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Ionic charge states of heavy ions associated with interplanetary shocks at 1AU

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Abstract: Measurements with advanced instrumentation on the SAMPEX, SOHO and ACE spacecraft show a large variability of the ionic charge of heavy ions in solar energetic particle (SEP) events with energy, in particular for Fe. In this paper we present a survey of ionic charge observations in interplanetary shock related SEP events obtained with the SEPICA instrument onboard ACE in the energy range ~0.18-0.43 MeV/nuc during the time period 1997 - 2000. We analyzed all interplanetary shock related events where SEPICA data are available. We find for most of the events for iron in the energy range 0.18 - 0.25 MeV/nuc mean ionic charge states of ~9 - 11, with a significant increase of Q_{Fe} between 0.18 and 0.43 MeV/nuc in only 3 of 35 cases. Two of these 3 events show high charge states for Fe (~16) at 0.18 - 0.25 MeV/nuc with a strong increase by 3 - 4 charge units between 0.18 and 0.43 MeV/nuc, similar to the observations in all Fe-rich and ^{3}He-rich events. For the majority of the events (32 of 35) the mean ionic charge is independent of energy in the energy range 0.18-0.43 MeV/nuc and consistent with typical charge states of iron in the solar wind and in suprathermal particles.

Introduction

The variability of the mean ionic charge of heavy ions was one of the parameters used in the last ~25 years for dividing SEP events into two classes, *gradual* and *impulsive*, following the classification of flares based on the duration of their soft X-ray emission [1, 2, 3]: (1) *Gradual Events*, showing large interplanetary ion intensities, small electron to proton ratios, on average elemental abundances similar to coronal abundances, and ionic charge states consistent with source temperatures of 1 - 2 10^6 K, characteristic for the solar corona and solar wind. These events show long duration soft X-ray emission and are associated with interplanetary shocks, driven by coronal mass ejections (CME). (2) *Impulsive Events* show small interplanetary ion intensities, a high electron to proton intensity ratio, enhanced abundances of heavy elements (e.g. by a factor ~10 for Fe relative to O), enhancements of ^{3}He relative to ^{4}He by up to a factor of 10^4, and high ionic charge states for Si (14) and Fe (20), which were interpreted as being due to a high temperature of ~10^7 K in the source region [4, 5, 6]. These events show short duration soft X-ray emission and the acceleration process is thought to be related to the flare. With new measurements over the last ~10 years that extended the ionic charge measurements to lower and higher energies, the view changed dramatically. In *impulsive* SEP events a systematic increase of the mean ionic charge of heavy ions at energies less than 1 MeV/nuc was observed, most pronounced for iron ions [7, 8], that could only be explained by additional ionization in a dense environment in the low corona, at altitudes less than ~1 solar radii [7, 9, 10]. In large (*gradual)* events the mean ionic charge of Fe at low energies (< 200 keV/nuc) is usually ~ 9 - 11 [11], similar to solar wind charge states [12]. At higher energies the mean ionic charge shows a variable energy dependence. The mean ionic charge of Fe at energies < 1 MeV/nuc, for example, is either constant or increases with energy, in a few cases by several charge units [13, 14]. At energies above ~10 MeV/nuc, however, the mean ionic charge is often observed to be significantly larger than at low energies, with Q_{Fe} ~15-20 [15, 16, 17, 18]. In these measurements, the mean ionic charge was usually derived by averaging over the SEP event, possibly averaging over different particle populations: (1) a particle population accelerated close to the Sun that is observed early in the event, and (2) a particle population accelerated locally at the IP shock. In this paper we will analyze the mean ionic charge of heavy ions during time periods around the passage of interplanetary shocks to investigate the ionic charge of the locally accelerated population.

Instrumentation and Data Analysis

The study reported here was carried out with the Solar Energetic Particle Ionic Charge Analyzer (SEPICA, [19]) onboard the Advanced Composition Explorer (ACE) spacecraft, which was launched in August 1997 into a halo orbit around the Lagrangian point L1 between the Earth and the Sun. SEPICA provides ionic charge distributions in the energy range ~0.18 – 0.45 MeV/nuc (for Fe) and elemental and isotopic (for He) abundances. For the evaluation of ionic charge states during intensity increases associated with CME driven interplanetary shocks, we selected all time periods during 1997 – 2000 when SEPICA data were available and an interplanetary shock was observed. For the shock times at ACE we used Table 1 of [20] and the ACE shock list (http://www.ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html). The mean ionic charge of Fe was then determined for 3 energy bands between 0.18 and 0.43 MeV/nuc (0.18-0.25, 0.25-0.36, 0.36-0.43 MeV/nuc) and for a time period of several hours around the interplanetary shock passage. The time period was adjusted to specifically exclude the onset phase of the event that is most likely dominated by particles accelerated close to the Sun. Figure 1 shows as an example of the selected time period the SEP event on June 7, 2000, with an interplanetary shock on June 8 (day 160).

Results

We found a total of 44 events where SEPICA data were available around an interplanetary shock passage. This sample was reduced to 35 events when requiring more than 6 counts in the lowest and highest energy bin. Figure 2 shows the distribution of the ionic charge of iron ions, Q_{Fe}, at 0.18-0.25 MeV/nuc for these time periods. The distribution is strongly peeked at Q_{Fe}~10–11, with a mean value of Q_{Fe} =10.6 ± 0.2, similar to typical charge states of Fe in the solar wind [12].

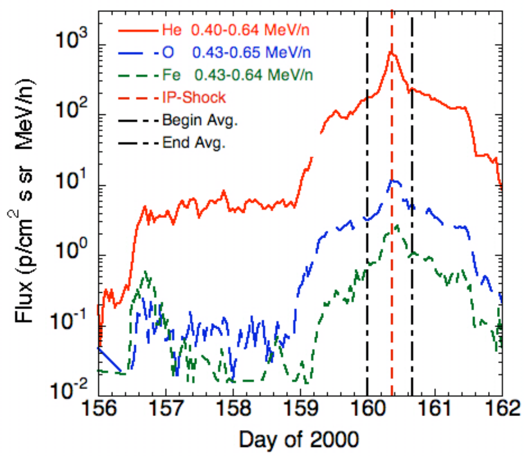

Figure 1: Example of averaging time period including an interplanetary shock related intensity increase of He, O, and Fe.

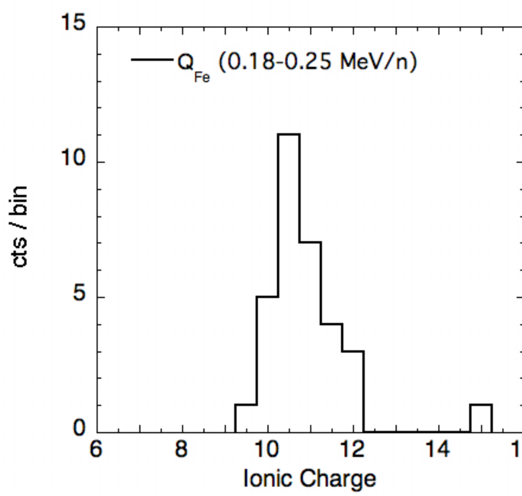

Figure 2: Distribution of Fe charge states in the energy range 0.18-0.25 MeV/nuc.

Figure 3 shows the mean ionic charge of iron ions in energy band 3 (0.36 – 0.43 MeV/nuc) versus Q_{Fe} at the lowest energy. Most of the data points

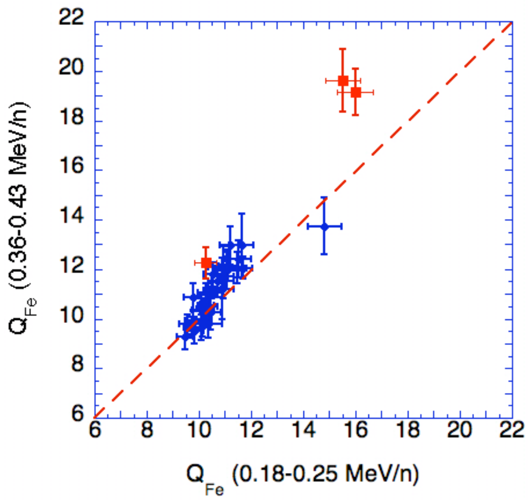

Figure 3: Mean ionic charge of Fe for 35 interplanetary shock related SEP events.

overlap within their 1 sigma error bars with the diagonal line, suggesting that the difference ΔQ_{Fe} between the highest and lowest energy of our measurement is not significant. We performed a t-test for a quantitative check of the significance of ΔQ_{Fe}. The filled squares in Fig. 3 indicate the 3 cases in our data set where the t-test showed a significant difference at the $p<0.03$ level. Thus for 32 out of our sample of 35 events, there is no significant energy dependence of Q_{Fe} in the energy range 0.18 – 0.43 MeV/nuc. The other three events show a significant increase of Q_{Fe} with energy, with ΔQ_{Fe} ~2 – 4. These events are investigated in more detail in Fig. 4. The ionic charge of Fe for event 8 of our event list is similar to the average of Q_{Fe} at low energies, the other two events show both, the largest ΔQ_{Fe} (3.1 and 4.1, respectively) and also a high value of Q_{Fe} at the lowest energy (16.0 and 15.5, respectively). Thus these two events show a similar energy dependence of Q_{Fe} as impulsive events [7, 8]. The investigation of the Fe/O-ratio and the oxygen flux also shows that these two events are low-intensity Fe-rich (Fe/O > 1) events. The large energy dependence at low energies < 1 MeV/nuc in these 2 events suggests additional ionization by electrons and ions during or after acceleration in the low corona [7, 10].

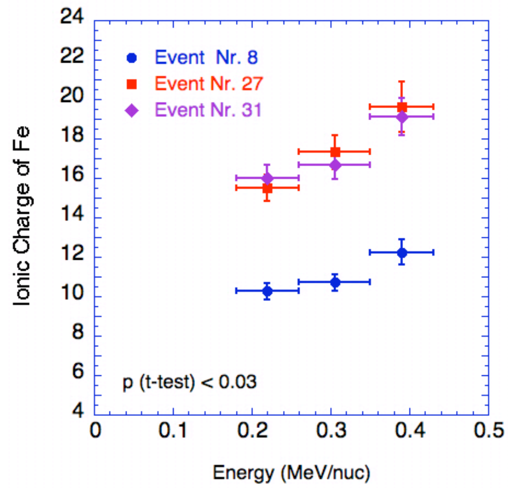

Figure 4: Average ionic charge of Fe for the three events of this study with significant energy variation.

Summary

Most of the interplanetary shock related heavy ion intensity increases show Fe ionic charge states in the range of 9 – 12, with a mean value of 10.6±0.2, similar to Fe ionic charge states in the solar wind and at suprathermal energies of ~10 – 100 keV/n [11, 12]. This is consistent with both a solar wind and a suprathermal source of the accelerated population [20]. Two events show a strong increase of the mean ionic charge of Fe from ~15 at 0.18 – 0.25 MeV/nuc to 19 – 20 at 0.35-0.43 MeV/nuc, an increase of Q similar to the one consistently observed in Fe-rich events. These two events (# 26 and #29 in Table 1 of [2]) show, indeed, also Fe/O > 1 and large $^3He/^4He$-ratios of 0.24 and 0.04, respectively [20]. The strong increase of Q_{Fe} at energies < 0.5 MeV/nuc thus suggests, that these ions are not accelerated locally at the interplanetary shock, but in the low corona. The only very small intensity increase, and low Mach number (~1.1, see [21]) also suggest, that there was not much local acceleration in these 2 events.

Acknowledgements

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