On The Energy Dependence of Ionic Charge States

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Abstract

In this study we evaluate the effect of power-law spectra with rigidity dependent exponential cut-off, as often observed, on the mean ionic charge of Fe. We show that power law spectra with an exponential cut-off, with e-folding energy $E_0(M/Q) \sim (Q/M)^\alpha$, $\alpha \approx 1$, and $E_0 \leq 0.4$ MeV/n (for $^{56}Fe^{10+}$), result in a moderate increase of the mean ionic charge of Fe by 1 - 2 charge units in the energy range of 0.1-1 MeV/n. We use the spectral information for oxygen and iron from the ULEIS experiment onboard ACE at energies of $\approx$ 0.11-3.6 MeV/n to compare the energy depence of the mean ionic charge of iron as expected from the M/Q dependent cut-off effect with the mean ionic charge measured with SEPICA onboard ACE.

1. Introduction

The ionic charge composition of suprathermal ions is a sensitive indicator for the temperature of the source region. Besides that, the acceleration and transport processes depend significantly on velocity and rigidity, i.e. on the mass and ionic charge of the ions. With experiments onboard SAMPEX an increase of the mean ionic charge at energies > 10 MeV/n has first been observed for two gradual solar energetic particle events (SEP) in October / November 1992 [1]. New measurements with improved resolution and sensitivity onboad SOHO and ACE showed that the mean ionic charge in the energy range $\approx$ 30 to 500 keV/n increases with energy in many events, with a large event-to-event variability ([2]. [3], [4], [5]). This energy dependence of the mean ionic charge, most pronounced for heavy ions (Si, Fe), could be caused by several processes, including stripping low in the corona and mass/charge dependent acceleration effects.

A monotonic increase of the mean ionic charge with energy would be a natural consequence if the particles are propagating in a sufficiently dense envi-

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ronment low in the corona. This has been pointed out by several authors ([6]. [7], [8]) and was recently observed in impulsive events where the acceleration generally is assumed to be low in the corona [9]. In this study we concentrate on events with low energy (<1 MeV/n) particle intensity increases correlated with the passage of interplanetary shocks at 1 AU, where stripping effects are not likely to be effective.

2. Acceleration and Propagation Effects on the Mean Ionic Charge

In the test particle limit of diffusive shock acceleration at a quasiparallel, planar shock, steady state conditions, and no losses, the distribution function of ions can be described as a power law in velocity, f $\sim$ $E^{-\gamma}$. In this ideal case the spectral index γ is determined by the shock compression ratio (e.g. [10]. [11]) and is independent of mass and ionic charge, i.e. no variations of the mean ionic charge (and elemental) composition with energy would be expected. Deviations from this simple power law energy dependence of the energy spectra can be expected if at least one of the above assumptions is violated. Non steady state conditions, particle losses, or finite shock size will generally result in a high-energy roll-over, with particle spectra falling off more steeply than described by a power law (e.g. [12], [13]). Spectra of the form

$$j(E) = j_0 \times E^{-\gamma} \times exp(-E/E_0), \tag{1}$$

have been reported recently for large, gradual events [14]. The observed spectra have been fitted using the spectral shape (1) and showed systematic differences of the e-folding energy E_0 for particles of different mass per charge ratio that could be approximated by

$$E_0(A/Q) \sim E_{0,p} \times (Q/A)^{\alpha}, \tag{2}$$

where $E_{0,p}$ is the e-folding energy of protons and with α in the range 0.8 - 2.3. In fact, [14] successfully used these systematic M/Q dependent differences of E_0 to infer mean ionic charge states of heavy ions. If this spectral form is assumed to hold for individual charge states, then it necessarily results (for $\alpha \neq 0$) in an energy dependent mean ionic charge [15]. As an example, Fig. 1 (left panel) shows the resulting energy dependence of the mean ionic charge of Fe, for 3 values of E_0 and for $\alpha = 1$, assuming γ=-1.5, and using a solar wind Fe ionic charge distribution as reported for May 1, 1998 [5], with a mean value of Q_{Fe}=10.1. The results show that the mean ionic charge of Fe increases by 1 charge unit between 0.1 and 0.4 MeV/n for E_0 (Fe^{10+}) = 0.15 MeV/n and between 0.1 and 1.0 MeV/nuc for E_0 = 0.4 MeV/n, respectively.

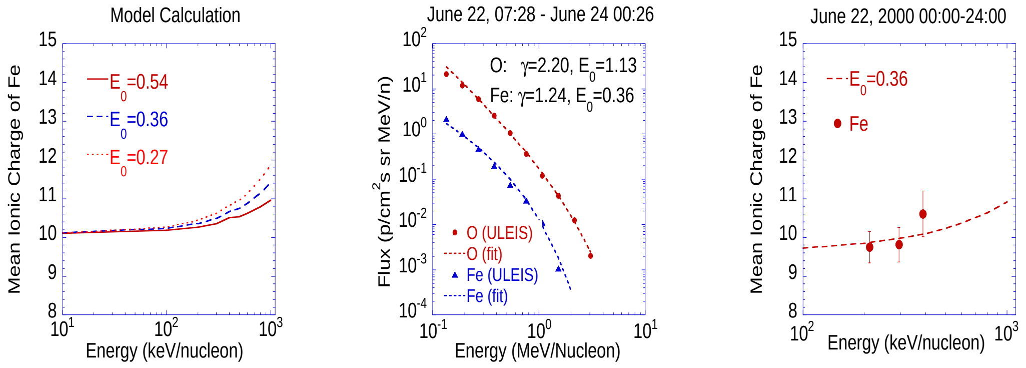

Fig. 1. Left panel: Variation of the mean ionic charge computed for 3 values of E_0 and α=1; Middle panel: spectra of O and Fe for the June 22-23, 2000 SEP event, with fits to the O and Fe spectra, using (1); Right panel: Mean ionic charge of Fe as measured with SEPICA during the same event and mean ionic charge variation using the fit parameters as shown in the middle panel.

3. Comparison with Ionic Charge Measurements

We use the energy spectra of oxygen and iron during CME / interplanetary shock related solar energetic particle events to check whether the energy dependence of the mean ionic charge of Fe as predicted from the spectral rollover is consistent with the mean ionic charge as measured for the the same event with the SEPICA instrument [16] onboard ACE [17]. We derive the parameters E_0 and γ by a fit of the oxygen and iron spectra as measured with the ULEIS experiment [18] onboard ACE. For the spectral analysis we use the energy range 0.113 - 3.62 MeV/n (O) and 0.113 - 1.81 MeV/n (Fe), respectively. An example of the spectral fit for an event with sufficiently soft Fe spectrum is shown in Fig. 1 (middle panel).

The mean ionic charge of Fe is obtained with the SEPICA instrument onboard ACE. We restrict the ionic charge analysis to energies $<$0.43 MeV/nuc, where scattering effects are sufficiently small that mean ionic charge states $>$10 do not need to be corrected (see also [9]). The data points (right-hand panel) show the SEPICA measurements in 3 energy ranges between 0.18 and 0.43 MeV/n. The error bars include the statistical error and a systematic error of 3% added quadratically. The dashed line in the right-hand panel shows the mean ionic charge of Fe as derived from (1) and (2), using the Fe distribution as measured in the solar wind with the SWICS instrument [19] onboard ACE during a time of ~24h centered on the arrival of the interplanetary shock on June 23, 2000, and using α=1 and E_0=0.36 MeV/n from the spectral fit obtained for Fe.

4. Discussion and Conclusion

We have shown that a M/Q dependent exponential roll-over of low energy Fe spectra in the energy range <2 MeV/nuc results in a systematic variation of Q_{mean} of Fe. The systematic increase of Q_{mean} depends critically on the value of E_0 and the mean ionic charge at <1MeV/n increases only for sufficiently soft spectra. We find that a significant increase between 0.1 - 1.0 MeV/n can be expected if $E_0(Fe^{10+}) < 0.4$. However, in the energy range available in the present study (< 0.43 MeV/n), an increase of the mean ionic charge by 1 charge unit would require extremely soft spectra, with E_0 $(Fe^{10+}) = 0.15$. In the case of the SEP event of June 22-23, 2000, with $E_0 = 0.36$, the observed small increase of the mean ionic charge of Fe is consistent with the values expected from the spectral roll-over. However, the measurement errors are too large to be conclusive. A sensitive test of the interpretation of small increases of the mean ionic charge being caused by M/Q dependent spectral roll-over would be provided by an extension of the energy range of the measurement to higher energies, where the mean ionic charge increase would become more significant. This is possible by considering the effects of scattering in the sensor and is planned to be done in a future study.

5. References

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