments on ACE, and from these spectra, H/He and Fe/O ratios were obtained at 0.4-0.8 MeV/nuc and 0.07-0.14 MeV/nuc, respectively.

Using the remote sensing data, solar source regions were identified for all of the multi-spacecraft events, although three of the 22 were located on the side of the Sun not visible by GOES and SOHO. The presence of associated CMEs was identified using the CME catalogs of CUA (a by-hand analysis of SOHO/LASCO observations; http://cdaw.gsfc.nasa.gov/CME_list/) and CACTus (an automated analysis performed on SOHO/LASCO and STEREO/SECCHI data; http://sidc.oma.be/cactus/). Movies of the coronagraph data were examined to confirm that the catalogs were listing the same CME and to verify the automated CACTus identification. Comparisons were made between the CACTus results obtained from the LASCO data and those given in the CUA catalog as well. As projection effects can alter the measured speed and width of a CME, the definitive CME characteristics were taken from observations made by the spacecraft that had the most orthogonal view of the CME of interest. Associated CMEs were found for 20 of the 22 selected events and ranged in width from 30 to 150 degrees and in speed from 200 to 1300 km/s.

Due to the low solar activity level, often there was only one active region flaring at the time of the type III burst and electron injection. Movies from both SECCHI/EUVI sensors and SDO/AIA were used to confirm flares when all three spacecraft were able to view the active region identified as the source. The presence or absence of high frequencies of the radio bursts was also examined for consistency with the source location relative to the observing spacecraft (e.g., radio burst frequencies greater than a few MHz should have been missing due to occultation if the source was on the far side of the Sun).

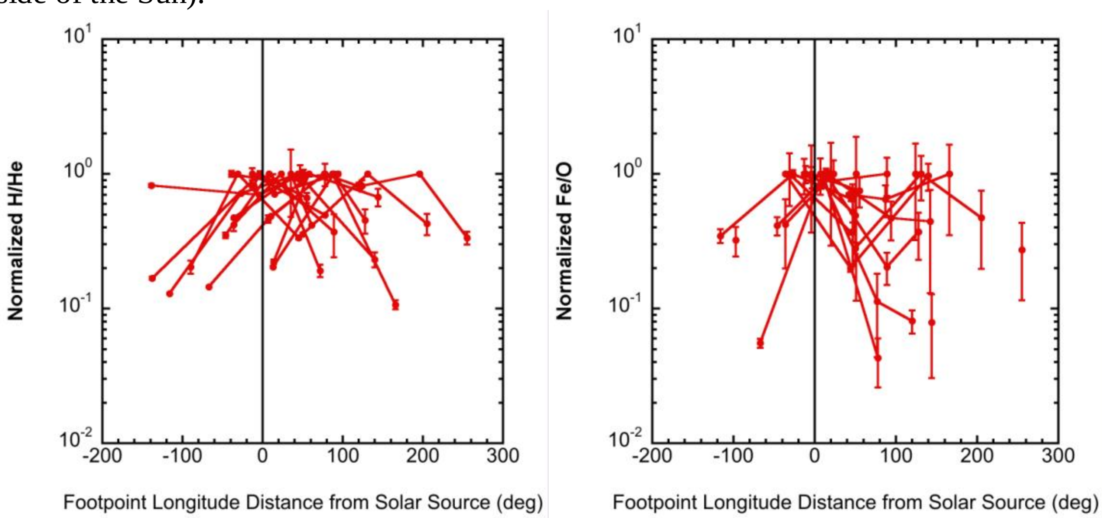

FIGURE 2. Abundance ratios H/He (left) and Fe/O (right) as a function of footpoint distance from the solar source region. The abundances have been normalized for each event to their peak value.

The solar footpoint longitudes for the three spacecraft were each calculated by assuming a nominal Parker spiral field line consistent with the average solar wind speed measured by that spacecraft during the SEP event. The distances in longitude between the footpoints and the identified source region were recorded and used to study the variation in composition with longitude. The results are shown in Figure 2, where the H/He and Fe/O ratios are normalized to their peak value for each event to better emphasize the longitude dependence. Lines connect data points measured by different spacecraft for the same SEP event. The vertical line at 0 indicates a spacecraft position that was directly connected to the source via a Parker spiral field at the time of the flare. Statistically significant H/He and Fe/O ratios were determined for 20 and 18 (respectively) of the 22 events. Of these, 16 (for H/He) and 11 (for Fe/O) were three-spacecraft events.

DISCUSSION

Although there is little organization apparent in the results shown in Figure 2, there are significant longitudinal dependences in the H/He and Fe/O ratios for some events, with ratios varying by an order of magnitude (and occasionally more for Fe/O). While the majority (13/18) of the Fe/O ratios peak near the source longitude, this is less the case for H/He (9/20). This may be an indication of an overall tendency for the H/He ratio to vary less with longitude than the Fe/O ratio.

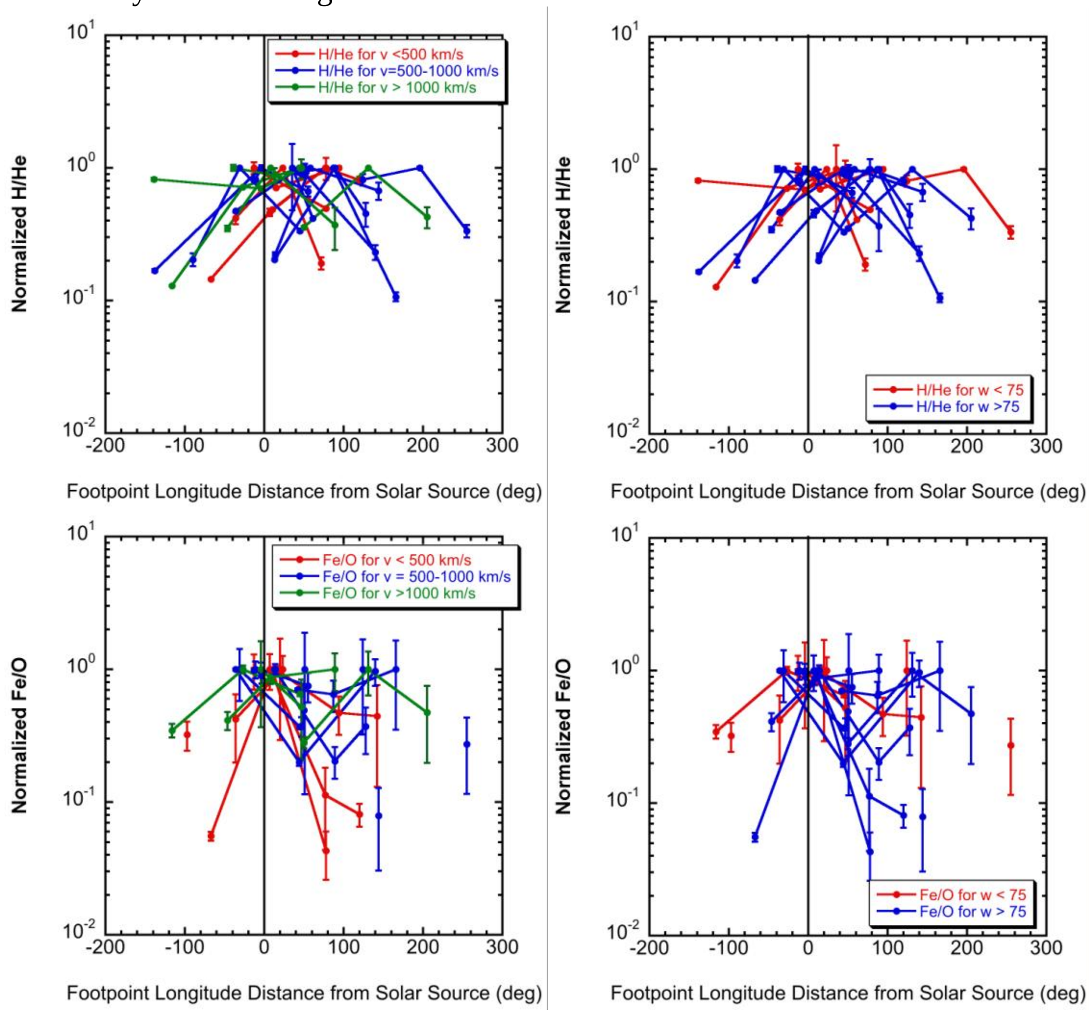

FIGURE 3. The same H/He (top panels) and Fe/O (bottom panels) abundance ratios as given in the previous plot but color coded to show CME speed (left panels) and CME width (right panels).

If the associated CME contributes to the acceleration process (most likely by driving an interplanetary shock) it is possible that narrower or slower CMEs would be less likely to create a shock with sufficient strength at the flanks for efficient acceleration giving rise to a longitude dependence in the abundances. It is also possible that even if the CME is not contributing directly to the acceleration process, it may affect the longitudinal distribution of field lines causing field lines populated with energetic particles to be observed farther from the nominal best connection to the solar source. In such a case, one would imagine a wider CME would have greater effect, possibly resulting in less longitudinal dependence in the SEP composition.

In an effort to determine whether the speed or width of the accompanying CME strongly affects the longitude dependence of the abundances, the data of Figure 2 are replotted in Figure 3 with color coding to identify 3 ranges of CME speed (v < 500 km/s, 500 < v < 1000 km/s, and v > 1000 km/s; left panels) and 2 ranges of CME width (w < 75 degrees and w > 75 degrees; right panels). Unfortunately, such categorization does not appear to provide any organization of the results. In neither H/He or Fe/O do events with stronger longitude dependences (i.e., more peaked distributions) fall primarily within the slower or narrower CME categories.

As it is difficult to completely exclude the possibility of a CME effect from the plots in Figure 2, an additional step was taken for those events with abundance ratios determined on three spacecraft. With three abundance-longitude points a Gaussian can be calculated. The sigma of the Gaussian then gives an indication of the magnitude of the longitudinal gradient of the abundance ratio, with smaller sigmas corresponding to larger gradients. While it is not expected that the longitude dependence would necessarily follow a Gaussian distribution, and there are not enough measurements to make a least-squares fit to the observations, the width of the calculated Gaussian should correlate with the width of the true distribution.

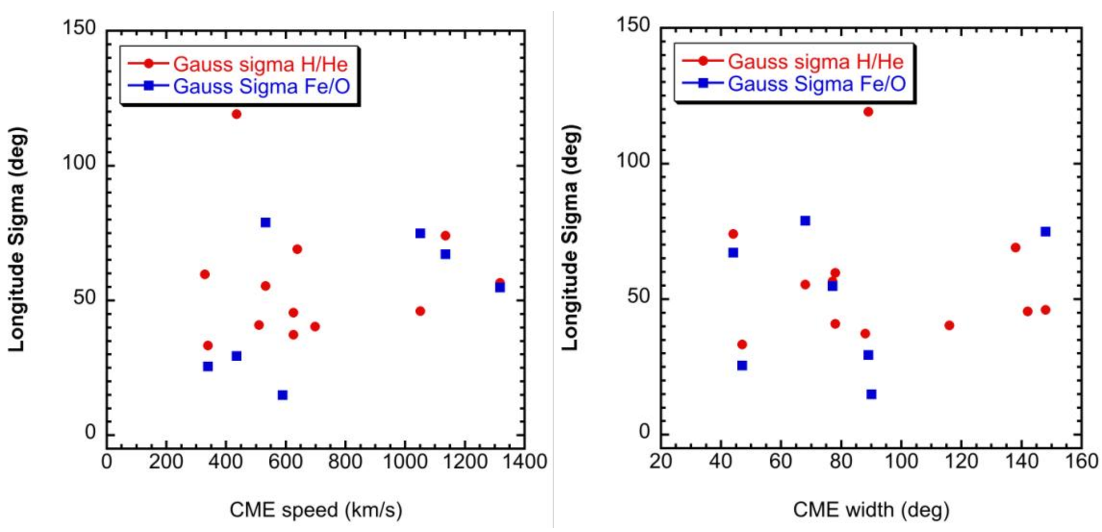

FIGURE 4. Resulting Gaussian sigmas (see text for explanation) as a function of CME speed (left) and width (right). Events with larger sigmas have less variation in abundance with longitude (see text).

Figure 4 shows the resulting sigmas for H/He and Fe/O, for events in which a calculation was possible, plotted as a function of CME speed (left panel) and width (right panel). As expected from Figure 3, there is no coherent dependence on either CME property; slow and fast CMEs are associated with both high and low sigma events (i.e., small and large longitudinal gradients) as are narrow and wide CMEs.

Several other aspects may be relevant to the variation in longitude dependence and are worth investigating. The presence of coronal holes near the source region may provide additional open field lines allowing a wider longitudinal distribution of the accelerated material, possibly lessening any longitudinal dependence on the abundances. The condition of the interplanetary medium before the SEP event is also likely to play a role. The presence of interplanetary coronal mass ejections (ICMEs) can result in strong deviations of the Parker spiral magnetic field resulting in connections to solar source regions much different than what was assumed in this study. Higher levels of activity, including preceding SEP events, ICMEs, and corotating interaction regions (CIRs) can also create increased turbulence levels in the interplanetary medium resulting in more field line meandering and/or particle diffusion which could lessen the composition dependence on longitude. Examining the interplanetary environment in which the SEP events occurred, as well as other aspects of the solar context, is the next step in this study. Additionally with the solar activity level increasing as solar cycle 24 progresses, it is expected that there will be multi-spacecraft SEP events that are larger than those studied here. This will allow better determinations of the composition as well as examination of the abundance ratios at higher energies where effects of shock orientation and/or flare contributions may be more evident.

ACKNOWLEDGMENTS

This work was funded by NASA under grants NNX08AI11G and NNX10AQ68G at Caltech, NNX10AT75G at JHUAPL, and subcontracts SA2715-26309 from UC Berkeley (NASA contract NAS5-03131) and N00173-10-1-G010 from NRL. The STEREO/SEPT project is supported under grant 50 OC 0902 by the German Bundesministerium für Wirtschaft through the Deutsches Zentrum für Luft und Raumfahrt (DLR). We thank Nariaki Nitta for useful discussions regarding solar source identifications. We used data from the CME catalog generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with NRL and from the CACTus CME catalog, generated and maintained by the SIDC at the Royal Observatory of Belgium.

REFERENCES

1. J. G. Luhmann, et al., *Space Sci. Rev.* **136**, 117-184 (2008).
2. E. C. Stone, et al., *Space Sci. Rev.* **86**, 1-22 (1998).
3. R. A. Howard, et al., *Space Sci. Rev.* **136**, 67-115 (2008).
4. J. L. Bougeret, et al., *Space Sci. Rev.* **136**, 487-528 (2008).
5. C. M. S. Cohen, et al., *Geophys. Res. Lett.* **26**, 2697-2700 (1999)
6. G. M. Mason, et al., *Geophys. Res. Lett.* **26**, 141-144 (1999)
7. H. V. Cane, et al., *J. Geophys. Res.* **111**, doi: 10.1029/2006JA011071 (2006)
8. A. J. Tylka, et al., *Astrophys. J.* **625**, 474-495 (2005)
9. G. Li and G. P. Zank, *Geophys. Res. Lett.* **32**, doi: 10.1029/2004GL021250 (2005)
10. C. M. S. Cohen, et al., "Examination of the Last Large Solar Energetic Particle Events of Solar Cycle 23" in *Particle Acceleration And Transport In The Heliosphere And Beyond: 7th Annual International Astrophysics Conference*, edited by G. Li et al., AIP Conf. Proc 1039, AIP, Melville, NY, 2008, pp. 118-123.