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# Time Variations of Solar Energetic Particle Abundances Observed by the ACE Spacecraft

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**Abstract**

The abundances of elements from Helium to Iron have been observed in nine different solar energetic particle (SEP) events using the Solar Isotope Spectrometer (SIS) on-board the Advanced Composition Explorer (ACE). SIS has a large geometry factor (~ 38 $cm^2$-sr), enabling us to observe abundances on a time scale of hours. In this paper we report on substantial temporal variations of the observed abundances within events and from event to event. We wish to understand these results in terms of acceleration and transport processes, taking into account factors such as first ionization potential, particle charge states, spectral shape, and event type (gradual and impulsive). It is essential that these variations be understood if we are to reliably estimate the composition of the sun from direct observations of SEP abundances.

## 1 Introduction:

Most previous studies of the elemental abundances in Solar Energetic Particle (SEP) events have used event-averaged abundances due to statistical limitations. A few events, however, were large enough to study temporal variations within a single event. For example, von Rosenvinge and Reames (1979) reported observations of the event of September 23, 1978 using data from ISEE-3. They observed that the Fe/O ratio at ~ 2 MeV/n declined by a factor of about 5 over a period of ~ 2 days, while, at the same time, the He/O ratio increased by a factor of about 2.5. This was interpreted to mean that the Fe charge state was quite low (~ 11) and that O, while more nearly fully stripped, also retained some electrons. In that case, Fe, with the highest rigidity, was able to escape from the acceleration region more rapidly than was O, and, in turn, the O was able to escape more rapidly than He. This then lead to relatively more Fe than O early in the event. With the launches of the WIND and the Advanced Composition Explorer (ACE) spacecraft, telescopes with much larger collection power have begun to examine temporal variations in a variety of different events. The observed behavior is much more complex than the simple pattern just presented. We present examples of such behavior in this paper. Due to this complexity, one can imagine that the interpretation of event-averaged abundances may not be as simple as previously thought.

## 2 Observations:

We present observations of SEP elemental abundances as obtained with the Solar Isotope Spectrometer (SIS) on the ACE spacecraft. SIS consists of two redundant telescopes of solid-state detectors. The first two detectors in each telescope have 64 strips on each side of each detector, forming an orthogonal grid for determining the position that a particle passes through the detector. Each strip has its own individual threshold discriminator and pulse height analyzer. The relatively small area of a single strip enables one to have a very large detector area (36 $cm^2$) without an excessively high counting rate in any one strip. Taken together, the first two detectors in each telescope provide the trajectory of each particle so that the path length that a particle has in each detector can be precisely determined. The first two detectors of each telescope are ~ 70 μm of Si thick, and successive detectors are increasingly thicker. A thorough description of the SIS telescope is given in Stone *et al.* (1998). Suffice it to say here that SIS, which was designed to separate individual isotopes of each element, easily resolves all the elements reported here (He to Fe) with essentially no background. The two isotope telescopes combined have a geometry factor of ~ 38 $cm^2$-sr.

During the time since ACE was launched on August 25, 1997, there have been 9 moderately large SEP events, which are listed in Table 1 with the (preliminary) start times and locations of their parent CMEs/active regions. CME speeds have been given where available; otherwise,where the corresponding shock was observed at earth, the mean transit speed is given in the same column in parentheses. An approximate time to peak, as observed at 14 MeV/n, is also given. Most of these have been western events which, judging from their locations and/or rise times, appear to have been reasonably well-connected magnetically to ACE at the start of the events and have had reasonably constant compositions as a function of time within the events. Exceptions include: the event of August 24, 1998, which originated at approximately E09 and which has a secondary peak associated with the corresponding interplanetary shock; the event of April 20, 1998 occurred at the west limb and has the longest time to peak; the event of September 30, 1998. These three events have the most pronounced abundance variations as a function of time within each event. They also appear to be the events which are most strongly affected by their corresponding shocks.

Table 1. Nine Observed SEP Events

| Date | Start | Location | CME Speed (km/sec) | Approx. Time to Peak (hrs) |
|---|---|---|---|---|
| 1997 Nov 4 | 0552 | S14W33 | 800 | 6 |
| 1997 Nov 6 | 1149 | S15W63 | 1560 | 13 |
| 1998 Apr 20 | 0938 | S43W90 | 1680 | 25 |
| 1998 May 2 | 1331 | S15W15 | 1050 | 4-5 |
| 1998 May 6 | 0758 | S11W65 | 1053 | 1.5 |
| 1998 May 9 | 0300 | W70?W90? | (850) | 18 |
| 1998 Aug 24 | 2150 | N35E09 | (1300) | 3, 28 |
| 1998 Sep 30 | 1300 | W35?W80? | (980) | 6 |
| 1998 Nov 14 | 0510 | W60? | ? | 8 |

The intensities of 14 different elements (He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe and Ni) were determined as two-hour averages during each of the 9 events listed in Table 1. The observed intensities were interpolated to an energy of 14 MeV/n for each of the observed elements; all of the SIS data reported in this paper correspond to this energy. Pulse discriminator thresholds were raised by ground command for a portion of the April 20 and of the August 24 events, resulting in a loss of He coverage. In the figures which follow, in order to maintain legibility, the displayed intensities are for representative elements only. The upper panels show time-intensity profiles, whereas the lower panels show ratios of the intensities of different elements to the intensity of O; these ratios are normalized to the corresponding (gradual) event-averaged abundance ratios given by Reames (1995). 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 the average values are immediately apparent. Further references to ratios in the rest of this paper will specifically mean these normalized ratios.

Figure 1 shows plots for the events of November 4, 1997 and November 6, 1997. Figure 2 shows the same plots for the event of November 14, 1998. These three events are all rather similar, showing strong enhancements in the Fe/O and Ca/O ratios and relatively little time dependence during the events. The He/O ratio in the November 6 event shows the largest temporal variation and that is rather irregular. Apart from the leading edge of the event, the Si/O ratio shows no enhancement at all in the November 6 event, whereas it is enhanced by almost a factor of 2 in the November 14 event. Tylka, Reames, and Ng (1999) show the Fe/O ratio for the November 6 event for three different energy intervals below the 14 MeV/n reported here. Their data shows an increase in the Fe/O ratio as a function of energy, a trend which continues in the data of Figure 1.

The event of April 20, 1998, shown in Figure 3, is in complete contrast to the events considered so far. The Fe/O ratio starts at ~1.0 at the beginning of the event and falls steadily to ~0.12 at ~00:00 on April 21. During the same interval, the He/O ratio falls together with the Fe/O ratio, contrary to the inverse behavior which was observed in the September 23, 1978 event. Afterwards, the Fe/O ratio shows an increase to above 0.2 and then falls back towards ~0.13. A corresponding peak in the Fe/O ratio is also seen in the data reported by Tylka, Reames, and Ng (1999), however at 2.5-3.2 MeV/n the value peaks at ~4, so an observer

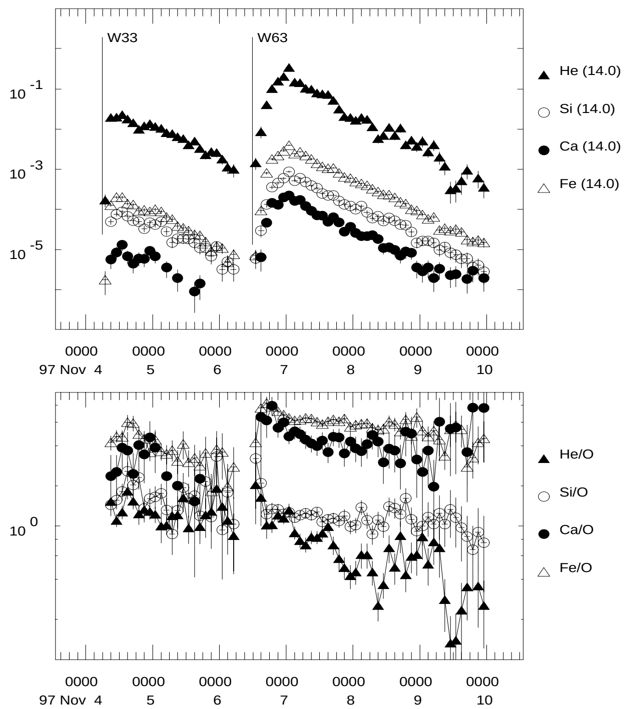

Figure 1. 2-hour averages for the events of November 4 and November 6, 1997.

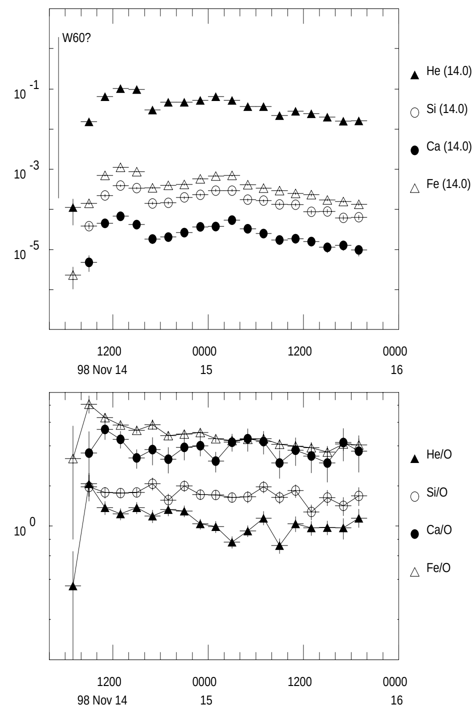

Figure 2. 2-hour averages for the event of November 14, 1998.

at low energies might regard this as an Fe-rich event, whereas at SIS energies it is an Fe-poor event. An explanation for this (suggested by D.V. Reames) could be that, if low energy Fe is escaping from the interplanetary shock, then relatively little Fe stays near the shock long enough to be accelerated to higher energies. Again, the progression of behavior observed at low energies by Tylka, Reames and Ng (1999) is nicely continued to higher energies by the SIS data.

Figure 4 shows the temporal variations of abundances during the September 30, 1998 event. We see once again that the He/O ratio and the Fe/O ratio are both declining rather than varying inversely at the beginning of the event. Here, however, unlike the case in Figure 3, the Fe/O ratio and He/O curves are considerably separated during this declining phase. The Si/O ratio is essentially constant at a value just somewhat greater than 1.

Figure 5 shows half-hour average intensities for the May 6, 1998 event. One can see that the He intensity at 14 MeV/n falls one and a half orders of magnitude in 2.5 hours, but then falls quite slowly to the end of the event at approximately 20:00 on May 8. One might argue that this event is a hybrid with an impulsive beginning superimposed on a long-lived gradual part. On the other hand, the durations of impulsive and gradual events have historically been measured and compared at a few MeV/n, instead of the 14 MeV/n used here.

## 3 Discussion:

Cohen, *et al.* (1999) discuss the fact that event-averaged abundances obtained by SIS for the events of November 6, 1997; May 2, 1998; May 6, 1998; and November 14, 1998 are seemingly characteristic of impulsive events and not of gradual events. The compositions of two of these events have already been shown for some elements in Figures 1 and 2. Tylka and Reames (private communication), on the other hand, regard all of the events in Table 1 as gradual events. For the November 6, 1997 event, the time to peak and the associated CME certainly argue for the continued shock acceleration associated with gradual events, however the relatively constant abundances suggest that wave generation in the shock is doing little to modify the observed composition. This is unlike the April 20 and September 30 events (and also the

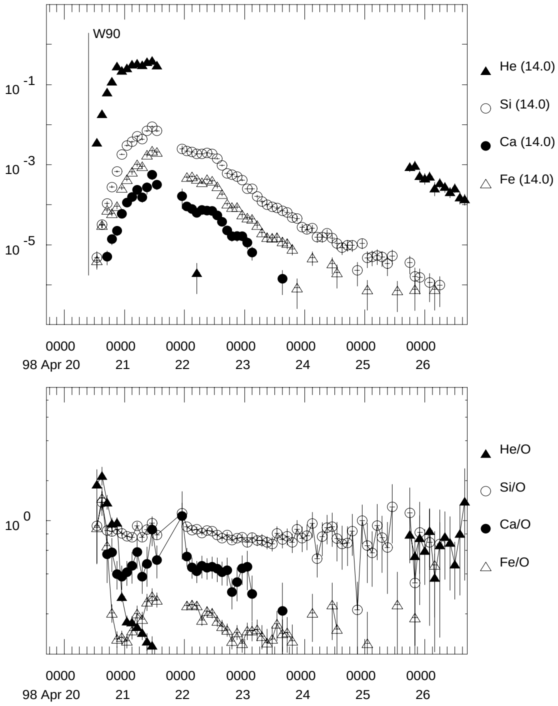


Figure 3. 2-hour averages for the event of April 20, 1998.

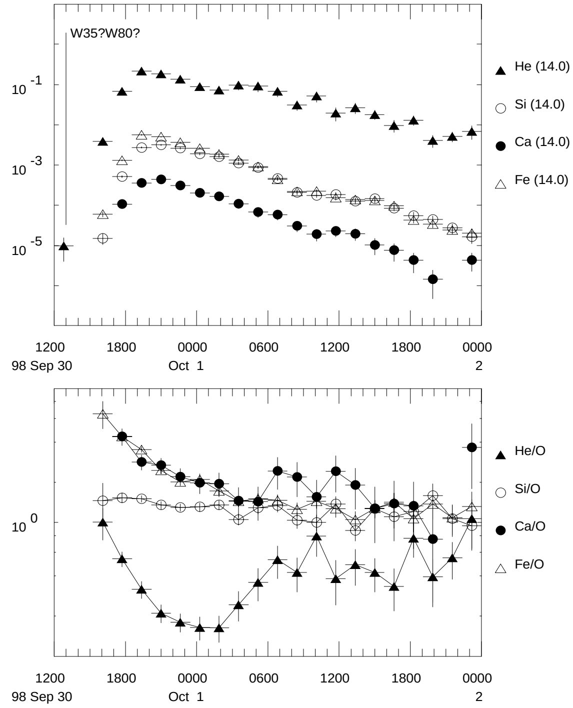


Figure 4. 2-hour averages for the event of September 30, 1998.

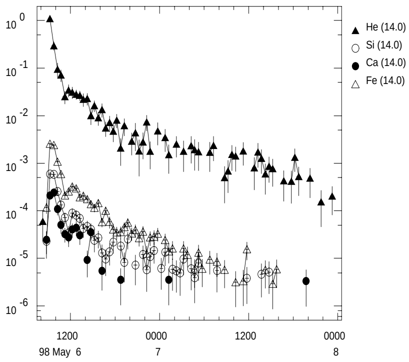


Figure 5. Half-hour averages for the event of May 6, 1998.

August 24, 1998 event, which has not been shown here), where the shock is clearly affecting the temporal structure of the observed abundances and apparently the event averaged abundances as well. The reader is referred to Ng, Reames, and Tylka (1999) for a description of these shock processes.

It is clear that we have a long way to go to completely understand the observations presented here. It may be that a more complex picture than the simple division into impulsive and gradual events will be required. In particular, it seems that particles strongly affect the accelerating shock (and vice versa) in some gradual events and not in others. The latter events seem to have compositions very similar to those of impulsive events.

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