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Variation of Ionic Charge States Between Solar Energetic Particle Events as Observed With ACE SEPICA

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Abstract

We present the charge state variation of O, Ne, Mg and Fe for a variety of solar energetic particle events in 1998, as obtained with ACE SEPICA. Compared with strong gradual events, there is a trend towards higher charge states for the small events that carry signatures of impulsive events. Many of them show a mean Fe charge state of about 20, and all elements up to Mg are almost fully ionized. Intermediate charge states between the two groups are also observed, with all elements following the same charge state trend. A correlation of the abundances of Ne and Fe with the Fe charge state is observed. This could be interpreted as support for a mass per charge dependent fractionation. However, it is puzzling that events with the largest deviations from coronal abundances appear to accelerate almost fully stripped ions up to Mg, which do not lend themselves easily to fractionation processes based on mass per charge.

1 Introduction:

It has become a widely accepted view that solar energetic particle events (SEPs) should be subdivided into two classes. Gradual solar events are accompanied by long duration radio emissions and are generally associated with shocks in the corona or even accompanied by coronal mass ejections (CME). They emit high fluxes of energetic particles with a low electron to ion ratio and a composition that reflects on average normal solar corona conditions (e.g. Reames, 1992). Impulsive events are characterized by short time scale (several minutes) electromagnetic (radio and X-ray) emission and generally low fluxes of energetic particles in interplanetary space with a high electron to ion ratio. They show substantial enhancements in the abundance of heavy ions and very often also of ^{3}He over ^{4}He (e.g. Mason et al., 1986; Reames, 1990). In contrast to gradual events, whose charge states are compatible with coronal temperatures in the neighborhood of 1 - $3 \cdot 10^6$ K (Hovestadt et al., 1981), substantially higher mean charge states of Si (≈ 14) and Fe (≈ 20) have been reported for impulsive events (Klecker et al., 1984; Luhn et al., 1987).

With the much larger sensitivity of the SEPICA sensor on ACE we will for the first time show ionic charge states of individual impulsive events and demonstrate their variation. This capability allows us to also study how the charge state variations of different species are related to each other and whether there is any relation to the observed abundance variations.

2 Instrument and Observations:

The ACE spacecraft was launched on August 25, 1997, and injected into a halo orbit around the Langrangian point L1 on December 17, 1997 (Stone et al., 1998). Within a complement of high-resolution spectrometers to measure the composition of solar and local interstellar matter, as well as galactic cosmic rays, SEPICA is the prime instrument for the ionic charge state distribution of energetic particles.

2.1 Instrumentation: The analysis of each ion starts with the determination of its energy/charge (E/Q) through electrostatic deflection in a collimator-analyzer assembly by measuring the impact position in a multi-wire proportional counter. The same counter is the energy loss (ΔE) element of a ΔE - E_{res} telescope where the residual energy (E_{res}) is determined in an ion-implanted solid state detector. Z is determined from the specific energy loss of the particle. Combining all energy losses including dead layers with E_{res} provides the original energy E, which together with E/Q leads to the ionic charge state Q. The instrument is based on the general design of the ULEZEQ sensor flown on ISEE (Hovestadt et al., 1978). A complete description of the SEPICA instrument and its data system may be found elsewhere (Möbius et al., 1998)

Table 1: Selected Solar Energetic Particle Events

Time Interval	**Flux** (0.58-2.3 MeV/n)			Q_{Mean}**(Fe)**	**Event Type**
	O	**Fe**	**Fe/O**	0.18 - 0.44 MeV/n	
110 06 - 114 24	0.209	0.067	0.33	11.26	Gradual
120 00 - 120 24	0.224	0.02	0.09	11.43	Gradual
121 00 - 121 24	0.825	0.033	0.04	11.45	Gradual
147 16 - 149 12	0.139	0.019	0.14	12.94	
122 06 - 123 24	0.158	0.098	0.62	14.46	
124 00 - 125 24	0.152	0.055	0.36	14.59	
126 00 - 127 24	0.214	0.106	0.5	14.17	
136 08 - 136 12	0.003	0.005	1.67	18.75	Impulsive
149 12 - 150 24	0.009	0.007	0.74	18.25	Impulsive
249 12 - 251 12	0.002	0.01	3.98	19.66	Impulsive
251 12 - 252 09	0.005	0.013	2.65	18.9	Impulsive
252 09 - 253 24	0.022	0.036	1.61	18.11	Impulsive

2.2 Observations: For the present study we have selected several SEPs in 1998 that show a wide range of characteristics. The time intervals with the respective average fluxes of O and Fe in cts/s cm^2 sr MeV/nuc and the mean charge state of Fe, as observed by SEPICA, are shown in Table 1. We have included typical gradual events with their generally low, but variable, Fe abundance and typical impulsive events with generally much lower ion fluxes, but a substantial Fe enhancement. We have organized Table 1 by the iron charge state. While the first 3 events with high fluxes and low Fe abundance show Fe charge states of ≈ 11, the last 5 events in the Table reach Q ≈ 18 - 20. This seems to justify an annotation as gradual and impulsive, respectively. However, there is also a group of events with intermediate values of Q ≈ 13 - 15 and Fe/O ratios between the almost coronal value of 0.15 and 0.6. It should be noted here that the Fe charge states, reported for gradual events by Luhn et al. (1984), coincide with the intermediate charge state values of our event selection. However, the value of Q_{Fe} ≈ 11 in the gradual events is consistent with the findings by Mason et al. (1995).

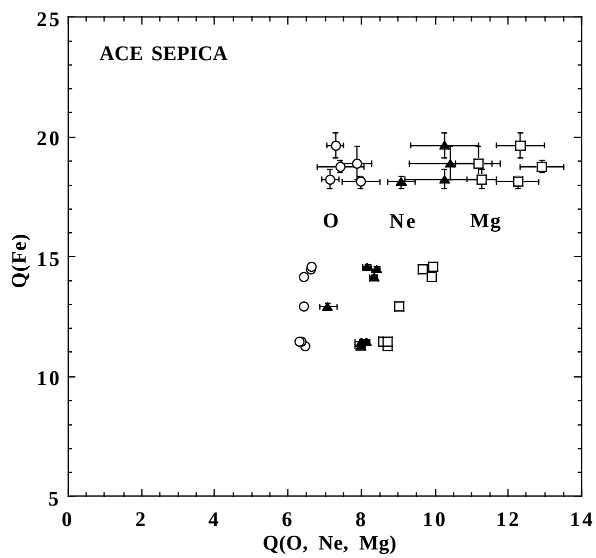

Figure 1: Charge state of Fe versus those of O, Ne and Mg for the SEP events under study along with lines indicating full ionization.

In Fig. 1 the mean charge states of O, Ne and Mg are shown as a function of the Fe charge state together with the standard error of the mean for each event. It is apparent that the charge states of these species follow a similar trend with the Fe charge state. In addition, the ionic charge states of all three species are consistent with fully stripped in all events with Q_{Fe} ≈ 18 - 20. The same trend is also observed for Si, but only weakly for C (not shown here), because it is close to fully stripped already in gradual events.

Meyer (1985) and Brenneman & Stone (1985) have organized the abundance variations in SEPs in terms of M/Q, because various plausible fractionation processes can be invoked as potentially responsible. Reames et al. (1994) have shown that also the abundances in impulsive events can be organized in terms of

M/Q. Because a change in Q directly affects the M/Q ratio, the variations in the ionic charge state may be reflected in the abundance ratios of different ion species. To test this hypothesis, we have compiled the Ne/O and the Fe/O ratio, two pairs of species with a large difference in their mass/charge ratios, as a function of the Fe charge state in Fig. 2. Because of the substantially lower fluxes, the error bars for both mean charge states and abundance ratios are much larger in the impulsive events. However, meaningful results can still be derived for each individual event, whereas the results obtained with ISEE-3 were averaged over all events.

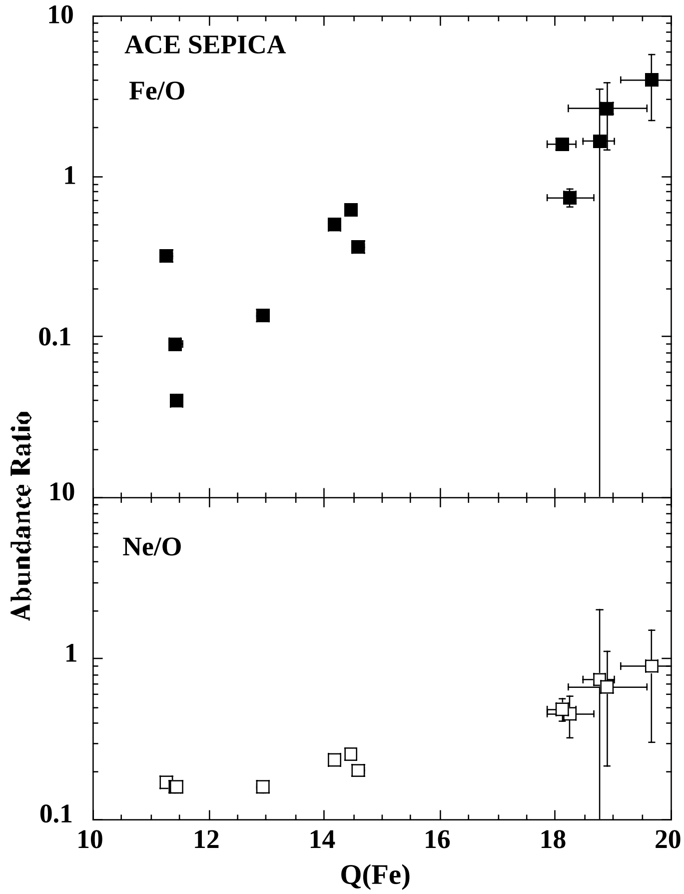

Figure 2: Fe/O and Ne/O ratio as a function of Q_{Fe} for the SEPs under study.

Fe seems to exhibit a much larger abundance variation within the gradual events than Ne. However, both the Ne and Fe abundance increase as a function of the ionic charge state. This seems to continue even among the impulsive events, although the current number of events is too small to allow a firm conclusion. In the same way the apparent gap in charge state coverage between Q = 15 and 18 may either be an indicator of a real bi-modal distribution among SEPs or at this point an artefact of the small sample of events.

3 Discussion:

We have confirmed ionic charge states that vary widely between gradual and impulsive events, from Q ≈ 11 to Q ≈ 20 for Fe. However, we have also found that charge states vary substantially from event to event among these groups, and they may even cover the entire range. In addition, the charge states of the other species vary in lockstep with those of Fe. While events that are clearly identified as gradual are mostly compatible with equilibrium charge states for temperatures of $\approx 1.5 \cdot 10^6$ K, as discussed in detail by Klecker et al. (1999), the ones in the impulsive events require a temperature of $6 - 10 \cdot 10^6$ K. In earlier reports charge states of gradual events have varied between Q ≈ 11 (Mason et al., 1995), Q ≈ 14 (Luhn et al., 1984) and Q ≈ 15 (Leske et al., 1995). While part of these differences may be due to observations at different energies, as significant variations of Q with energy have been reported (Oetliker et al., 1997; Möbius et al, 1999), we have now shown that substantial variations can occur from event to event that include all previously reported values. At this point, it is not clear that these are genuine variations of the mean charge state of a single population. It is also possible that most of the variations can be related to variable contributions of two different sources, a high charge state distribution from an impulsive event and a low charge state distribution from a gradual event, such as shock accelerated coronal material. Temporal variations of charge states during individual events related to the variable contribution of such populations are discussed by Popecki et al. (1999).

We have also found that the overabundance of heavy ions can apparently be organized by the observed ionic charge states. Higher charge states of Fe appear to be synonymous with increased abundance of Ne and Fe. When taken just for the clearly gradual and impulsive events, this may just reflect the known difference in abundance between these two classes of events. However, a continuous trend is observed within the groups and for intermediate charge states. A study of a larger group of events will be needed to confirm whether this trend reflects a substantial correlation. It should be noted that Ne seems to show the trend better than Fe. The Fe abundance itself varies substantially among gradual events, while the Ne/O ratio for these events is relatively constant (e.g. Reames et al., 1994). On the other hand both Ne and Fe show variations of about one order of magnitude within impulsive events. This puts the strongest deviations from the coronal abundances into events, for which we have confirmed that heavy ions through Mg are essentially fully stripped. While Fe could still be affected by M/Q dependent fractionation, when compared with O, Ne clearly cannot. Therefore, this result turns into a severe constraint and a great challenge for models that attempt to explain the observed abundance variations. Reames (1999) has suggested that the ions be stripped after their acceleration out of a low T ($\approx 3 \cdot 10^6$K) environment, which would preserve the M/Q dependence for the fractionation. However, this would require the energetic particles to remain in a hot (10^7K) environment for an extended time or the presence of a very intense electron beam after the acceleration for effective stripping to occur. As an alternative one might speculate that a pure mass dependence could be considered. Most of the observations would show a similar behavior when presented as a function of M. However, no purely mass dependent fractionation process that would be suitable has been demonstrated to date.

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