Investigating the longitude dependence of solar energetic particle spectra

C. M. S. Cohen, G. M. Mason, R. A. Mewaldt, and R. A. Leske

Related Articles

Generation of residual energy in the turbulent solar wind
Phys. Plasmas 19, 102310 (2012)

Wave associated anomalous drag during magnetic field reconnection
Phys. Plasmas 18, 102902 (2011)

The effect of spectral anisotropy of fast magnetosonic turbulence on the plasma heating at the proton kinetic scales
Phys. Plasmas 17, 112902 (2010)

Laboratory experiments simulating solar wind driven magnetospheres
Phys. Plasmas 16, 043112 (2009)

Application of grazing incidence x-ray fluorescence technique to discriminate and quantify implanted solar wind
J. Appl. Phys. 105, 064905 (2009)

Additional information on AIP Conf. Proc.

Investigating the Longitude Dependence of Solar Energetic Particle Spectra

C. M. S. Cohen[a], G. M. Mason[b], R. A. Mewaldt[a], and R. A. Leske[a]

[a]*California Institute of Technology, MC 290-17, Pasadena, CA, 91125*
[b]*Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, 20723*

Abstract. We examine the traits of six solar energetic particle events observed simultaneously by instruments on ACE and at least one of the twin STEREO spacecraft. We compare the time profiles and spectra of energetic oxygen as a function of the longitudinal separation of the observer from the solar source region. We find systematic trends in the rise and peak times with source longitude that are consistent with those determined from single spacecraft studies. However, we also find two events where the rise times were surprisingly rapid when the source region was over the western limb relative to the observer. This has potential consequences for space weather predictions of radiation hazards. No clear trend is apparent for hardness of the event-integrated spectra with source longitude contrary to trends seen in the single spacecraft studies.

INTRODUCTION

With its increasing number of space-based assets, society is becoming increasingly susceptible to the hazards of space weather. Communication, military and science satellites are vulnerable to the effects solar activity whether in the form of x-ray flares, solar energetic particles (SEPs) or coronal mass ejections (CMEs) causing geomagnetic storms. In response to these concerns the Space Weather Prediction Center (SWPC) at the National Oceanic and Atmospheric Administration (NOAA) routinely issues warnings and predictions regarding the probability of a solar flare, an SEP event, or a geomagnetic storm occurring (www.swpc.noaa.gov/forecast.html).

Successful predictions require accurate understanding of how these hazards are created. For SEP events, this involves understanding how active regions produce CMEs, how particles are accelerated by the shocks driven by the CMEs, and how the SEPs are transported through the interplanetary medium. Currently SEP event prediction is limited to the probability of an SEP event of a minimum peak intensity occurring. Predictions of specific properties such as the onset time, rise time, peak time and peak particle intensities, not to mention the spectral hardness and composition of the event, are desirable but beyond current ability.

Event to event variability in SEP event characteristics is substantial and while some aspects are roughly understood, much work remains and is key to the future success of SEP predictions. Most of our understanding of event variability is from statistical analysis of many events using single spacecraft measurements. Such studies have

examined the dependence of various SEP event characteristics on an observer's position relative to the solar source [e.g., Cane et al. 1988, Tylka et al, 2005, Cane et al. 2006, 2010]. In particular, the time-intensity profile of an SEP event was found by Cane et al. [1998] to vary significantly if the source was to the west or east of an observer. Western events typically showed rapid rise times, with peak intensities occurring early in the event followed by an exponential decay. In contrast, eastern events exhibited much more gradual rises and typically peak intensities were reached at or after the passage of the associated interplanetary shock. The spectral hardness of an event was also found to be sensitive to longitude, with western events typically being harder than their eastern counterparts.

With the launch of the twin STEREO spacecraft we have the ability to measure SEP events simultaneously from 3 vantage points at similar radii but different longitudes (by combining STEREO data with those from spacecraft near the Sun-Earth line, e.g., ACE). This allows us to examine the longitude dependence of SEP time-intensity profiles and spectral hardness within a given event as well as investigate event-to-event variations in this dependence. For some events it is also possible for one spacecraft to be positioned such that the source region is on the 'backside' of the Sun (i.e., more than 90° east or west of the spacecraft) while another views the event as a 'frontside' event. Such geometries provide an opportunity to examine a situation not routinely included in the previous statistical studies because of the uncertainty of the location of a backside source when there is only one view available.

TABLE 1. Properties of selected SEP events

Flare Date and Time	X-ray Flare Size	X-ray Flare longitude	STEREO-B/A Longitude *	Observing Spacecraft
7 Mar 2011 2012	M3.7	W48	E95 / W88	STB, ACE, STA
21 Mar 2011 0215**	--	W117***	E95 / W88	ACE, STA
22 Sep 2011 1101	X1.4	E78	E97 / W103	STB, ACE, STA
26 Nov 2011 0710	C1.2	W47	E106 / W106	ACE, STA
23 Jan 2012 0359	M8.7	W21	E114 / W108	STB, ACE, STA
27 Jan 2012 1856	X1.7	W85	E114 / W108	ACE, STA

* degrees longitude from the Earth-Sun line
** taken from radio burst time
***estimated

OBSERVATIONS

For this study we focused on measurements of SEP oxygen in events observed by ACE and at least one of the two STEREO spacecraft. By combining the data from the Suprathermal Isotope Telescope (SIT) [Mason et al., 2008] and the Low Energy Telescope (LET) [Mewaldt et al., 2008] on the STEREO spacecraft and the Ultra-Low-Energy Isotope Spectrometer (ULEIS) [Mason et al., 1998] and the Solar Isotope Spectrometer (SIS) [Stone et al., 1998] on the ACE spacecraft, the oxygen intensity was measured from 0.1 to >10 MeV/nuc. Additional instrumentation on the STEREO spacecraft as well as on SDO and SoHO was used to identify solar sources. The STEREO/SECCHI suite [Howard et al., 2008] obtains extreme-ultraviolet images of the solar disk as well as coronagraph images of CMEs over a range of coronal heights.

Similarly, near ACE, SDO/AIA provides solar disk images at a variety of wavelengths and SoHO/LASCO obtains coronagraph images.

Six SEP events were selected between March 2011 and January 2012 that were large enough for reliable event-integrated oxygen fluence spectra to be obtained to at least 20 MeV/nuc. Three of these events were observed by ACE and both STEREOs. The date and times of the associated x-ray flare, its size, and position are given in Table 1. The flare associated with the event on 21 March 2011 was on the backside of the Sun as viewed from Earth, so there is no knowledge of the x-ray flare magnitude (STEREO does not carry an x-ray sensor). The location of the flare was estimated by examining the STEREO/SECCHI EUV movies and we list the time of the radio type III burst. Also included in the table are the longitudinal positions of STEREO-B and STEREO-A (relative to the Earth-Sun line) and which spacecraft observed the event.
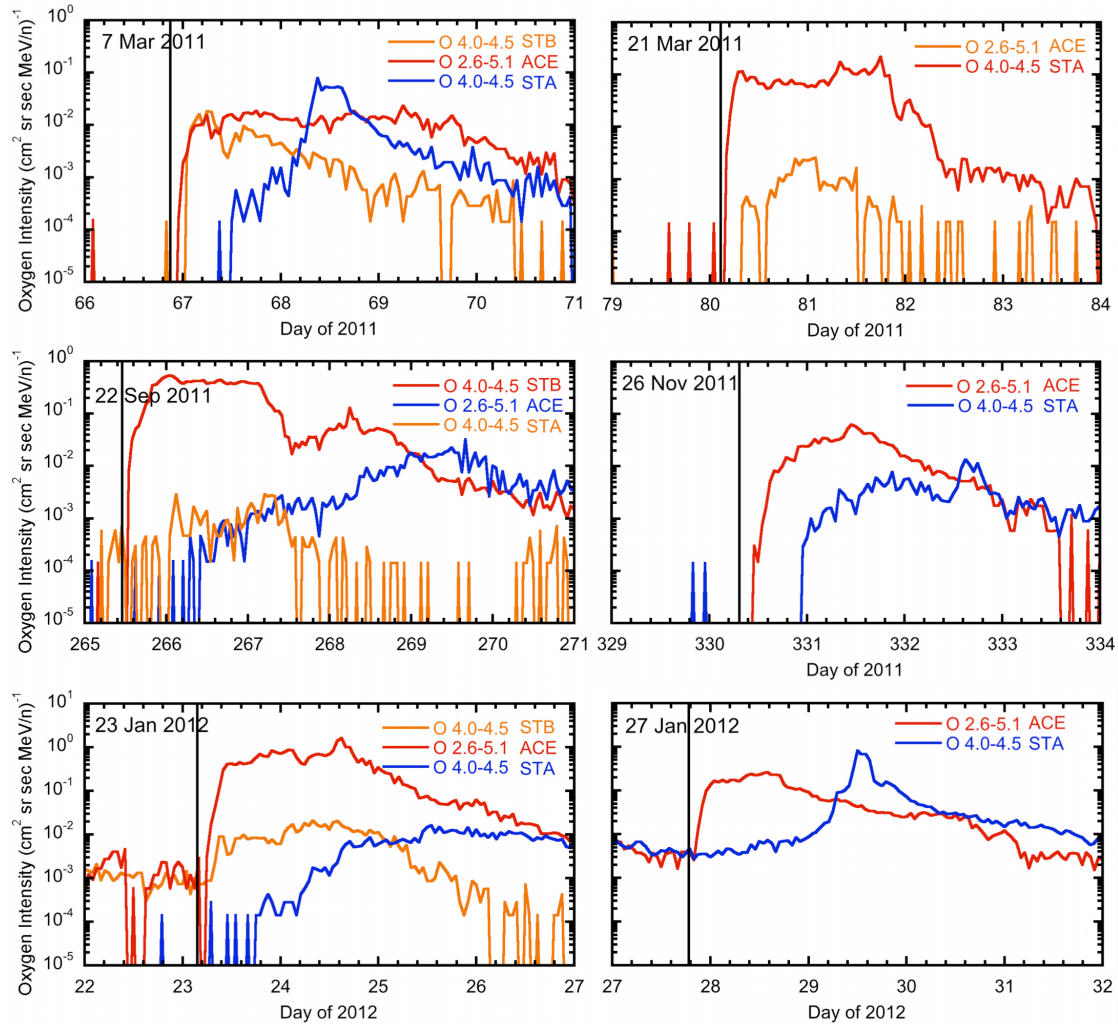

FIGURE 1. Time-intensity profiles for oxygen from the observing spacecraft for each event. The traces are color coded according to where the source region was relative to the observing spacecraft: red=0-90° west; orange=90-180° west; blue=0-90° east; purple = 90-180° east (none shown). Black vertical lines indicate the time of the associated x-ray flare (as given in Table 1).

Figure 1 presents the hourly-averaged intensities of ~3-4 MeV/nuc oxygen versus time for each event as observed by STEREO/LET and ACE/ULEIS. Each time-

76

intensity trace is color coded according to the position of the flare/solar source relative to the observing spacecraft as noted in the caption. The oxygen intensities measured by ULEIS and SIS on ACE and SIT and LET on STEREO were integrated over the entire event to obtain fluence spectra from 0.1 to ~20 MeV/nuc (often higher for ACE). The spectra were then corrected for GCR contributions at high energies. Figure 2 shows the resulting event-integrated oxygen fluences for each event with the same color coding as in Figure 1. The uncertainties are based on statistical uncertainties only and are typically smaller than the symbols.
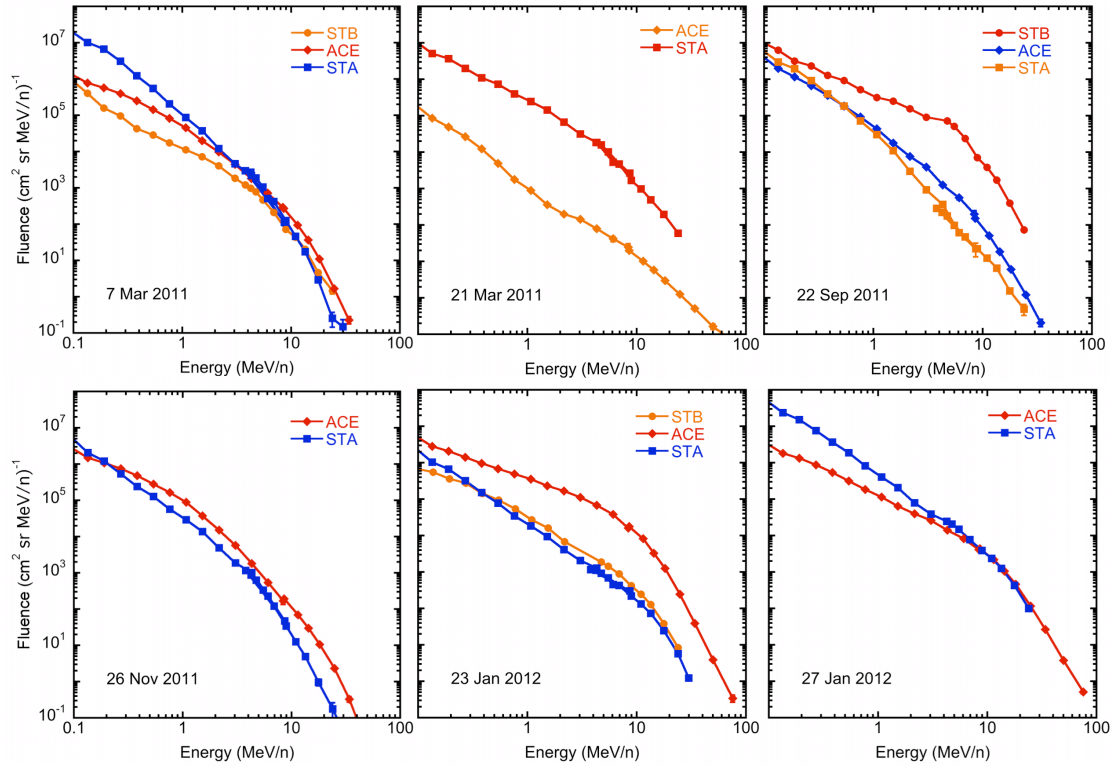

FIGURE 2. Event-integrated fluence spectra for oxygen for each event. Low energy data are from ACE/ULEIS and STEREO/SIT while higher energy data are from ACE/SIS and STEREO/LET. The spectra are color coded in the same manner as Figure 1.

DISCUSSION

From the time profiles (Figure 1) it is clear that the general trend expected from western versus eastern events is present within individual SEP events. In all cases, the onset and peak times of the blue traces (equivalent to an eastern event) are later than those of the red traces (equivalent to a western event). With the exception of the 26 November 2011 event, all the blue traces show significantly slower rise times as well. What is perhaps unexpected is the similarity in the onset and rise times for the red and orange traces in the 7 March 2011 and 23 January 2012 events. In both these events, the solar source region is well over the western limb for STEREO-B, while being in the western hemisphere for ACE.

For the 7 March 2011 event there was an M1.7 x-ray flare at E21 6 hours before the flare listed in Table 1. This earlier flare was western as viewed by STEREO-B and it

77

is clear from the ~1 MeV electrons and >10 MeV protons intensities from the High Energy Telescope (HET [von Rosenvinge, et al. 2008]; not shown) that this event did produce particles. However, the protons intensities from this event were decaying when a second, stronger increase due to the later solar activity occurred (both events were also distinctly observed in electrons). There is no clear evidence of this earlier event in the LET oxygen data at ~10 MeV/nuc energies. Thus, while it is possible that there are particles from this earlier event contributing to the 4-4.5 MeV/nuc oxygen intensities given in Figure 1, upper-left panel, we do not believe it is the dominant cause of the quick rise time of the orange trace. However, more detailed analysis of the arrival times of the measured particles is necessary to confirm this. There is no such complication for the 23 January 2012 event, which has much the same spacecraft/source region geometry.

The orange trace in the 22 September 2011 event does not show this same behavior, however the position of the flare relative to STEREO-A is nearly 180° and so the trace could be colored either orange or purple. The orange trace in the 21 March 2011 event does not show as fast a rise or similar onset time as the red trace, however it does not appear to be as slow or late as many of the blue traces. There are two other events for which the source was backside-west for STEREO-B, 26 November 2011 and 27 January 2012, but the SEP event was not clear in 4 MeV/nuc oxygen. Understanding why these events, which were 10° and 18° farther around the limb than the 7 March 2011 event, were not observed may require comparing the interplanetary conditions in which the events occurred.

The fact that backside-west events can result in SEP events with rapid rise times provides some resolution to the puzzle of the source region for the 16 August 2001 SEP event. This event exhibited a fairly quick rise time, yet there was no suitable source region on the Earth-facing side of the Sun. A large active region had passed over the western limb five days prior, radio data indicated bursts from a backside source at an appropriate time, and a backside CME was observed [G. Lawrence, private communication 2001]. However, this region was doubted as the source due to the prompt time profile of the SEP event.

The statistical study of Cane et al. [1988] showed that western events tended to have harder spectra than their eastern counterparts. In Figure 2 this is not so evident; in several events at energies above 10 MeV/nuc the red spectra are softer than the orange or blue spectra. In the 7 March 2011 and 27 January 2012 events the spectra at all locations are remarkably similar above 1 MeV/nuc even though the time profiles are very different (at a few MeV/nuc; Figure 1). Although nearly all the spectra show breaks (typically between 1 and 10 MeV/nuc), the location of the breaks varies not only from event to event but also often by observing position for a given event.

Two characteristics of a shock have the primary influence on the hardness of the accelerated particle spectrum: the strength and the orientation relative to the local magnetic field. Stronger and quasi-perpendicular shocks both accelerate more particles to higher energies, resulting in harder spectra [Li et al., 2005; Zank et al. 2006]. Generally the shock is stronger at the nose relative to the flanks and weakens overall as it propagates away from the Sun. The orientation of the shock can vary with both time and position along the shock front. An observer's magnetic connection to the shock front also evolves with time, generally moving eastward (due to the Parker

78

spiral) as the shock propagates radially outwards. Thus, differently positioned observers may measure particles accelerated under very dissimilar conditions in terms of shock strength and orientation.

To understand the effects of observing location on the event-integrated spectra it is necessary to examine and model the evolution of the shock strength and orientation as well as the magnetic connections in the interplanetary medium. Analysis of this kind has been done for a few events [e.g., Rouillard et al., 2011, 2012], with some success but is beyond our current study. From the work presented here, it can only be said that conclusions regarding spectral hardness versus source longitude drawn from statistical analysis of single-point measurements of many events (such as have previously been done) may be hampered by the strong variability potentially present within an event as well as from one event to the next.

In regards to space weather, the results shown in Figure 1 make it clear that potentially active source regions cannot be ignored once they rotate beyond the west limb (as viewed from Earth). Even regions 40-50° beyond the limb are capable of producing SEP events with rapid rise and onset times. Luckily with the positioning of the STEREO spacecraft and the beacon data from the SECCHI imagers, active regions can currently be monitored all the way around the Sun in real time. However, accurate predictions of a prompt SEP event occurring still await a better understanding of the solar and/or interplanetary conditions conducive to such events. Similarly, predicting the spectral hardness of an SEP event will require significantly more careful study of events observed simultaneously from distinct vantage points. Fortunately as the solar cycle progresses, the opportunities for such studies will undoubtedly increase.

REFERENCES

1. H. V. Cane, D. V. Reames, and T. T. von Rosenvinge, *J. Geophys. Res.* **93**, 9555-9567 (1988).
2. H. V. Cane, et al., *J. Geophys. Res.* **111**, doi: 10.1029/2005JA011071 (2006).
3. H. V. Cane, I. G. Richardson, and T. T. von Rosenvinge, *J. Geophys. Res.* **115**, doi: 10.1029/2009JA 014848 (2010).
4. A. J. Tylka, et al., *Astrophys. J.* **625**, 474-295 (2005).
5. G. M. Mason, et al., *Space Sci Rev* **136**, 257-284 (2008).
6. R. A. Mewaldt, et al., *Space Sci. Rev.* **136**, 285-362 (2008).
7. G. M. Mason, et al., *Space Sci. Rev.* **86**, 409-448 (1998).
8. E. C. Stone, et al., *Space Sci. Rev.* **86**, 357-408 (1998).
9. R. A. Howard, et al., *Space Sci. Rev.* **136**, 67-115 (2008).
10. T. T. von Rosenvinge, et al., *Space Sci. Rev.* **136**, 391-435 (2008).
11. A. P. Rouillard, et al., *Astrophys. J.* **735**, doi: 10.1088/0004-647X/735/1/7 (2011).
12. A. P. Rouillard, et al., *Astrophys. J.*, **752**, doi:10.1088/0004-637X/752/1/44 (2012).
13. G. P. Zank, et al., *J. Geophys. Res.*, **111**, doi: 10.1029/2006JA011524 (2006).
14. G. Li, G. P. Zank, and W. K. M. Rice, *J. Geophys. Res.*, **110**, doi: 10.1029/2004JA010600 (2005).