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Time Profiles of Ionic Charge States for Rapidly Rising Solar Active Periods

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Abstract

Measurements of iron charge states in three selected SEP events are presented. The temporal evolution of brief injections can be observed. The association of high iron charge states with impulsive events, and low charge states with gradual event, shock-accelerated iron appears consistent with these observations. The observed time variations, as obtained with ACE/SEPICA, suggest that events with mean charge states between typical impulsive and gradual values may be a combination of charge states near Q_{Fe}=10-12 and Q_{Fe}=18-20.

1 Introduction:

In the past, charge states have been measured for entire events, regardless of size (Luhn et al., 1987). With the SEPICA instrument on ACE, it is possible for the first time to measure the time profile of ionic charge states during individual SEP events. It is known that SEPs vary substantially in their fluxes, spectra and composition. Therefore, it can be expected that charge state variations also occur during these events.

Generally, SEPs have been divided into two classes. Gradual solar events are generally associated with shocks in the corona or even accompanied by coronal mass ejections (CME). They emit high fluxes of energetic ions with a composition that reflects on average normal solar corona conditions (e.g. Reames, 1992). These events can show drastic variations in spectra and composition as the shock travels through interplanetary space. Impulsive events are generally characterized by short injections of energetic particle fluxes 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 at al., 1986; Reames 1990). Usually, these events can be identified with flare events observed in the western half of the solar disk. Although an individual event may have a simple injection time profile, at times a group of impulsive events may overlap. The charge states of gradual events are compatible with coronal temperatures in the neighborhood of 1-3 10^6 K (Hovestadt et al., 1981). Substantially higher mean charge states for Si (≈14) and Fe (≈20) have been reported for impulsive events (Klecker et al., 1984; Luhn et al., 1987).

Klecker et al. (1999) have selected "pure" gradual events and find charge states that are compatible with an equilibrium temperature of ≈1.5 10^6 K and Fe charge states of Q≈11. Möbius et al. (1999b) have studied the variation of charge states between different events that vary from gradual to impulsive and find charge states for Fe from 11 to 20, including intermediate values of 13-14. In this paper we present three examples of SEPs that exhibit a significant time variation in their Fe charge state. The first event starts with an elevated charge state that drops as the event evolves. The next example has a charge state typical of a gradual event, with the brief arrival of higher charge Fe usually seen in impulsive events. The third event closely follows, and exhibits high Fe charge states typical of an impulsive event and a slow rise of the mean charge state with time. The charge distributions taken during these events seem to suggest the simultaneous presence of a high and low charge state component, as found recently by Möbius et al. (1999a) in the November 7, 1997 event.

2 Observations:

The charge state measurements presented here were made with the SEPICA instrument on the ACE spacecraft, which is in a halo orbit about the Lagrangian point L1 (Stone et al., 1998a). SEPICA views the hemisphere centered on the Sun, with a field of view that extends from 20° to 100° away from the Sun. .

2.1 Instrumentation: SEPICA consists of a ΔE-E_{res} telescope with a proportional counter for the energy loss measurement (ΔE), and a solid state detector for the residual energy (E_{res}) measurement. The element number Z is determined from the specific energy loss (ΔE) of the incoming ion. Combining the residual energy with the energy loss in the proportional counter gas and windows results in the total energy E. The energy per charge (E/Q) of the ions is determined in a collimator/electrostatic deflector assembly by measuring the impact position in the proportional counter. Finally, combining E/Q and E leads to the charge state Q. A complete description of the instrument may be found elsewhere (Möbius et al., 1998).

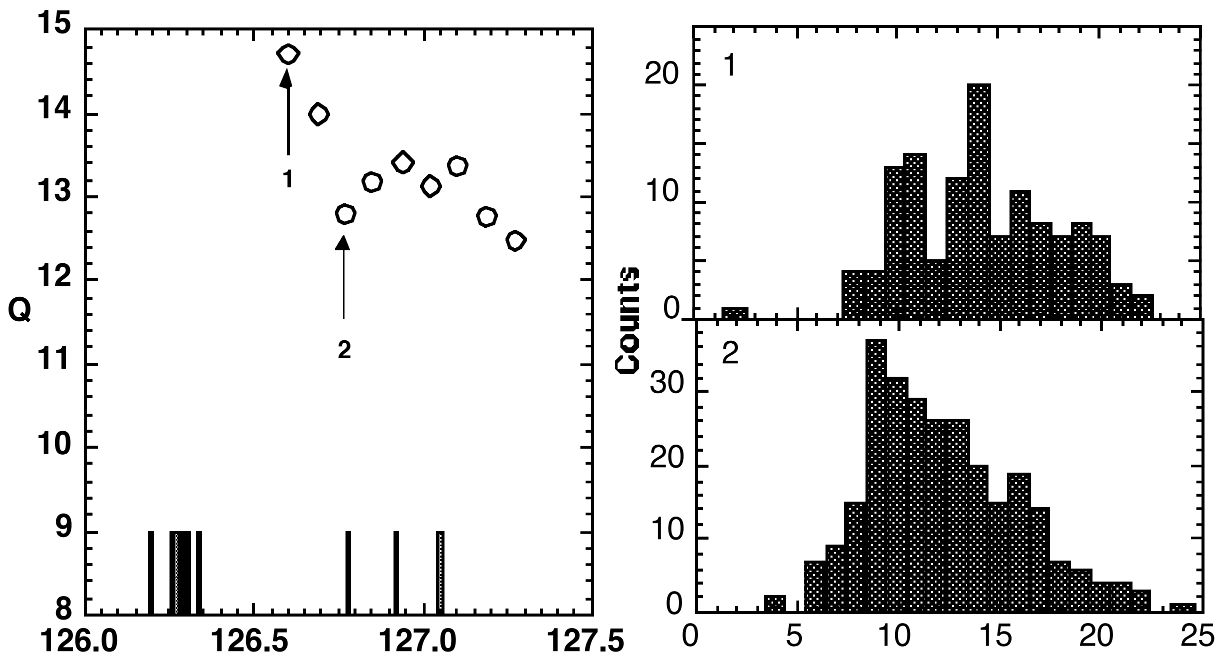

Figure 1: Left panel: 4 hour averages of the mean charge state of Fe as a function of time and indicators for flare activity on the sun for the SEP on May 6, 1998. Right panel: Q histograms for the indicated time periods on the left.

2.2 Observations: Three examples of SEP events will be presented. The first occurred on May 6-7, 1998 (126-127), and is shown in Figure 1. The six vertical bars in the lower left corner indicate Xray flares with optical counterparts that occurred at W63-66. The rest of the bars are for western flares at W32, 72, and 40. This event has both impulsive and gradual characteristics. The mean charge state begins at approximately 14.8 and declines to about 13. Two charge state histograms are shown, one for the first two hour period, and one for the third. The charge states are almost evenly distributed between Q=10 and 20 in the first period, but they become peaked later at approximately 10, with a tail extending to about 20. This later period resembles the charge state distribution observed during the November

7, 1997 activity (Möbius et al. 1999a). This evolution suggests that a CME related low charge state population became more prominent later in the event. There are no shocks or clouds noted at ACE or WIND for this time, but a CME occurred at 0829 UT. The velocity dispersion in the arrival of energetic ions was strong at the beginning, and was approximately consistent with propagation from an X class Xray flare with an optical counterpart at W65 on May 6, 0809 UT. During the event, three more flares occurred between W32 and 72 that may have contributed to the event.

The next example is a gradual event on September 24-25, 1998 (267-268). Flare activity during this time was observed in the center of the disk, and thus not expected to be well-connected to the Earth. Charge state measurements for individual ions are shown in the top panel of Figure 2, along with four hour averages in the bottom panel. The iron charge state remains at Q=10-11 for nearly the entire event, with a brief injection of higher charge states at the end. During this event, a possible shock was reported at WIND at 98/267 2320 UT, near the beginning of the event. In addition, a magnetic cloud was detected passing WIND during the period 268 0600 - 269 1900 UT. These observations are consistent with the general characteristics of gradual, shock-accelerated events. The observed arrival time of the brief injection after the flare at W18 is consistent with the minimum travel time for a 14 MeV Fe ion for a typical interplanetary magnetic field line. The gradual portion of this event is discussed by Klecker et al. (1999).

The last example is also shown in Fig. 2. It occurred during a series of western flares, on Sep 26-28, 1998 (269-271). No shocks were noted at WIND and ACE. This is one of the highest iron charge state SEP events of 1998. There is a brief period of charge 15-16 Fe at the beginning, after which the mean Fe charge rises a typical value of 18. The cutoff in the middle of day 271 is from an instrument shutdown.

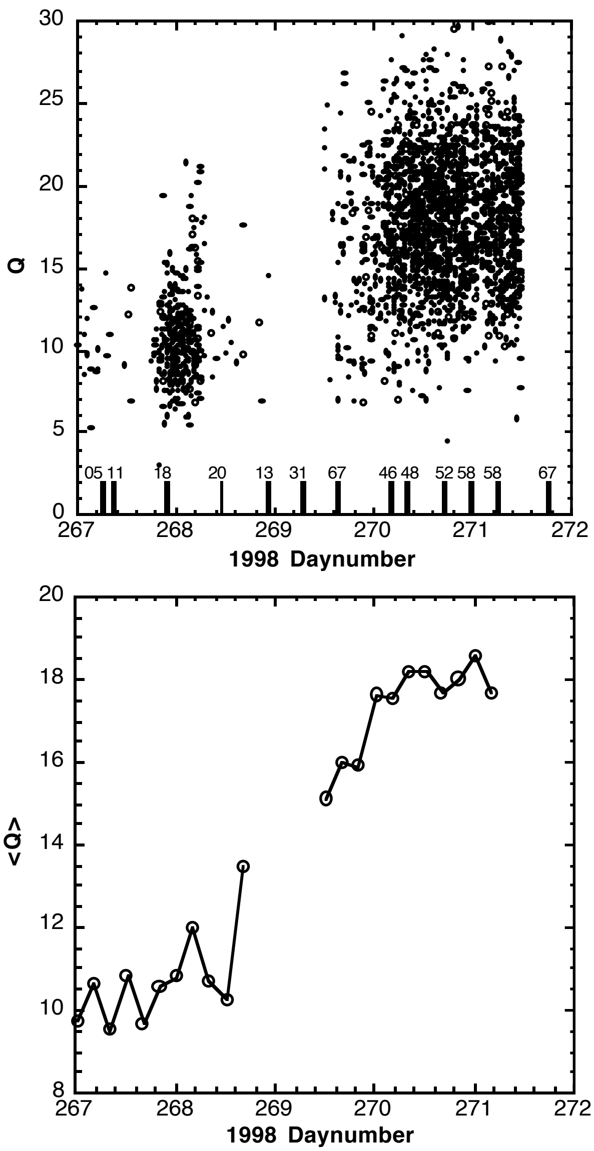

Figure 2: Iron charge state vs. time for the September 24-25 (267-268), 1998 gradual event and the for September 26-28 (269-271), 1998 impulsive event. The top panel shows a scatterplot of individual ions and the bottom shows averages for four hour periods throughout the event. The vertical bars in the top panel indicate Xray flares with optical counterparts at the western longitudes noted by the numbers.

3 Discussion:

In the three examples presented here, there were substantial variations of the mean Fe charge state with time. High Fe charge states are commonly viewed as coming from flare sites, while low charge states are typical of shock accelerated events (Reames, 1999). Separate injections of high and low charge Fe were clearly identifiable in the September events. They were consistent with a distinct and varying contribution from two sources of energetic iron: one with a charge state of Q=17-20, and the other one with a charge state of Q= 10-11.

During the May 6 event, the intensity of the higher charge state component decreased, leaving an asymmetric distribution with a peak near Q=10-11, but a mean of 13. This result is similar to the low charge peak and high charge tail distribution observed in the November 7, 1997 solar energetic particle event (Möbius et al. 1999a). It is plausible that the initial portion of the May 6 event had a mixture of high and low charge Fe, and that later in the event the low charge state population became more prominent. This low charge state population could be related to the emerging CME observed during this period. This mixing of two populations might well produce the intermediate average charge state Fe of $<Q>=13-14$ as reported by by Möbius et al. (1999b) for this and several other events. Temporal charge state measurements such as these provide a valuable complement to compositional measurements, by offering additional information to distinguish between particle populations and their relative contributions in solar active periods.

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