Strong Energy Dependence of Ionic Charge States in Impulsive Solar Events

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Abstract

We have combined the ionic charge state data from ACE SEPICA for all impulsive events in 1997 - 2000 and sorted them according to the mean charge of Fe in individual events for 0.18 - 0.43 MeV/n. Subdivided by energy, a strong increase of Q with energy is observed, with Fe charge states at the low end of the energy range between 14 and 17. Here the charge states tend to reflect the plasma environment of the flare rather than the effects of stripping.

1. Introduction

The first direct charge state measurements for solar energetic particle events (SEP) showed values compatible with coronal temperatures for gradual events [1], while substantially higher average charge states were reported for a collection of impulsive events during one year of the ISEE-3 mission ($\approx$ 20 for Fe [2]; $\approx$ 14 for Si [3]. With the much larger sensitivity of the SEPICA sensor on ACE it has become possible to determine ionic charge states of individual impulsive events and to see their variation. A study of SEP events during the first year of the ACE mission, which included both gradual and impulsive events [4], demonstrated that the mean charge states are quite variable and cover a wide range ($\approx$ 11 - 20 for Fe). It also showed a correlation between Fe charge-state and Ne/O and Fe/O ratios. It is puzzling that (1) the charge states of events with impulsive composition showed substantially lower charge states (Q $\approx$ 15 - 20 for Fe) than the average of $\approx$ 20 reported for impulsive events [2] and (2) a correlation between abundance and charge state is observed, while most of the heavy elements (up to Mg) are essentially fully stripped. It should be noted that ACE SEPICA can determine charge states to much lower energies than its predecessor, ISEE ULEZEQ, and that substantial variations of ionic charge states with energy have been reported for some SEP events [5, 6, 7]. These dramatic changes in charge state of Fe are interpreted as stripping during and after the acceleration via the passage of the ions through a substantial column density in the solar atmosphere [8, 9, 10]. Because the energetic particles from impulsive

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Table 1. Selected Impulsive Events

Year	E[MeV/n] 0.18 - 0.43 Time (DOY hh:mm)	Q(Fe)	ΔQ
1998	252 00:29 - 253 23:45	17.1	0.61
1999	184 21:36 - 186 06:00	16.0	0.65
1999	201 02:19 - 202 22:19	16.2	0.60
2000	272 00:00 - 273 23:46	15.4	0.56
2000	122 04:05 - 122 23:54	17.4	0.57
2000	156 04:19 - 156 22:48	17.6	0.56
2000	67 21:36 - 68 00:00	17.6	0.73

events are thought to stem from the flare region they should also show strong energy dependency with Q at low energies that reflects the plasma environment. Therefore, we will test this idea by using the SEP events observed with ACE SEPICA during 1997 through 2000.

2. Instrumentation and Data Analysis

Within the complement of high-resolution spectrometers on ACE [11] to measure the composition of solar and interstellar matter, SEPICA provides the ionic charge state distribution of energetic particles. A complete description of the SEPICA instrument and its data system may be found elsewhere [12]. We have accumulated the charge states for all individual energetic particle events during the time period of full operation of SEPICA with the deflection high voltage above 20 kV from 1997 through 2000. Events were identified from the time profiles of 1 MeV protons with ACE EPAM and 1 MeV/n O and Fe with ACE SEPICA and ULEIS. The mean charge state of Fe was computed for the energy range 0.18-0.43 MeV/n. The lower limit reflects the energy below which the energy loss of Fe approaches that of Si and Mg at the same energy per nucleon and a clear separation without further assumptions becomes impossible. The upper limit is chosen so that no corrections to the mean charge states (as low as Q = 10) have to be made for angular scattering beyond the edge of the solid-state detector at small deflections. We have excluded all shock or CME related events and selected those with $Q_{mean} \geq 14$ for Fe.

We have computed the mean charge states of Fe for the energy ranges 0.18-0.25, 0.25-0.35, and 0.35-0.55 MeV/n, safely extending the upper limit to 0.55 MeV/n, because only SEP events with Q $\geq$14 with larger deflection are included. The uncertainty is computed as the statistical standard error of the mean charge state with a 3% systematic uncertainty added quadratically which increases strongly for the relatively small impulsive events. Therefore, we have

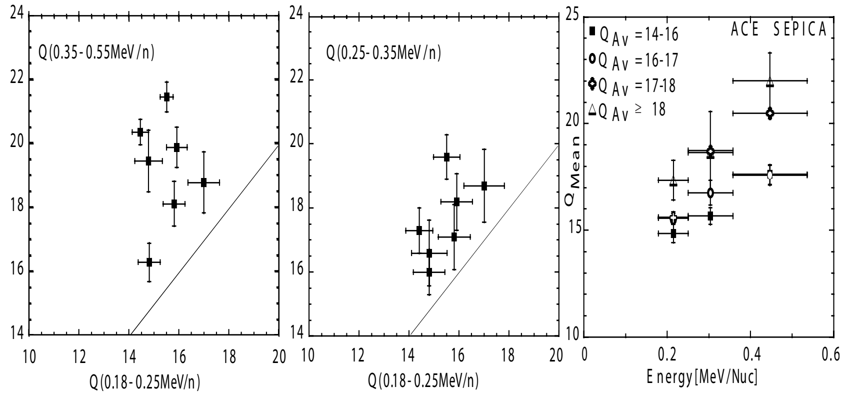

Fig. 1. Left and middle panels: Mean charge states of Fe for three different energy ranges in seven impulsive SEP events with the lowest statistical uncertainties. The highest (left panel) and the center (middle panel) energy range are shown vs. the lowest energy range. The diagonal lines indicate equal charge states at different energies. Right panel: Average charge states of Fe as a function of energy for all SEP events with a mean charge state greater than 14, subdivided into four consecutive charge state ranges.

started with a few events with good counting statistics. Figure 1 (middle and left panels) shows the mean charge states in the center and in the high energy range versus the mean charge state in the lowest energy range for seven SEP events that meet the criteria outlined above and show an uncertainty ΔQ in all three energy ranges of better than or approximately $\pm$ 1 (Table 1). For all seven events the charge states in both upper energy ranges are higher than those in the bottom range. They are above the diagonal line that indicates equal charge states, with a separation that exceeds 2ΔQ for most of the events. This result appears to indicate a substantial increase of the Fe charge state with energy, similar to the one reported for the first strong SEP event observed with ACE [7]. In the following we have subdivided all SEP events in our survey that meet the criteria outlined above into groups, with Q_{mean} for Fe at 0.18-0.43 MeV/n falling into 14-16, 16-17, 17-18, and $\geq$ 18. The ions of all events were combined within these groups, and the mean charge states and their uncertainties were computed for the same energy ranges as used in Fig. 1 (left and middle panels). The resulting charge states are compiled as a function of energy in Fig. 1 (right panel). The average charge states of all four groups of SEP events increase strongly with energy from the lowest to the highest energy.

3. Discussion and Conclusions

We have observed a substantial increase of the mean charge state of Fe in impulsive SEPs in the energy range 0.18-0.55 MeV/n. While the average charge states are between 14.5 and 17 at low energies, they are as high as about 17.5 to 22 at the highest energies. Only the highest energy band of SEPICA overlaps with the energy range of ULEZEQ, which starts at 0.43 MeV/n for Fe, and the two lower bands of SEPICA fall clearly below that range. The range of Q_{mean} for Fe of 17.5 to 22 found at 0.35-0.55 MeV/n is now consistent with the earlier average value of $Q_{mean} \approx 20$ for impulsive events [2]. Consequently, the apparent discrepancy between the ACE SEPICA observations and the earlier results is resolved as a combination of our extension to lower energies and the strong variation of the charge states with energy in impulsive events. The substantial increase of the Fe charge state at energies below 0.5 MeV/n is consistent with predictions by models that combine acceleration in high-density plasma environments with stripping during and after acceleration [8, 9, 10]. At these energies there is a transition from the charge states being dominated by the temperature of the plasma in the flare region to being dominated by stripping at higher energies. Selective heating and acceleration are usually controlled by the conditions of the plasma environment. Therefore a physical connection between the charge state and the overabundance of ions may be found at the lowest energies of the energetic particles.

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4. References

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