Energy Dependence of the Ionic Charge State Distribution During the November 1997 Solar Energetic Particle Event

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Abstract. Ionic charge state distributions for a variety of species, such as C, O, Ne, Mg, Si and Fe were obtained with the Solar Energetic Particle Ionic Charge Analyzer (SEPICA) on ACE for the strongest of a series of energetic particle events after the November 4 and 7, 1997, flares. The capabilities of SEPICA allow a much more detailed analysis of the charge distributions than previous instrumentation. Over the energy range from ≈ 0.2 to 1 MeV/Nuc a trend is observed that shows charge states increasing with energy, in particular for Mg, Si and Fe. In addition, for Fe a mixed charge state distribution with a distinct peak at lower charge states (10 - 14) is observed simultaneously with a tail reaching to charge states up to ≈ 20. This may be an indication of a mixture of different energetic particle populations.

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Introduction

The ionic charge state Q is an important parameter for deciphering the local conditions at the origin of energetic particle populations as well as the processes involved in their selection, acceleration and transport. First direct measurements of the charge state of solar energetic particles (SEP) in the energy range of 0.3 - 3 MeV/nucleon were carried out using the Ultra Low Energy Z E Q (ULEZEQ) sensor on the International Sun-Earth Explorers (ISEE-1 and -3) (e.g. Hovestadt et al., 1981). More recently charge state analysis has been extended to higher energies by utilizing the Earth's magnetic field as a spectrometer with several sensors on the polar orbiting Solar Anomalous and Magnetospheric Explorer (SAMPEX) mission (Oetliker et al., 1997 and references therein) and by comparing interplanetary fluxes on IMP-8 with magnetospheric fluxes measured with the Long Duration Exposure Facility (Tylka et al., 1995). These approaches have allowed the determination of average charge states in solar cosmic rays over a large energy range. However, questions concerning the detailed charge state and/or individual physical processes involved have been left open because of either the lack of individual charge state resolution or poor counting statistics.

Over the last decade it has been recognized that SEP events can be traced back to basically two classes. Impulsive events are characterized by short time scale (several minutes) electromagnetic (radio and X-ray) emission, generally low fluxes of energetic particles in interplanetary space, a high electron to ion ratio, and substantial enhancements in the abundances of heavy ions and ^{3}He (e.g. Reames, 1990). Gradual solar events are accompanied by long duration radio emissions that are generally associated with shocks in the corona and emit high fluxes of energetic particles with a low electron to ion ratio and abundances that reflect on average normal solar corona conditions (e.g. Reames, 1992). It is common to deduce a coronal temperaturewithin the source region from the measured mean charge states assuming ionization equilibrium (e.g. Arnaud and Rothenflug, 1985), because the charge states are quickly frozen in during the acceleration process and the column density of matter between the sun and the observing spacecraft is very low. In contrast to impulsive flares, for which significantly higher mean charge states of Si and Fe have been reported (Klecker et al., 1984; Luhn et al., 1987), gradual events exhibit charge states that reflect substantially lower temperatures in the neighborhood of $2 - 4 \cdot 10^6$ K (Hovestadt et al., 1981). In addition, the mean ionic charge states as observed for different species seem to indicate different temperatures. Attempts to explain these variations in terms of non-thermal equilibrium conditions in the flare site or through interaction of the accelerated particles with the coronal plasma have been unsuccessful (Luhn and Hovestadt, 1987). In the most promising interpretation Mullan (1986) suggested that heating and ionization in flares through local X-ray generation plays a role. In order to study the significance of such processes on the ionic charge states it is necessary to improve the charge state resolution sufficiently to derive charge distributions rather than mean charge states, since this will allow a much more precise deconvolution of the energy distribution of the electrons and/or X-rays that have produced the observed charge states.

In this paper we will report about ionic charge state distributions obtained with the Solar Energetic Particle Ionic Charge Analyzer (SEPICA) on Advanced Composition Explorer (ACE) during the strong SEP event over the period November 7 - 9, 1997. The results extend previous measurements to lower energies, provide higher charge state resolution and demonstrate a substantial variation of the charge states with energy for heavy ions.

Instrumentation 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., 1998a). Within a complement of high-resolution spectrometers to measure the composition of solar and local interstellar matter, as well as galactic cosmic ray particles SEPICA is the prime instrument for the determination of the charge state distribution of energetic particles. To simultaneously determine the energy E, nuclear charge Z and ionic charge Q of incoming particles SEPICA combines several different measurement methods.

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 represents the energy loss (ΔE) element of a $\Delta E - E_{res}$ telescope where the residual energy (E_{res}) is determined in a solid state detector and Z is determined from the specific energy loss. Combining all energy losses with E_{res} provides the original energy E, and finally Q together with E/Q. The instrument is based on the general design of the ULEZEQ sensor flown on the ISEE spacecraft (Hovestadt et al., 1978). To simultaneously achieve the two competing goals, higher charge state resolution and a larger geometric factor than its predecessor, SEPICA consists of three independent sensor units, one with high resolution ($\Delta Q/Q \approx 0.1$ for E < 1 MeV/Q) and the remaining two with their resolution reduced by a factor of three, but with larger geometric factor. A complete description of SEPICA and its data system may be found elsewhere (Möbius et al., 1998)

After an extended period of low solar activity during solar minimum two consecutive major flares occurred on Nov 4 and 6, 1997, which were magnetically well connected with the Earth. Associated with the solar flares strong energetic particle fluxes were observed over the period from Nov 4 through Nov 11, consisting of two consecutive flux increases on Nov 4. The detailed evolution of the particle events is described in the paper by Mason et al. (1998). For the analysis in this paper we have selected the time period that starts after the passage of the CME related shock on Nov 7 at 0400 UT and ends on Nov 9 at 2400 UT. This comprises a sample of the strongest event, excluding the immediate neighborhood of the shock. We will report on charge distributions obtained with the high resolution sensor unit. During this time SEPICA was operated with its deflection voltage at 24 kV, i.e. 80% of its final value, corresponding to $\approx 80\%$ of the nominal charge state resolution.

Figure 1 shows scatter plots of the measured ionic charge states for Fe, Si, Ne and O (from top to bottom). The shaded bar at the top of each panel indicates the energy range chosen for further quantitative analysis. The upper limit reflects an energy of 3 MeV/Q for the lowest charge state that contributes significantly to the distribution. This corresponds to a total deflection of ≈ 2.5 mm (diagonal line in each panel) for the actual deflection voltage of 24 kV. At this point a small but noticeable fraction of the ions may be cut off at the edge of the solid state detector. We have chosen our energy range such that the measured charge distribution does not reach this edge up to the upper limit of the highest energy interval. The width of the charge state distributions reflect both the contribution of different charge states and the intrinsic resolution of the sensor, ranging from $\Delta Q \approx 1$ to $\Delta Q \approx 3$ (FWHM) from the lowest to the highest energy. The distributions of O and Ne (lower two panels) are concentrated around one or two charge states and show very little variation with energy up to the limit of the selected energy range. However, Si and Fe have a much wider distribution, and their mean charge states increase visibly with energy. It should be noted here that the absolute calibration of the charge states is still preliminary, but variation of the calibration parameters to their possible limits allows a range of at most ± 5% of the values reported in this paper.

The corresponding charge distributions of Fe for four different energy ranges in Fig. 2 appear to contain a wide range of charge states. Because the electrostatic deflection decreases with energy, while the width of the collimated particle image remains constant, the charge resolution degrades at higher energies. The width (FWHM) of the main peak increases from ≈3 to ≈6 charge states over the energy range. The width of the measured distribution is partly due to the instrumental resolution and partly due to a mix of charge states. At the lowest energy the measured distribution should most closely resemble the real one. Here two different components can be clearly identified, a narrow peak at $Q \approx 10$ - 12 and a tail that extends to $Q \approx 20$. At higher energies the presence of the tail is still visible as an asymmetry in the distribution. In addition, it is obvious that both the center of the peak and the mean charge, as obtained over the entire distribution, increase substantially with energy (more than 30% over the energy range). A Chi^2-test for adjacent charge distributions returns probabilities of $1.6 \cdot 10^{-3}$ for the lowest two energies, $2.6 \cdot 10^{-3}$ for the next two, and 0.29 for the highest two to be identical and thus clearly supports an increase of charge state with energy.

The values of both peak and mean charge state for Fe are compiled in Fig. 3 together with the mean charges for C, O, Ne, Mg, and Si. The energy intervals for O, Ne, Si and Fe correspond to the ones indicated in Fig. 1. The error is the standard deviation of the mean charge state and the peak position, respectively. The mean charge states of C, O and Ne remain relatively constant within one charge state, while they increase noticeably for Mg, Si and Fe (≈ factor of three).

Discussion and Conclusions

Ionic charge state distributions have been measured directly with high resolution for a major SEP event. Whereas only one or two charge states dominate for C, O and Ne with small contributions from neighboring charge states, a much broader distribution is found for Mg, Si and Fe. In fact, during the event under study, associated with the solar flare on Nov 6, 1997, a distinct peak at low charge states and a tail that extends up to $Q \approx 20$ is identified for Fe. This seems to indicate the presence of two different charge state components. Also, when displayed as a function of energy the charge states of all heavy ions indicate a clear trend to increase with energy, i.e. they are significantly energy dependent.

Let us first concentrate on the peculiar finding of potentially two different Fe charge state distributions. One of the key results obtained with ISEE ULEZEQ was that impulsive events with a substantial enrichment in Fe and ^{3}He showed a significantly higher mean charge state for Fe (Klecker et al., 1984) and Si (Luhn et al., 1987) than during large gradual events (Luhn et al., 1984). The intensity-time profiles of oxygen (Mason et al., 1998) show that in the time period and energy range of our investigation, we have a mixture of several particle populations: (1) particles from a shock of the Nov 6 event, accelerated locally in interplanetary space, (2) particles from the Nov 6 event accelerated close to the Sun, and, (3) much less abundant, particles from the decay phase and associated shock of the Nov 4 event. Both, populations (2) and (3) show significant enrichment in heavy ions in the energy range 0.15 - 60 MeV/Nuc (Mason et al., 1998, Cohen et al., 1998). This could be taken as an indication for contributions from an impulsive event. Thus, the apparent presence of Fe charge states up to 20 in addition to the main distribution showing charge states of 11 to 14 over the energy range of our study suggests that we observe two different particle populations. The dominant particle population with low charge states could be attributed to population (1), i.e. locally accelerated particles of presumably solar wind origin with ionization states typical for solar wind values (≈10 - 12, e.g. Ipavich et al., 1992). The less abundant high charge states could then be attributed to contributions from an impulsive event to population (2). In fact, the coexistence of low (11 - 12) and high (16 - 18) Fe charge states has also been reported for a ^{3}He- and Fe-rich event in 1974 by MaSung et al. (1981). A more detailed future study of the temporal evolution of the two events may help to unravel the different particle populations.

The second interesting finding is the energy dependence of the ionic charge states below 1 MeV/Nuc for the heavy ions. The variation with energy is relatively strong for Fe, Si and Mg, but insignificant (less than one charge state) for C, O and Ne. For comparison the mean charge states averaged over three gradual SEP events, as obtained by Luhn et al. (1984) have been added to Fig. 3. Compared with these results our charge states generally are somewhat lower, but they have been obtained at lower energies. Our results tend to approach the previous average values at the upper end of our energy range except perhaps for Ne. When combined these results seem to express the energy trend even more clearly, if we assume that the event under study is a typical large SEP event. In their detailed studies Luhn et al. did not find a variation of the charge states with energy. There could be two reasons for this negative finding. Either the resolution and statistics were insuffcient, or there was no noticeable trend in the energy range covered. A recent study using the combined set of SAMPEX instruments and the cut-off by the Earth's magnetic field over the energy range of 0.3 - 70 MeV/Nuc (Oetliker et al., 1997) has also presented evidence for an energy dependence of the Fe mean charge. Our new findings extend this result with a direct determination of the charge states to lower energies and to Mg and Si. This variation of the charge states is found at much lower energies than reported earlier. Mazur et al. (1998) also report the same trend of charge states for the time period studied in this paper, using the magnetic cut-off method with the SAMPEX LICA sensor. Thus the finding is confirmed with two independent methods. It should be noted though that at this point there is a noticeable difference in the absolute charge states as obtained with the two methods. Our charge states appear somewhat higher, by ≈10 - 15%, than the values reported by Mazur et al. (1998). Before a final conclusion the cross calibration needs to be tested with other cases. More importantly there are some inherent differences in the two methods. For example, the magnetic cut-off method is sensitive mainly to the peak of the distribution as opposed to a wide tail (apparent for Fe in this event). On the other hand the direct measurement may be biased slightly (0.2 Q to 0.4 Q) towards higher charge states for very broad charge distributions, when limits in energy/nucleon are used. Notwithstanding these potential differences, there is a strong case for an energy dependent charge distribution in this event. This trend may be extended to even higher energies. In their attempt to explain the observed abundance ratios by mass/charge dependent acceleration Cohen et al. (1998) deduce a charge state for Fe of ≈18.5 above 10 MeV/Nuc. This could be seen as an extension of the observed trend at low energies.

This leaves us with the puzzle of how this remarkable energy variation may be explained. So far several possibilities have been discussed (Oetliker et al., 1997), but no quantitative explanation has been given yet. Possible mechanisms may include energy dependent stripping processes during the acceleration, which would require acceleration in relatively dense regions of the corona, rigidity dependent acceleration processes, such as the one studied for ^{3}He-rich events by Möbius et al. (1982), or the combination of different seed populations. It is interesting to note that it is the heavy ions Fe, Si and Mg which show the energy variation most prominently. Fe and Si have been found to vary strongly in charge state between impulsive and gradual solar events. Therefore, an explanation of the energy variation may be linked to the contribution from different particle populations during the event under study. The information obtained with SEPICA during this and future solar events will help to unravel these questions.

Acknowledgments. The authors are grateful to the many individuals at the University of New Hampshire and the Max-Planck-Institut für extraterrestrische Physik for their enthusiastic contributions to the successful completion of the ACE SEPICA instrument. They thank F. Gliem, K.-U. Reiche, K. Stöckner and W. Wiewesieck for the implementation of the S3DPU. The assistance by C. Carlson at the Brookhaven National

Lab and P. McMahan at the Lawrence Berkeley Lab during the sensor calibrations is gratefully acknowledged. W. Schmidt acknowledges the hospitality during his visit at the University of New Hampshire. The work on SEPICA was supported under NASA Contract NAS5-32626.

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(Received August 24, 1998; accepted September 18, 1998)

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Figure Captions (1-column)

Fig. 1: Scatterplot of ionic charge state Q versus total energy E for the time period Nov 7, 400 UT, to Nov 9, 2400 UT. The shaded bar represents the energy range and the vertical lines the intervals for further analysis. The diagonal lines indicate an electrostatic deflection of 2.5 mm, below which a small fraction of the ions falls beyond the edge of the sensitive area of the solid state detectors. Histograms of the distribution in the lowest energy range (lowest two for Ne and Si) are shown as inserts.

Fig. 2: Charge state distribution of Fe separated into four energy bins in the energy range 0.18 - 0.54 MeV/Nuc for the time period Nov 7, 400 UT, to Nov 9, 2400 UT.

Fig. 3: Mean charge states, for Fe also peak values, as a function of energy and average charge states as obtained for three events with ISEE ULEZEQ (Luhn et al., 1984, large symbols).

Figure Captions (2-column)

Fig. 1: Scatterplot of ionic charge state Q versus total energy E for the time period Nov 7, 400 UT, to Nov 9, 2400 UT. The shaded bar represents the energy range and the vertical lines the intervals for further analysis. The diagonal lines indicate an electrostatic deflection of 2.5 mm, below which a small fraction of the ions falls beyond the edge of the sensitive area of the solid state detectors. Histograms of the distribution in the lowest energy range (lowest two for Ne and Si) are shown as inserts.

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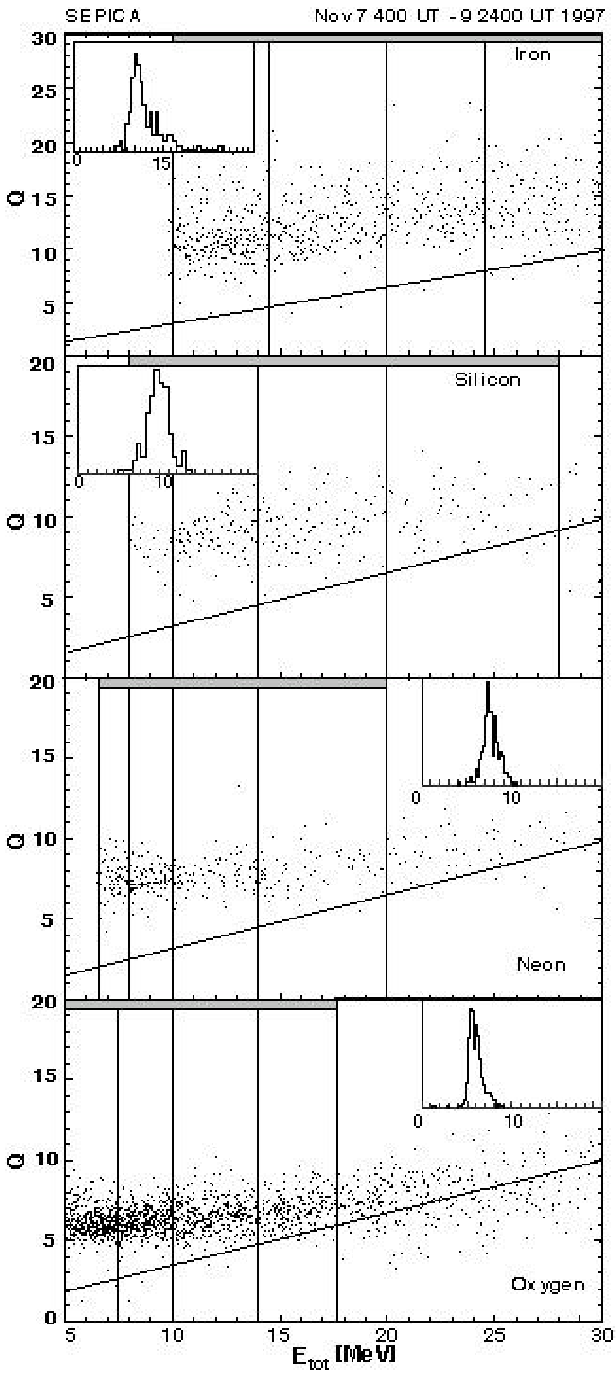
SEPICA
Nov 7 400 UT - 9 2400 UT 1997
Iron
Silicon
Neon
Oxygen
Q
E_{tot} [MeV]

Fig. 1:

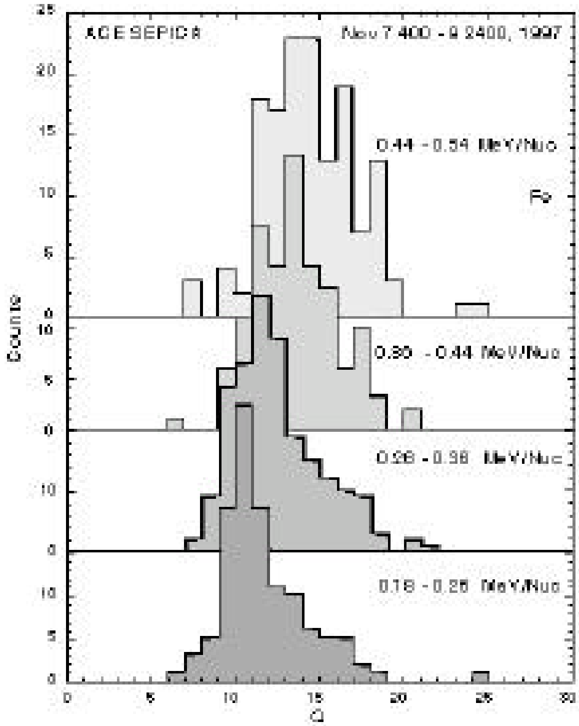
ACE SEPICA
Nov 7.400 - 9.2400, 1997
0.44 - 0.54 MeV/Nuc
Fe
0.36 - 0.44 MeV/Nuc
0.26 - 0.36 MeV/Nuc
0.18 - 0.26 MeV/Nuc
Counts
Q

Fig. 2

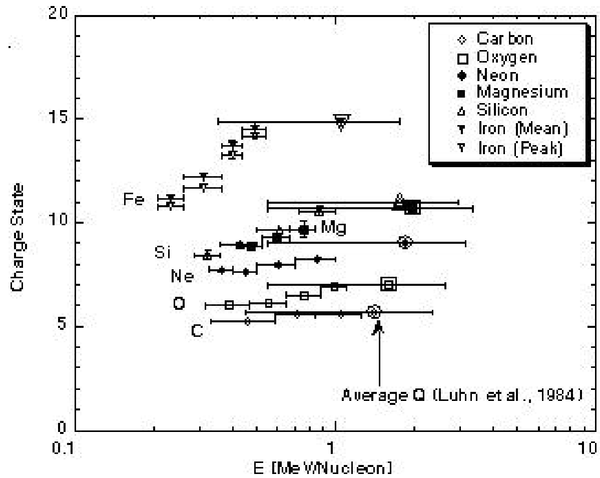
Carbon
Oxygen
Neon
Magnesium
Silicon
Iron (Mean)
Iron (Peak)
Charge State
Fe
Si
Ne
O
C
Mg
Average Q (Luhn et al., 1984)
E [MeV/Nucleon]
0.1
1
10
0
5
10
15
20

Fig. 3