

# The Ionic Charge Composition of CME Related Solar Energetic Particle Events as Observed With SEPICA Onboard ACE

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## Abstract

We determined the mean ionic charge of C, O, Ne, Mg, Si, and Fe for a number of large, gradual, solar energetic particle events in 1998, using the SEPICA particle spectrometer onboard the ACE spacecraft. SEPICA provides high resolution ionic charge measurements with unprecedented sensitivity. This capability has been used to examine the heavy ion composition and mean Fe ionic charge state as a function of time during individual large SEP events for the selection of those events for further analysis that clearly show small Fe/O ratios ( $\text{Fe/O} \leq 0.3$ ) and low mean Fe ionic charge states ( $Q_{\text{Fe}} \sim 11$ ) throughout the event, characteristic of average normal coronal and low speed solar wind conditions. Using this selection criterion we exclude possible admixtures from impulsive events. In contrast to previous observations at somewhat higher energies, we find for this sample of ‘pure’ gradual events, that the mean ionic charge states of C, O, Ne, Si, and Fe in the energy range of  $\sim 0.2\text{-}0.7$  MeV/nuc are similar to solar wind ionic charge states and consistent with equilibrium charge states for temperatures of  $\sim 1.3\text{-}1.6 \cdot 10^6$  K.

## 1 Introduction:

Until recently, ionic charge measurements in solar energetic particle (SEP) events were limited to a small energy range at  $\sim 1$  MeV/nuc. Furthermore, they were limited by counting statistics to event averages (for Gradual Events) or even to averages over many events (for Impulsive Events). Gradual events are generally associated by Coronal Mass Ejections (CMEs) and interplanetary shocks and the elemental composition reflects on average normal solar corona conditions (e.g. Reames, 1992). Impulsive events are characterized by short time scale radio and X-ray emission, by low fluxes of particles in interplanetary space with large enhancements of heavy ions and  $^3\text{He}$ , relative to coronal abundances (e.g. Mason et al., 1986; Reames 1990). These two types of SEP events showed striking differences of the mean ionic charge states of heavy ions: the mean ionic charge of Fe and Si (Klecker et al., 1984, Luhn et al., 1987) in  $^3\text{He}$ - and heavy ion-rich events were significantly larger ( $\sim 14$  and  $\sim 20$  for Si and Fe, respectively) than in gradual events. In gradual events, the mean ionic charge could be determined for individual SEP events and was found to be on average  $\sim 11$  and  $\sim 14.9$  for Si and Fe, respectively (Hovestadt et al., 1981, Luhn et al., 1985). In Gradual Events, the mean ionic charge for C, O, Si, S, and Fe was compatible with equilibrium temperatures of  $\sim 2 \cdot 10^6$  K. The mean ionic charge of Ne and Mg, however, was found to be significantly higher, not consistent with the same equilibrium temperature (Luhn et al., 1985).

Recent studies with SAMPEX have extended the energy range of the measurements to higher energies by using the geomagnetic cutoff for the determination of the ionic charge. They showed a significant energy dependence of the mean ionic charge of Fe, increasing from  $\sim 11$  at 0.3 MeV/nuc to  $\sim 15$  at 40 MeV/nuc (Mason et al., 1995; Leske et al., 1995; Oetliker et al., 1997). New results from

SAMPEX (Mazur et al., 1999) and first results from SEPICA (Möbius et al., 1999a) confirmed the energy dependence of the mean ionic charge state of Fe for another SEP event on November 6, 1997 and extended the measurement to Ne, Mg, and Si, where also an energy dependence of the mean ionic charge was found. So far it is not clear, however, whether this energy dependence is a general feature in gradual events, or whether it is a result of averaging over different particle populations that possibly exist in the case of the Nov. 6, 1997 event (Mason et al., 1999), or whether it is a result of the injection and acceleration processes. In this paper we make use of the high sensitivity of SEPICA to select ‘pure’ gradual events by their signatures of heavy ion abundances and Fe mean ionic charge with the expectation to derive a clearer picture of the mean ionic charge for the elements C, O, Ne, Mg, Si, and Fe.

## 2 Observations

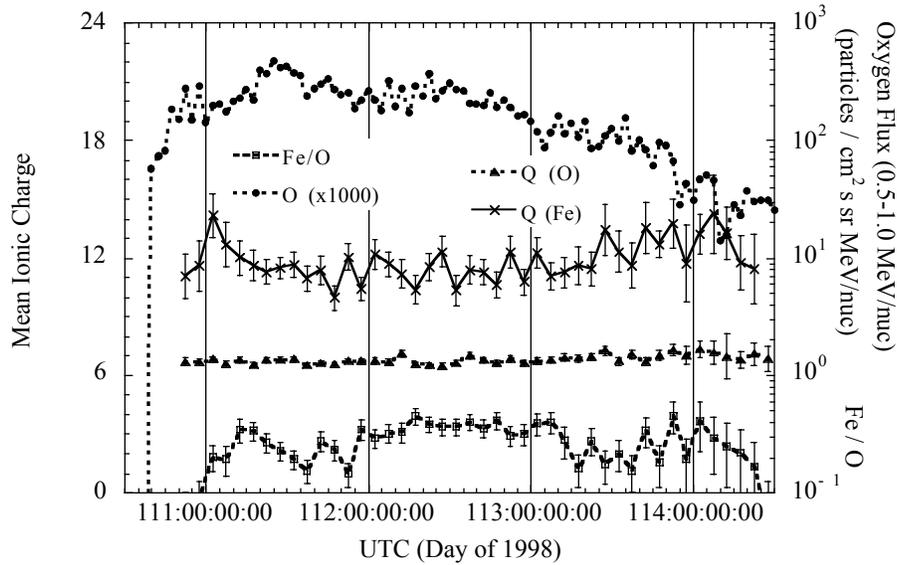
The ACE spacecraft was injected into a halo orbit around the Langrangian point L1 on December 17, 1997 (Stone et al., 1998). ACE is designed to study particle composition from solar wind energies to galactic cosmic rays. Within the ACE instrumentation SEPICA is the prime instrument to study the ionic charge distribution of energetic particles in the energy range  $< 3$  MeV/nuc.

**2.1 Instrumentation:** SEPICA combines electrostatic deflection in a collimator-analyzer assembly for the determination of energy/charge (E/Q) with the measurements of residual energy ( $E_{res}$ ) and energy loss ( $\Delta E$ ) in a solid state detector and multi-wire proportional counter, respectively, for the determination of the nuclear charge (Z) of the particles. From the residual energy and the nuclear charge Z the incident energy can be derived, which, in combination with the E/Q measurement, provides the ionic charge Q of the ions. The instrument is based on the general design of the ULEZEQ sensor on-board the ISEE spacecraft (Hovestadt et al., 1978), with much improved charge resolution and sensitivity. In order to combine high charge resolution with high sensitivity, the sensor consists of 3 units, one unit with small geometric factor ( $A\Omega = 0.03$  cm<sup>2</sup> sr) but high resolution ( $\Delta Q/Q \sim 0.1$  for  $E < 1$  MeV/Q), and two units with large geometric factor ( $A\Omega = 0.2$  cm<sup>2</sup> sr) and moderate ionic charge resolution ( $\Delta Q/Q \sim 0.3$  for  $E < 1$  MeV/Q). A complete description of the SEPICA instrument may be found elsewhere (Möbius et al., 1998). For the present study the two high sensitivity units have been used.

**2.2 Observations:** We have selected several SEPs in 1998 that show characteristics of large, gradual events by examining heavy ion elemental abundances and the mean ionic charge of iron. Figure 1 shows as an example the oxygen flux, the Fe/O ratio, and the mean ionic charge of O and Fe during a large, gradual event in April 1998. It is apparent from Fig. 1 that the Fe/O ratio is low ( $\sim 0.1-0.3$  at 0.5-1.0 MeV/nuc) and that the mean ionic charge is  $\sim 11-12$  throughout the event, typical for gradual

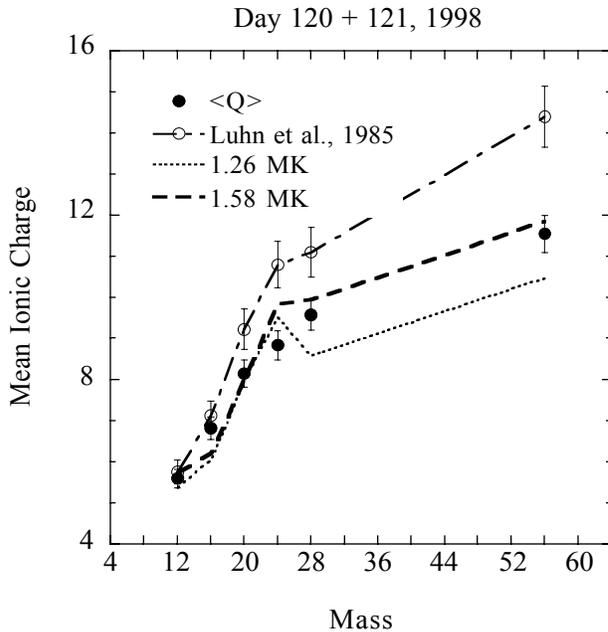
**Table 1** Selected time periods with gradual solar energetic particle events

Time Day of 1998	<sup>16</sup> O Flux .5-1.	Fe/O .5-1	Mean Ionic Charge												Event Type
			C	1 $\sigma$	O	1 $\sigma$	Ne	1 $\sigma$	Mg	1 $\sigma$	Si	1 $\sigma$	Fe	1 $\sigma$	
111 00-24	0.28	0.24	5.58	0.3	6.89	0.3	8.20	0.4	8.88	0.4	9.50	0.5	11.25	0.5	G
112 00-24	0.24	0.35	5.74	0.3	6.94	0.3	8.19	0.4	9.10	0.5	9.60	0.5	11.70	0.5	G
113 00-24	0.10	0.28	5.72	0.3	6.92	0.3	8.41	0.4	8.94	0.5	9.90	0.5	12.10	0.5	G
120 00-24	0.19	0.09	5.67	0.3	6.82	0.3	8.15	0.4	8.78	0.4	9.64	0.5	11.44	0.5	G
121 00-24	0.76	0.04	5.53	0.3	6.81	0.3	8.14	0.4	8.89	0.4	9.52	0.5	11.63	0.5	G+S
267 18-24	1.27	0.08	5.54	0.3	6.70	0.3	7.91	0.4	8.80	0.4	9.10	0.5	10.80	0.5	S
310 07-24	1.82	0.06	5.60	0.3	6.58	0.3	8.00	0.4	8.85	0.4	9.36	0.5	11.40	0.5	G+S
311 00-24	1.87	0.05	5.64	0.3	6.77	0.3	8.33	0.4	8.96	0.4	9.59	0.5	11.73	0.5	G+S



**Figure 1:** Oxygen flux (filled circles), Fe/O ratio (open squares), and mean ionic charge of O (triangles) and Fe (crosses) during the time period of April 21 (day 111) - 24, 1998.

events (see also Möbius et al., 1999b). Thus, using the Fe/O composition and Fe mean ionic charge we can exclude any contributions from Impulsive Events in order to determine the mean ionic charge states of C, O, Ne, Mg, Si, and Fe for a ‘pure sample’ of gradual events.



**Figure 2:** Mean ionic charge of C, O, Ne, Mg, Si, and Fe for days 120 and 121, 1998 (from Table 1) and mean charge for equilibrium temperatures of 1.26 and 1.58  $10^6$  K ( from Arnaud & Raymond, 1985, and Arnaud & Rothenflug, 1992)

for a number of days that passed this selection criterion. Table 1 shows the average flux of oxygen in units of particles/cm<sup>2</sup> s sr MeV/nuc and the Fe/O ratio at 0.5-1.0 MeV/nuc, the mean ionic charge and 1  $\sigma$  uncertainty for C (0.5-0.8 MeV/nuc), O (.25-.5 MeV/nuc), Ne (0.25 - 0.5 MeV/nuc), Mg (0.3 - 0.6 MeV/nuc), Si (0.36 - 0.72 MeV/nuc), and Fe (0.2 - 0.4 MeV/nuc). The 1  $\sigma$  uncertainty includes a possible 5% systematic error of the ionic charge determination. The last column of Table 1 indicates whether during the time period of the gradual event (‘G’) an interplanetary shock with significant increase of low energy particle intensities has been observed (‘S’).

### 3 Discussion:

Table 1 shows that for the ‘pure’ gradual events investigated so far, the mean charge states of C, O, Ne, Mg, Si and Fe do not vary much from event to

event and during events, and do not show the high charge states, as observed in particular for Ne, Mg, Si, and Fe in impulsive events (see Möbius et al., 1999b, this volume). In Figure 2 we compare the present results for the mean ionic charge with previous measurements (Event '1' of Luhn et al., 1985) and with the mean ionic charge expected for equilibrium charge states for temperatures of  $1.26 \cdot 10^6$  and  $1.58 \cdot 10^6$  K (Arnaud and Rothenflug 1985; Arnaud and Raymond, 1992). Figure 2 shows that the mean ionic charge states as determined with SEPICA for 'pure' gradual events are lower than previous measurements reported from ISEE, in particular for Ne, Mg, Si, and Fe. With the exception of Mg, our new measurements at low energies are consistent with equilibrium temperatures of  $\sim 1.3\text{-}1.6 \cdot 10^6$  K and with typical solar wind values, suggesting acceleration from a solar wind source. Whether the difference between our measurement of the mean ionic charge of Mg ( $\sim 9$ ) and typical low speed solar wind values ( $\sim 10$ , e.g. v. Steiger et al., 1995) is significant, needs further investigation.

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