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Citation: AIP Conf. Proc. **1539**, 151 (2013); doi: 10.1063/1.4811010
View online: http://dx.doi.org/10.1063/1.4811010
View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1539&Issue=1
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Solar Energetic Particle Characteristics and Their Dependence on Longitude in Solar Cycle 24

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Abstract. In previous solar cycles, most studies examining the longitude dependence of solar energetic particle (SEP) event characteristics (such as composition and spectral hardness) have involved statistical analysis of single-point measurements. With the significant separation between the two STEREO and near-Earth spacecraft during solar cycle 24, these SEP characteristics can be examined simultaneously from multiple vantage points. Using SEP measurements from sensors on STEREO and ACE, we have examined the longitude dependence of the Fe/O abundance ratio at 10 MeV/nuc and the oxygen spectral index for energies above 10 MeV/nuc. Longitudinal patterns were sought that support or refute the scenarios put forth by Tylka et al. and Cane et al. to explain the Fe-enriched large SEP events of cycle 23. Unfortunately few Fe-enriched events have occurred in cycle 24 and their longitudinal behavior is not entirely consistent with either of the proposed scenarios.

Keywords: Solar energetic particles, SEP composition, SEP spectra
PACS: 96.50.Vg, 96.60.Vg

INTRODUCTION

One of the goals of the STEREO mission is to investigate possible longitudinal dependencies of the characteristics of Solar Energetic Particle (SEP) events. Before STEREO, longitudinal studies were predominantly limited to statistical studies of single spacecraft measurements. One of the primary difficulties with such studies is that the conditions within which the SEP events occur can vary dramatically from one event to the next. From the single-point measurements, the presence or absence of a longitudinal dependence to the Fe-enrichments observed in some large SEP events at energies above several MeV/nuc (see e.g., [1] and [2]) remains debatable, as does the cause of these enrichments (see [3] and [4] for opposing suggestions). Simultaneous composition measurements at locations well separated in longitude, as is possible with STEREO and near-Earth spacecraft, within a single event should yield clues favoring one explanation over the other [e.g., 5].

The scenario proposed by Cane et al. [4,6] involves a combination of CME-driven, shock-accelerated material with nominal or low Fe/O ratios and flare-accelerated material with high Fe/O ratios. Which component will dominate the observations near 1 AU depends not only on the strength of the shock but also how well the observer is magnetically connected to the flare site, thus resulting in a longitudinal dependence to the observed SEP composition.

In contrast, the scenario of Tylka et al. [3] requires the presence of a seed population comprised of solar wind suprathermals and flare suprathermals such that the composition is energy dependent (with the Fe/O ratio increasing with energy as the flare component dominates). According to Tylka et al., the orientation of the CME-driven shock then determines whether the resulting SEP event will be Fe-rich or not as a quasi-perpendicular shock will accelerate particles starting at a higher energy than will a quasi-parallel shock. This difference in injection threshold will result in a more Fe-rich seed population to be accelerated by a quasi-perpendicular shock, ultimately producing an SEP event enhanced in Fe. In this picture, the observed SEP composition has no longitudinal dependence.

In this study we have selected SEP events observed by at least two spacecraft of the STEREO-B + ACE + STEREO-A combination. We concentrate on events large enough that Fe/O ratios can be determined at 10 MeV/nuc and examine the dependence of not only the Fe/O ratio, but also the hardness of the oxygen spectra as a function of longitude.

OBSERVATIONS

The 12 selected events and their properties are given in Table 1. The corresponding solar information (column two) was determined by examining radio and X-ray data, and EUV images and movies from instruments on Wind, GOES, SOHO, SDO, and STEREO. The SEP data were combined from the

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AIP Conf. Proc. 1539, 151-154 (2013); doi: 10.1063/1.4811010

TABLE 1. Characteristics of Selected Events

Event Start Day at ACE	Flare Max Time, Longit., Active Reg. #	Observing Spacecraft	Long. Sep. Angle for Obs S/C (°)	O Spectra Longit. Character	Fe/O Longitude Character
15 Feb 2011	1405/W10/11158	STB,ACE	36/-44	Peaked	Peaked
7 Mar 2011	2012/W48/11164	STB,ACE,STA	79/-9/-84	Peaked	Valley
21 Mar 2011	0215*/W117**/11169	ACE,STA	58/-18	Peaked	Valley
4 Aug 2011	0345/W38/11261	ACE,STA	-12/-113	Peaked	Peaked
22 Sep 2011	1101/E78/11302	STB,ACE,STA	123/-25/-133	Peaked	Valley
4 Nov 2011	2336p*/E150**/***	STB,ACE,STA	-101/34/133	Decreas. East	Peaked
26 Nov 2011	0710/W47/11353	ACE,STA	-12/-111	Peaked	Peaked
23 Jan 2012	0359/W21/11402	ACE,STA	-36/-133	Peaked	Valley
27 Jan 2012	1856/W85/11402	ACE,STA	23/-80	Flat	Valley
4 Mar 2012	1052/E65/11429	STB,ACE	-15/-130	Peaked	Valley
7 Mar 2012	0024/E31/11429	STB,ACE	43/-83	Flat	Peaked
17 May 2012	0147/W88/11476	ACE,STA	26/-60	Valley	Peaked

* from radio burst time; p=previous day
** estimated from STEREO/SECCHI images
*** no number given

Ultra-Low-Energy Isotope Spectrometer (ULEIS; [7]) and the Solar Isotope Spectrometer (SIS; [8]) on ACE and the Suprathermal Ion Telescope (SIT; [9]) and the Low Energy Telescope (LET; [10]) on the twin STEREO spacecraft. The combined data permitted event-integrated spectra to be determined from 0.1 to 20 MeV/nuc. An example of the resulting spectra is given in the left panel of Figure 1 (for the 22 Sep 2011 event). Similar spectra can be made for Fe, allowing the energy dependence of the Fe/O abundance ratio to be determined (e.g., Figure 1, right panel). As can be seen from these plots, various characteristics of the spectra (e.g., spectral shape and hardness) can differ substantially from spacecraft to spacecraft. For example, while the O fluences are higher at STEREO-B for this event, the higher energy portion of the spectrum is significantly softer at STEREO-B than at ACE. The STEREO-A spectrum appears to break at lower energies, however the higher energy portion is harder than that seen at either of the other spacecraft.

The Fe/O ratios show some distinct differences between the three spacecraft as well, however at energies above 10 MeV/nuc the ACE and STEREO-B measurements are nearly identical. Although the STEREO-A Fe/O ratio begins to increase with energy at a lower energy than observed by ACE or STEREO-B, the rate of increase is very similar.

In order to better understand how such differences relate to the relative positioning of the spacecraft, we have calculated the longitudinal separation angle (in degrees) between the position of the flare and the magnetic footpoint of each spacecraft (using the observed solar wind velocity during the event and assuming a corresponding Parker spiral). This angle is then smallest for the most well-connected spacecraft. While we acknowledge this is a potentially over-simplistic characterization, particularly in the presence of interplanetary CMEs, a detailed modeling of the magnetic field line connections for each spacecraft in each event is beyond the scope of this study.

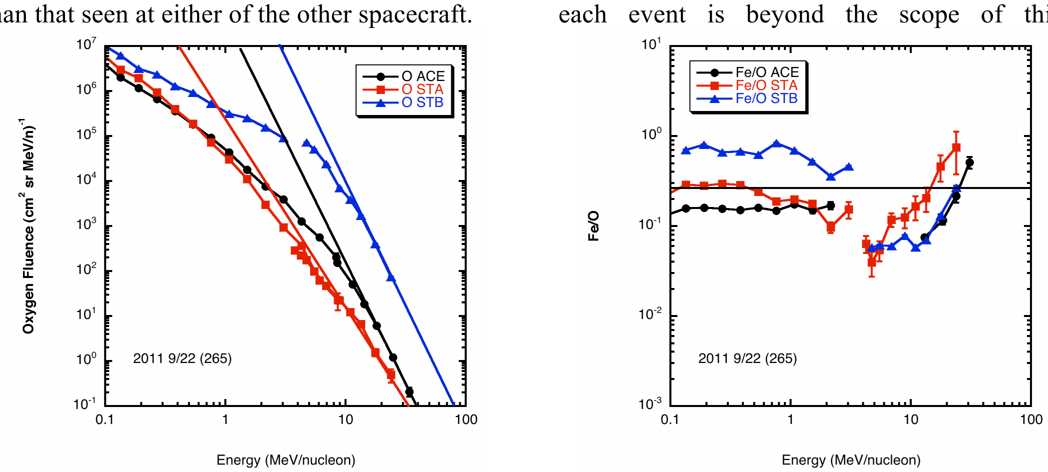

FIGURE 1. Oxygen event-integrated fluence spectra (left) and the Fe/O ratios as a function of energy (right) from the two STEREOs and ACE for the SEP event on 22 Sep 2011. The solid lines show the power law fits to the >10 MeV/nuc portion of the O spectra. The horizontal line at Fe/O = 2x0.134 indicates twice the nominal SEP Fe/O abundance at 5-12 MeV/nuc [11].

The oxygen spectra were characterized by fitting the portion of the spectrum above 10 MeV/nuc with a power law, $E^{-\gamma}$. The spectral index, γ, and the Fe/O ratios at 10 MeV/nuc were then plotted versus the longitude separation angle for each observing spacecraft in each event in Figures 2 and 3. Lines connect points for measurements made within the same event. The pair or triplet of points for a given event was then described as 'peaked' if the point closest to angle = 0 had the highest value (of either γ or Fe/O ratio), or as 'valley' if the point had the lowest value. It should be noted however, that in most cases this description is possibly misleading due to having only two points rather than three. In one case (4 Nov 2011) the γ values continued to decrease from west to east, resulting in neither 'peaked' nor 'valley' behavior. These characterizations are given for both the oxygen spectral index and the Fe/O abundance ratio for each event in Table 1.

DISCUSSION

The scenario of Cane et al. [4] suggests that the longitudinal dependence should be exhibited by peaked behavior in the Fe/O ratio, indicating higher Fe/O values obtained by the observer most closely connected to the flare site. Additionally, the oxygen spectrum should be harder in the flare-accelerated material so a valley characteristic would be expected in the γ values. The scenario of Tylka et al. [3] generally predicts no longitudinal dependence, however an argument could be made that quasi-perpendicular shocks are more likely to occur on the flanks of a CME, rather than at the nose [12]. If one assumes that the nose of the CME corresponds roughly with the location of the flare, then one might expect reaccelerated flare material to be preferentially present away from the best connection. This would be evidenced by peaked behavior in the γ values and valley behavior in the Fe/O ratios. Eight of the 12 events show peaked behavior in the oxygen spectral indices. For the Fe/O ratios, six events are peaked and six are valley, yielding no overall preference.

The mixing processes involved in the Tylka and Cane scenarios do not, a priori, dictate that the resulting SEP event be Fe-rich, just that it have a higher Fe/O ratio than had the mixing not occurred. However, since both scenarios were put forth to explicitly explain Fe-rich events, we can limit our sample to only those events with Fe/O ≥ 2 x 0.134 (twice the nominal SEP Fe/O ratio at 5-12 MeV/nuc; [11]) for one or more of the observing spacecraft. This leaves us with only three events: 15 Feb 2011, 21 March 2011, and 4 Nov 2011. Of these, two were peaked in Fe/O and two were peaked in O spectral index (the third was unique in being the event mentioned earlier with neither peaked nor valley behavior for γ). Thus the observations are not entirely consistent with either of the proposed scenarios.

Plotting the Fe/O ratios at 10 MeV/nuc versus the γ values (Figure 4) shows an anti-correlation which generally suggests that events with higher Fe/O abundances have harder O spectra above 10 MeV/nuc. As the orientations of the line segments show, this characteristic is present in many individual events as well. However, there are exceptions including two of

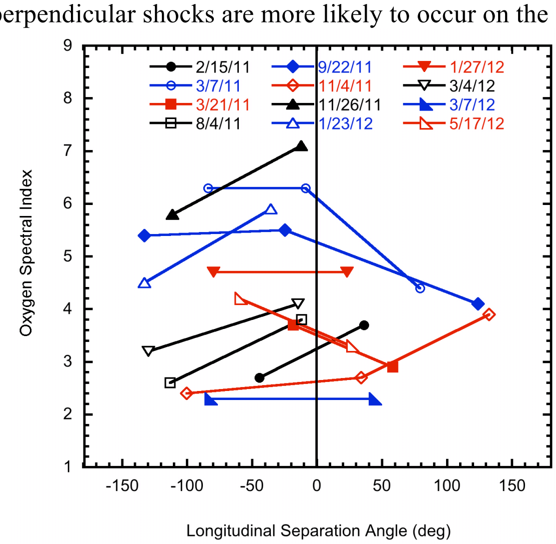

FIGURE 2. Oxygen spectral index above 10 MeV/nuc as a function of the longitudinal separation angle between the flare and the spacecraft magnetic footpoint for each event. Lower indices indicate harder spectra. Lines connect multiple spacecraft measurements for a given event.

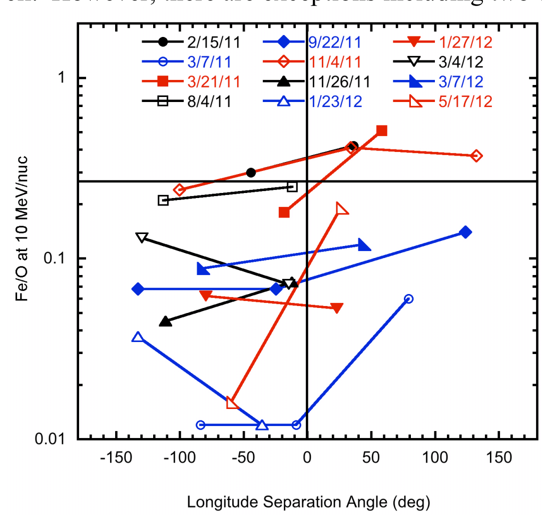

FIGURE 3. Fe/O abundance ratios at 10 MeV/nuc as a function of the longitudinal separation angle between the flare and the spacecraft magnetic footpoint for each event. Lines connect multiple spacecraft measurements for a given event. The horizontal line indicates twice the nominal SEP Fe/O ratio at 5-12 MeV/nuc [11].

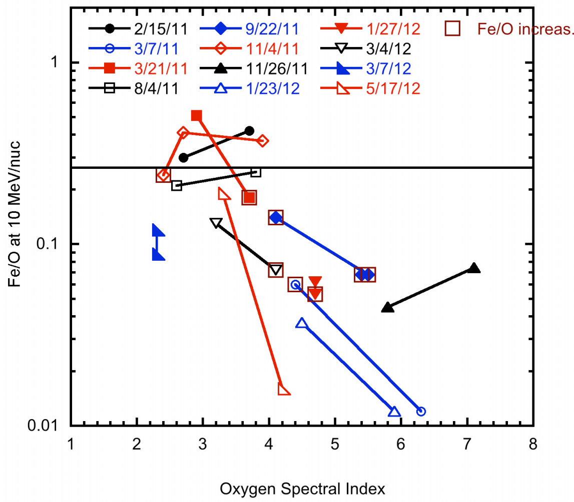

FIGURE 4. Fe/O abundance ratios at 10 MeV/nuc as a function of oxygen spectral index above 10 MeV/nuc for each event. Points surrounded by boxes indicate the Fe/O ratio is increasing with energy. Lines connect multiple spacecraft measurements for a given event. The horizontal line indicates twice the nominal SEP Fe/O ratio [11].

the three Fe-enriched events where the higher Fe/O ratios have softer oxygen spectra. In this plot, we also indicate those observations in which the Fe/O ratio is increasing with increasing energy by encasing the data point in a larger square symbol. Obtaining Fe/O abundances at a higher energy would result in these points moving upwards, but how that would affect the overall trend is unclear. Unfortunately, any correlation between γ and Fe/O does not help distinguish the plausibility between the two proposed scenarios as both suggest/assume that the Fe-enriched flare material has a harder spectrum.

It should be mentioned that although this study has concentrated on the contrasting predictions of the Cane et al. and Tylka et al. scenarios, there are other potential explanations for the Fe-enriched events. These include the possibility of strong longitudinal variations in the seed population composition sampled by different portions of an interplanetary shock and the effects of particle transport on the SEP composition evaluated at a common energy. Studies of the latter was recently performed by [14,15] and it was found that transport can have a significant influence on observed SEP composition. Such possible transport effects will be examined in a future study of the temporal evolution of the Fe/O ratios in these events.

The large majority of the Fe-enriched SEP events seen by ACE in solar cycle 23 occurred during the rise to solar maximum, primarily from late 1997 through late 1998 [1]. Although the onset of solar cycle 24 was delayed compared to expectations [13], the rise in sunspot number for the year 2011 is remarkably similar to that of late 1997 – late 1998. However, the number of Fe-enriched events in this portion of cycle 24 appears to be significantly less than in cycle 23. In particular, there have been no large SEP events with event-averaged Fe/O ratios > 0.7 at 10 MeV/nuc thus far in cycle 24 as compared to 4 of the 9 events reported in [1]. Hence it is possible that we have yet to observe the right 'type' of SEP event to appropriately test the Cane and Tylka scenarios.

It is unclear why the occurrence rate of Fe-enriched SEP events is so different between the two cycles. It is perhaps relevant that the fraction of time in which energetic ^{3}He was present in the interplanetary medium was often significantly lower during 2011 as compared to the late 1997 – late 1998 period (see http://www.srl.caltech.edu/ACE/ACENews/ACENews154.html and [16]). This may indicate a dearth of flare suprathermals to be reaccelerated or perhaps a result of fewer strongly flaring regions. Whether more Fe-rich SEP events will occur later remains to be seen.

ACKNOWLEDGMENTS

This work was supported by NASA under grants NNX11A0756, NNX08AI11G and NNX10AQ68G at Caltech, NNX10AT75G at JHUAPL, subcontracts SA2715-26309 from UC Berkeley (NASA contract NAS5-03131) and by NSF grant AGS-1156004 at Caltech and AGS-1156138 at JHUAPL. We thank Nariaki Nitta for useful discussions regarding solar source identifications.

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