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Temporal variations in solar energetic particle events

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Abstract. The Solar Isotope Spectrometer (SIS) on-board the Advanced Composition Explorer (ACE) spacecraft has measured elemental abundances in large solar energetic particle (SEP) events as a function of time for more than 25 such events. There are large temporal variations in the observed abundances within events, from event to event, and as a function of particle energy. Such variations have been previously attributed to the combination of an initial impulsive phase having enhanced heavy element abundances with a longer gradual phase with coronal abundances. More recently they have been attributed to rigidity dependent escape from CME-driven shocks through plasma waves generated by wave-particle interactions. Both these models can be expected to depend upon solar longitude since impulsive events are associated with longitudes well-connected magnetically to the observer, and shock properties and connection of the observer to the shock are also longitude dependent. We present evidence of longitude related variations. In addition, we show that there are events with little time variation and heavy element enhancements similar to those of impulsive events. These events appear to be difficult to explain in current models in which particles are accelerated with coronal abundances. Rather, these events seem to require abundance enhancements either in the source material or in the acceleration process.

1 Introduction

Event-to-event variations in elemental abundances have been known for a long time (e.g., see the review by Reames, 1999). The causes of these variations, however, have been relatively slow in being understood. An important step was the work of Breneman and Stone (1985), who showed that the elemental abundances in specific solar events could be ordered as power laws in Q_X/M_X , where Q_X and M_X are the mean ionic charge state and the mean elemental mass for element X. The corresponding power laws had exponents ranging from roughly -2.5 to +2.5, corresponding to both heavy element enhancements and heavy element depletions. No explanation for this behavior was provided other than to presume that particle rigidity was the essential parameter governing both particle acceleration and escape from the sun. Reames, *et al.* (1990) and Cane, *et al.* (1991) were the first to report on an organization of abundance data by the longitude of the source region. They suggested that solar event elemental abundances as a function of longitude could be understood in terms of two particle sources: 1) particles originating out of flare-heated material and 2) particles accelerated at coronal and interplanetary shocks. Fe-rich, high Q-state, flare-heated material would only have access to the observer when the observer was magnetically well-connected to the flare site. Reames (1999) has subsequently rejected this interpretation, instead attributing the longitude dependence of Fe enhancements to the fact that the observer connects along magnetic field lines to different regions of the shock depending upon the solar longitude of the location where the CME originates. For example, the observer is connected to the nose of a CME shock (where the shock is presumably the strongest) when the CME originates at a western location. The longitude dependence of SEP abundances has been largely ignored since the time of Cane, *et al.* (1991) but will be revisited in the present paper.

Recent work by Reames, Ng and Tylka has explained some unexpected temporal behavior in solar event composition in terms of shock acceleration and the build-up of plasma waves, predominantly due to proton wave-particle interactions (e.g., Tylka, *et al.*, 1999; Reames, *et al.*, 2000; Ng, *et al.*, 1999). The Ng, *et al.* (1999) model can create an enhancement of Fe/O above the coronal value at low energies for some observers for at least a portion of the event. In particular, it has been able to inject particles with coronal abundances and produce a peak in the modeled Fe/O time-intensity curve at a few MeV/n as reported by Tylka, *et al.* (1999), in the 20 April 1998 event. This peak was enhanced over the coronal

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value by a factor of about 4. A constant, high value of Fe/O, however, would be difficult to achieve in this model.

The model of Ellison and Ramaty (1985) produces a Q/M dependent energy spectrum by accounting for first order Fermi acceleration and rigidity dependent escape at a shock, although the predicted spectral shape applies at the shock and not to the remote observer. Furthermore, there is no time dependence in the Ellison and Ramaty (1985) model. This model has fit differential intensity spectra quite well and has been useful in deriving Q/M ratios for different elements (Tylka, *et al.*, 2000). This is possible since the model spectrum consists of a power law in momentum modified by an exponential factor, $\exp(-E/E_{0X})$, produced by the finite spatial extent of the shock. Here E is kinetic energy/nucleon and $E_{0X} = E_{0H}(Q_X/M_X)$, where X denotes element X and E_{0H} is the appropriate E_{0X} for hydrogen. The exponential factor gives rise to characteristic spectral knees which can, for example, account for depletions of Fe relative to O above $\sim E_{0Fe}$ since in general Q_{Fe}/M_{Fe} is less than Q_O/M_O. However, this model cannot account for enhancements of Fe/O above coronal values seen in many events, including the 6 November 1997 event in which the Fe/O ratio was enhanced as high as 6 times the coronal value at SIS energies. It also cannot account for the Fe/O ratio increasing with energy as was observed for the 6 November 1997 event (von Rosenvinge, *et al.*, 1999).

In this paper we will present evidence of longitude related variations for event-averaged abundances and for variability in abundances within events. It is found that the events showing heavy element depletions are either near or east of central meridian or, in one case, near the west limb. Events showing the most variability within the events are also associated with either central meridian or the west limb. In addition, we show that there are events with little time variation and heavy element enhancements similar to those of impulsive events. These events appear to be difficult to explain in current models in which particles are accelerated with coronal abundances. Rather, these events seem to require abundance enhancements either in the source material or in the acceleration process.

2 Observations

The measurements reported in this paper are from the Solar Isotope Spectrometer (SIS) on-board the ACE spacecraft (Stone, *et al.*, 1998). The large geometry factor of SIS ($\sim 38\ cm^2$-sr), enables us to observe abundances on a time scale typically of hours.

Figure 1 shows measurements of event-averaged Fe abundance enhancements relative to C, for the kinetic energy interval 12-60 MeV/nucleon, versus the solar longitude of the corresponding flare event. The ACE-SIS event number from Table 1 is printed for each event in place of a data point. Events beyond $W90°$ have been plotted at $W90°$ due to uncertainty in the actual location. This figure shows that all events occurring between $W15°$ and $W85°$ have Fe enhancements greater than one. All events with enhancements ~ 1 or less are either to the east of $W15°$ or, in the case of the unusual 20 April 1998 event, at ($\sim W90°$). Events with large Fe enhancements also occur at or beyond the west limb, but not near central meridian.

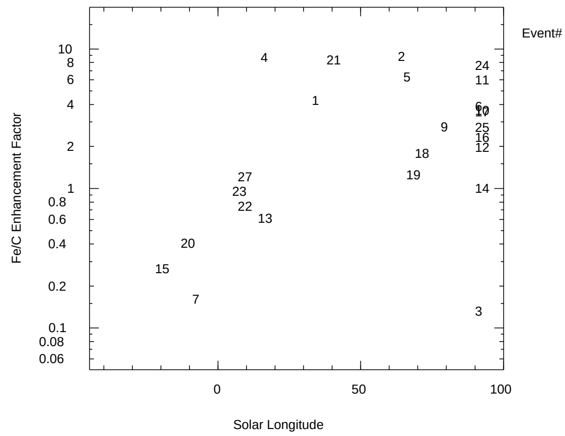

Fig. 1. Shows the enhancement of Fe/C over the average gradual event abundance reported by Reames (1995) for multiple events versus the solar longitude of the associated flare event.

Figure 2 shows, for each separate event, the ratio of the maximum Fe/O ratio to the minimum Fe/O ratio versus the solar longitude of the associated flare event. The ratios are determined at 14 MeV/nucleon. This then gives a measure of the variability of Fe/O during each event. We see that, with the exception of event 19, there is very little variability within events between $\sim W15°$ and $\sim W80°$. Events with relatively large variability are either close to central meridian or towards the west limb. Events with low variability, however, can occur at all longitudes.

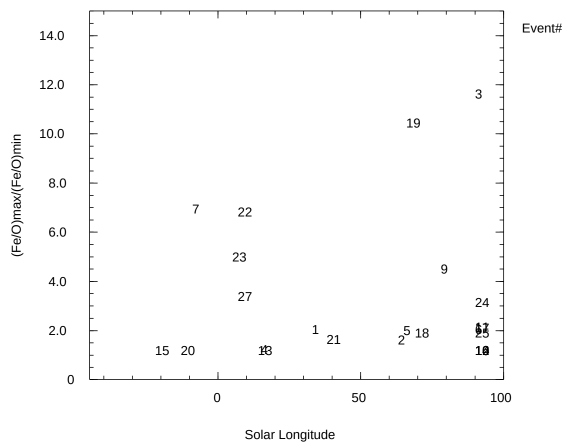

Fig. 2. Shows the ratio of the maximum Fe/O ratio during each event to the minimum Fe/O ratio versus the solar longitude of the associated flare event.

Figure 3 shows time-intensity profiles (upper panel) and ratios (lower panel) at 14 MeV/nucleon normalized to average gradual event values for representative elements in the

Table 1. SIS particle events.

#	Start UT	End UT	Flare UT	Longitude	Comments
1	1997 Nov 4 06:00	1997 Nov 6 12:00	Nov 5 05:52	W33	X2.1, 2B
2	1997 Nov 6 12:00	1997 Nov 10 00:00	Nov 6 11:49	W63	X9.4, 2B
3	1998 Apr 20 12:00	1998 Apr 27 00:00	Apr 20 09:38	W90	M1.4, no H_α
4	1998 May 2 12:00	1998 May 5 00:00	May 2 13:31	W15	X1.1, 3B
5	1998 May 6 08:00	1998 May 8 00:00	May 6 07:58	W65	X2.7, 1N
6	1998 May 9 04:50	1998 May 11 12:00	May 9 03:04	W90	M7.7, no H_α
7	1998 Aug 25 00:00	1998 Sep 1 00:00	Aug 24 21:50	E09	X1.0, 3B
8	1998 Sep 24 12:00	1998 Sep 25 12:00	Sep 23 07:13	E09	M7.1, 3B, strong ESP spike after Sep 24 12:00 UT
9	1998 Sep 30 12:00	1998 Oct 5 00:00	Sep 30 13:50	W78	M2.8, 2N
10	1998 Oct 19 00:00	1998 Oct 20 18:00	Oct 18 21:15	W90	no X-rays, no H_α, Type III
11	1998 Nov 14 06:00	1998 Nov 18 12:00	Nov 14 05:05	W90	weak X-rays, no H_α
12	1999 Jan 21 00:00	1999 Jan 27 12:00	Jan 20 19:06	W90	M5.2, no H_α
13	1999 Feb 16 00:00	1999 Feb 19 00:00	Feb 16 02:49	W14	M3.2, SF
14	1999 Apr 24 12:00	1999 Apr 26 12:00	Apr 24 12:36	W90	no X-rays, no H_α, CME
15	1999 May 4 00:00	1999 May 9 12:00	May 3 05:50	E32	M4.4, 2N
16	1999 May 9 18:00	1999 May 11 00:00	May 9 18:07	W90	M7.6, no H_α
17	1999 Jun 2 00:00	1999 Jun 4 08:00	Jun 1 19:30	W90	no X-rays, no H_α, CME
18	1999 Jun 4 08:00	1999 Jun 8 00:00	Jun 4 07:00	W69	M3.9, 2B
19	2000 Apr 4 12:00	2000 Apr 9 00:00	Apr 4 15:12	W66	C9.7, 2F
20	2000 Jun 7 00:00	2000 Jun 10 00:00	Jun 6 13:24	E12	X1.1, 3B
21	2000 Jun 10 12:00	2000 Jun 13 00:00	Jun 10 16:40	W38	M5.2, 3B
22	2000 Jul 14 00:00	2000 Jul 19 00:00	Jul 14 10:03	W07	X5.7, 3B
23	2000 Sep 12 12:00	2000 Sep 16 00:00	Sep 12 13:31	W05	
24	2000 Oct 16 00:00	2000 Oct 20 00:00	Oct 16 07:00	W90	M2.5, no H_α
25	2000 Oct 25 12:00	2000 Oct 29 00:00	Oct 25 09:30	W90	no X-rays, no H_α
26	2000 Nov 9 00:00	2000 Nov 15 00:00	Nov 8 23:28	W77	M7.4, 3F
			Nov 9 16:13	E10	M1.0, SF
27	2000 Nov 24 00:00	2000 Nov 29 00:00	Nov 24 05:02	W05	X2.0
			Nov 24 15:13	W07	X2.3
			Nov 24 21:59	W14	X1.8

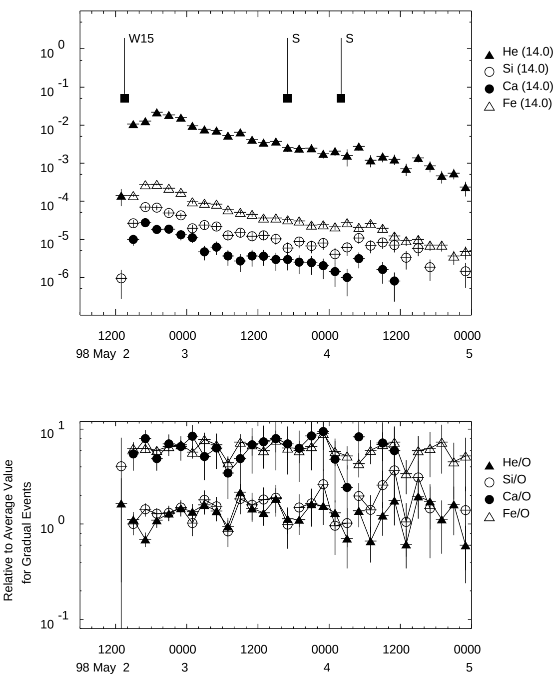

Fig. 3. Example of an event where Fe/O is essentially constant throughout the event at an enhanced level.

event of 2 May 1998. This normalization means that ratios which are the same as the corresponding event averages given by Reames (1995) are plotted with a value of 1.000 and enhancements above (or depletions below) the average values are immediately apparent. The average gradual event values are thought to represent average coronal values (Reames, 1995). There was a corresponding flare at $W15°$ at 1998 May 2 13:31 UT. Figure 3 shows that the normalized Fe/O ratio is quite constant throughout the event with a value of approximately 6. It also shows that the normalized Ca/O ratio is similarly constant with a similar value. The ratios He/O and Si/O show only slight enhancements. Note also the two interplanetary shocks shown in Figure 3 and separated by only 9 hours. The presence of these two shocks potentially complicates the interpretation of this event. On the other hand, as shown in Figures 1 and 2, well-connected events with relatively constant Fe/O during each event and large enhancements of Fe are fairly common. Three other events with relatively constant Fe/O (6 November 1997, $W33°$, 14 November 1998, $> W90°$, and 6 May 1998, $W65°$) are shown in von Rosenvinge, *et al.* (1999) and von Rosenvinge, *et al.* (2000).

3 Summary and Discussion

It is clear from the data presented here that the observed event-to-event average abundances depend on the solar longitude of associated solar flare events. It is also clear that the temporal variability of abundances within individual events also depends upon solar longitude. At this point there is no accepted model which we know of that accounts for these dependences, although the model of Cane, *et al.* (1991) cannot be ruled out. In fact, this model is consistent with the observation that the mean Fe charge state in large events is correlated with Fe/O (Leske, *et al.*, 2001).

We have also shown that events originating from beyond $\sim W15°$ commonly show large Fe/O enhancements which vary little during the course of the events. Such enhancements cannot be explained within the context of the Ellison and Ramaty (1985) model and injection of relative abundances at low energies corresponding to coronal abundances. It is possible that injections from multiple impulsive events can fill the inner solar system with enhanced heavy elements which are then accelerated by CME related shocks (Mason, *et al.*, 1999). However, events with large Fe/O enhancements have heavy element composition essentially identical to that of impulsive events, so this process would have to completely dominate the acceleration of normal coronal/solar wind material. And why, then, would there be no Fe enhanced events east of $\sim W15°$?

It is not clear either how the Ng, *et al.* (1999) model can account for events with large, constant Fe/O enhancements. The Ellison and Ramaty (1985) model, however, does appear to have successfully accounted for spectral shapes for elements from H to Fe for the event of 20 April 1998 (at the west limb) and the event of 25 August 1998 (at $E09°$) (Tylka, *et al.*, 2000). Similar analysis of spectral shapes for events with near constant Fe-enhancements has yet to be done.

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