Composition Variations during Large Solar Energetic Particle Events

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Abstract. Recent theoretical work has posited that proton-generated Alfvén waves scatter ions according to their rigidity during propagation from the acceleration region to the observed position. In particular, predictions have been made for the initial behavior of the high energy (> 2 MeV/nucleon) He/H and Fe/O ratios during large solar energetic particle (SEP) events based on this theory. In this paper, we have examined the temporal variations of low energy (~0.3 MeV/nucleon) hydrogen, helium and iron ions throughout thirty large SEP events using the ULEIS instrument on the ACE spacecraft. These events originated from different solar longitudes; hence we compare events that have similar magnetic connection to minimize the transport effect. All events exhibited an eventual decrease in the He/H ratio as is suggested by the wave-particle model, but the degree of variation of He/H varies from event to event. However, the time variation of the Fe/O ratio does not correlate at all with that of the He/H in most of the events that we studied.

INTRODUCTION

Large solar energetic particle (SEP) events are believed to be associated with Coronal Mass Ejection driven shocks. Mason et al. [1] first reported that there are large variations of the He/H, O/He and Fe/O ratios within SEP events. Recently, Ng, Reames & Tylka [2] suggested that self-generated Alfvén waves at the traveling shock and throughout the transport region can modify the abundance ratio of species that have different rigidity. In particular, they predict that any abundance ratio of high-rigidity/low rigidity ions at the same velocity (example; He/H, Fe/O) will begin at high value and decline with time. According to their model, the Alfvén waves will scatter ions with lower A/Q compared with those with high A/Q (since rigidity A/Q). Hence high-rigidity ions should arrive earlier than low-rigidity ions, even when they share the same velocity. However, in some events He/H ratios may also rise with time, which is a signature of events that have hard spectra according to [3]. Reames, Ng & Tylka [3] using Wind, ICE, and IMP8 data have examined four large SEP events and claim a qualitative agreement with Ng et al. theory [2]. In this paper, using composition data from the Ultra-Low Energy Ion Spectrometer (ULEIS) on the Advanced Composition Explorer (ACE) spacecraft, we examine the low energy (230-450 keV/nucleon) He/H and Fe/O ratios in thirty large SEP events (including those examined by [3]).

INSTRUMENT DESCRIPTION

The ULEIS instrument is a high-resolution mass spectrometer that measures both elemental and isotopic ion compositions from 50 keV/nucleon to a few MeV/nucleon. The overall instrument geometric factor is about 1.3 cm²-sr. This large geometric factor enables us to examine low energy ion elemental ratio variations at hourly resolution or better. Mason et al. [4] describe the instrument in full detail.
OBSERVATIONS

We selected gradual SEP events in the ACE/ULEIS data set from November 1997 to December 2002. The criteria for our selection are as follows:

1. The event onset at 0.23-2.0 MeV/nucleon is isolated from other increases (necessary for onset ratio study);
2. There are SOHO/LASCO observations to provide us an estimate launch location and time of the associated Coronal Mass Ejection back at the Sun (except for the event in September 1998);
3. Positive identification on the associated Hα flare location;
4. No compound events (necessary for fluences study)

With these criteria we should minimize effects that could obscure the transport mechanism. The CME observations are taken from the LASCO web site at http://cdaw.gsfc.nasa.gov/CME_list/. For most of the events, the Hα associations have been analyzed in [5].

For this paper, we study both the time history and event averaged He/H and Fe/O variations in large SEP events as a function of their associated solar longitudes, and event maximum intensities.

Event Averaged Ratio

Figure 1 shows the event averaged He/H, C/O and Fe/O for all selected events as a function of their Hα flare longitudes. The event with the highest Fe/O ratio in our survey is associated with a Hα flare located at W69, a magnetically well-connected region. However, the remainder of the events show no clear longitude signature. If we average the Fe/O ratios for those events at W61-W70, the mean Fe/O = 0.63 is more than three times the SEP based coronal value (0.17). However, the spread of those ratios is also large for the four events in that longitude (Fe/O from 0.1 to 1.3). In addition, the C/O ratios for all events have a relatively constant value as compared to the variations we observed for the Fe/O ratios.

von Rosenvinge et al. [6] have found at higher energy (12-60 MeV/nucleon) that Fe/O ratios are higher for magnetically well-connected events. In Figure 2, we plot the Fe/O ratio as a function of both the solar longitude and indicate the maximum event proton intensity at 230-450 keV (by the size of the circular marker). Only the prompt impulsive peak intensity was included regardless of the delayed peak of the shock associated ESP event. The highest intensity event in our survey had maximum proton intensity of 52500 particles/[cm²·sec·str·MeV] at ~300 keV which was associated with an Hα flare at W83, while the lowest intensity event had maximum proton intensity of only 98 particles/[cm²·sec·str·MeV] that was associated with an Hα brightening at E02.

FIGURE 1. Event averaged elemental ratios for all selected thirty large SEP events from September 1997 to December 2002. Horizontal dashed lines indicate the coronal values from [7].

FIGURE 2. Fe/O ratios for events with different maximum intensities (excluding the ESP portion of the SEP event) as a function solar longitude. Larger circles denote higher intensity events.
Temporal Variations

Prior to the launch of ACE, limited data sets were available to study the temporal variation of low energy elemental ratios within large SEP events [1]. However, from [1] we know that the He/H, O/He and Fe/O can have large fluctuations about their means within a large SEP event. The temporal variations of the elemental ratio within an event can be attributed to many factors. The model by [2] suggests these variations are caused by transport effects through self-generated Alfvén waves.

Figure 3 shows three well-connected events (W61-W90) having similar duration and intensity. The hour zero is defined as the time when intensity rises above the pre-event level. Top: $^4$He hourly intensity. Middle and Bottom: hourly He/H and Fe/O ratios respectively.

Given the possible close relationship between the temporal elemental ratio variations and transport effects [2], we first attempt to minimize effects of magnetic connection by organizing our events according to their respective longitudes. Figure 3 shows three selected events that have similar intensity and duration between W61 to W70 in solar longitude. The hour $t = 0$ is defined as the time when the proton intensity rises above the pre-event level. The first panel in Figure 3 shows the background-subtracted hourly $^4$He intensity. Both He/H and Fe/O ratios are shown in the second and third panels respectively. All three events have a similar He/H pattern (i.e. a rapid increase and then decreasing He/H). However, the Fe/O ratio for February 9, 2000 (Day of Year 40, blue) event increases throughout the event, which is opposite to the other two despite similar event connections.

Figure 4 shows three events that originated from western longitudes (W81-W90) and that have similar particle intensities (same format as Figure 3). Again, all three events have a similar He/H pattern. However, the Fe/O ratio for the April 1998 (DOY 110, red) event, that was modeled by [8] at higher energies (>2 MeV/nucleon), shows drastically different temporal variations compared the other two similar events. At higher energy (>2.5 MeV/nucleon), [8] shows a rapid increase and then an exponential decrease of the Fe/O for the same event. However, at 0.23-0.45 MeV/nucleon, the Fe/O ratio shows only a gradual increase and then stay relatively constant throughout the event.

Discussion

Some years ago Mason et al. [1] reported that during the onset of large, well-connected SEP events, the Fe/O, O/He, and He/H ratios showed large temporal changes that in most, but not all, cases could be understood as an interplanetary propagation effect caused by the scattering mean free path increasing.
with particle rigidity. Recently, Ng, Reames and Tylka [2] explored another approach to these onset phase abundance variations by modeling the effects that proton-generated Alfvén waves would have on the scattering of energetic ions during propagation from the acceleration region to the observer. This rigidity dependent scattering can also modify the abundance ratio of species even when they have the same velocity. In particular, the latter theory predicts in events with soft energetic particle spectra an initial decrease in both the He/H and Fe/O ratios at energies >2 MeV/nucleon during large SEP events.

Recently, investigators on both ACE and Wind spacecraft have shown that ion composition variations observed in a few large SEP events at the higher energies (>2 MeV/nucleon) qualitatively agreed with these rigidity dependent transport models [3,8]. However, the same type of variation has not been studied systematically at lower energies, and we present here initial results of such a study.

We examined the event averaged low energy (~300 keV/nucleon) abundance ratio of He/H and Fe/O ratios as a function of longitude and event maximum intensity. No obvious correlation is evident. However, the mean Fe/O ratio for those magnetically well-connected events (W61-W60) has a larger value (0.63) than those from other longitudes. But the spread of those ratios is also large for the four events in that longitude (Fe/O from 0.1 to 1.3). A similar result at higher energy (12-60 MeV/nucleon) was also reported by [6].

In Figures 3 and 4, we showed the temporal variations of He/H and Fe/O for selected events originating from well-connected and west limb longitudes. We thus attempt to minimize effects of magnetic connection by comparing events that have similar longitudes. The majority of the events that we studied exhibited a rapid increase, and then an eventual decrease in the He/H ratio as suggested by the wave-particle model. However, unlike the well eventual decrease of He/H ratio, we observed large fluctuations in the Fe/O ratio in most of our events. These large fluctuations happened not just at the onset of an event (February, 2000 event in Fig. 3). In the three events that we show in Figure 4, the Fe/O ratio in the April 1998 event (DOY 110) even increases within the event, which is completely different from the expected pattern at higher energy.

### SUMMARY AND CONCLUSIONS

Thirty large SEP events were selected for this study from September 1997 to December 2002. We only selected clear and isolated events to study both the event averaged and within event elemental ratios variations. We have grouped our events according to their associated Hα longitudes; hence we minimize any connection effect for these large SEP events. We have found the following:

1. The event averaged Fe/O ratios show a large range of values for those events between W61 and W70. The largest value is more than three times the coronal value.
2. No correlation is observed for the event averaged Fe/O as a function of event maximum intensity.
3. When we examined the temporal elemental ratios within an event, all exhibited an eventual decrease in the He/H ratio as suggested by the wave-particle model, but the degree of variation of He/H varies from event to event.
4. We observed large temporal fluctuations in the Fe/O ratio in most of our events; and these large fluctuations were not restricted just to the onset of the events.
5. Even in events that have similar characteristics (magnetic connection, and intensity), the Fe/O ratios can vary drastically from one to another.

### REFERENCES