Observation of Energy-Dependent Charge States in Solar Energetic Particle Events

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Abstract

Ionic charge states of solar energetic particles (SEPs) provide information about their source environment and acceleration process. For example, SEPs in flare-associated events typically have higher charge states than those in large, interplanetary shock-associated events. This may be explained by the different temperatures of the ion populations undergoing acceleration. Recently, some large SEP events have been observed with energy dependent charge states. In these cases, higher energy ions have higher charge states. This phenomenon may be a result of acceleration by shocks or flares in a collisional plasma close to the Sun. In the interplanetary medium, a moderate energy dependence may be created by rigidity-dependent shock acceleration. We present observations of energy dependent charge states for three large SEP events, using data from the ACE, SAMPEX and SOHO spacecraft. The energy range for these data extend from 0.1 MeV/nuc up to as high as 20 MeV/nuc. In each event, the iron charge states increase by at least 9 units over this energy range. These results will be discussed with respect to the cited models for energy dependent charge states.

1. Introduction

Ionic charge states of solar energetic particles (SEPs) can provide tracers for their acceleration processes. The observed charge state at Earth is the combined result of the source region temperature, the influence of collisional processes and the rigidity-dependence of the acceleration. Luhn et al., (1987) reported on charge states from two classes of SEP events. One type had abundance enhancements including 3He enrichment, while the other had no abundance enhancements. The latter events are often referred to as gradual events (Reames, 1999). The average Fe charge state in gradual events was 14.1+, while in 3He-rich events

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it was 20.5+. This result was interpreted as an indication of the source region temperature. They estimated the source temperature at 2-4 MK for the gradual events, and approximately 10 MK for the 3He-rich events. The two state view was altered somewhat by the observations of Oetliker et al (1997). They detected an energy dependence in the Fe charge state during an SEP event series of October and November, 1992. In this case, the Fe charge state increased with energy. These observations were made with instruments aboard the SAMPEX spacecraft (Baker et al., 1993). Later, in the November 6, 1997 event, SEPs with energy dependent charge states were observed once more. This time, both Si and Fe charge states displayed this pattern (Moebius et al, 1999, Mazur et al., 1999). The energy dependence was observed simultaneously at SAMPEX and ACE. This work presents charge state measurements for three events over a wide energy range. It combines data from up to four instruments on three spacecraft. The energy range is of unprecedented width, spanning 65 keV/nuc to 37 MeV/nuc.

2. Observations

The instruments in this study are STOF on the SOHO spacecraft (Hovestadt et al., 1995) SEPICA on ACE (Moebius et al., 1998), and finally LICA (Mason et al., 1993) and MAST (Cook et al., 1993), both on SAMPEX. STOF uses electrostatic deflection, time of flight and energy measurements to determine ionic charge state directly. It provides Fe charge states at 69 kev/nuc. SEPICA uses an energy loss/residual energy telescope and electrostatic deflection to directly measure charge states. It covers the energy range from 65-310 keV/nuc for Fe in this study. SOHO and ACE both orbit the L1 Lagrange point in the solar wind.

SAMPEX/LICA and MAST both measure elemental composition. The SAMPEX spacecraft is in a polar orbit around the Earth. It uses the geomagnetic cutoff method to determine ionic charge states (Mason et al., 1995; Leske et al, 1995; Klecker et al., 1995). LICA covers the energy range 0.25 to 1.0 MeV/nuc for Fe, and MAST covers 25 to 50 MeV/nuc.

Figure 1 shows Fe charge states for three large events: 11/7/97 (97/311), 9/30/98 (98/273) and 11/6/98 (98/310). In the 11/7/97 event, the mean Fe charge state is 9.4+ at 109 keV/nuc. It increases to 14.7+ at 800 keV/nuc. At 37 MeV/nuc, the average Fe charge state is 19.5+. This event may exhibit a rollover in the charge state between 1 and 20 MeV/nuc. The gradient in charge state with energy is approximately 4.5 charge units over the 0.1-1.0 MeV/nuc energy range.

The 9/30/98 event also shows an increase in charge state with energy. At 105 keV/nuc, the mean Fe charge state is 8.0+. It increases to 20.5+ at 37 MeV/nuc. This event shows no apparent rollover in charge state up to the maximum energy. The gradient is approximately 3.2 units in the 0.1-1.0 MeV/nuc energy range. The MAST data are from Mazur et al. (1999) and Larson et al.

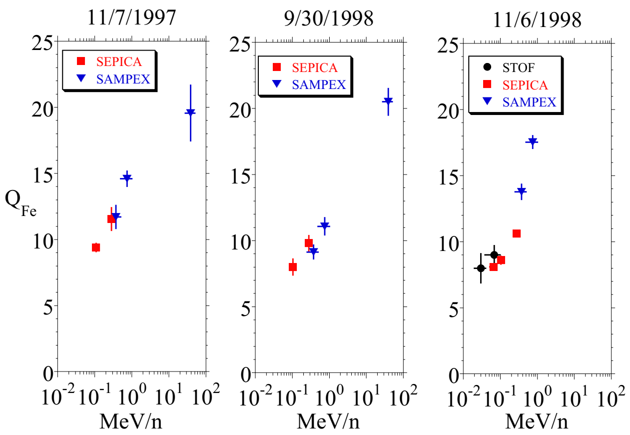

Fig. 1. Fe charge states are shown for the three large events in which multiple instrument observations are available. Data are from SAMPEX/MAST and LICA, ACE/SEPICA and SOHO/STOF. Each event has a gradient of charge state with energy.

(1999).

Finally, Figure 1 shows the 11/6/98 event. This event includes data from STOF, SEPICA and LICA. MAST data are not available. The Fe charge state is between 8+ and 9+ at 65 keV/nuc, and increases to 17.5+ at 800 keV/nuc. The gradient of charge state with energy is the steepest in this event, at 9 units in the 0.065-1.0 MeV/nuc range.

3. Discussion

Several theoretical efforts have attempted to explain energy dependent charge states. Barghouty and Mewaldt (1999, 2000), Reames (1999b) and Stovpyuk and Ostryakov (2001) considered the effects of shock acceleration close to the Sun, in a collisional environment. Energy-dependence in flare acceleration has been explored with a similar mechanism by Ostryakov et al. (2000). In these models, the acceleration proceeds simultaneously with charge-changing collisions. The ions with the largest product of residence time and target density experience the largest energy gain and the largest increase in charge state. In these cases, the mean charge state does not directly indicate the source region temperature. In the interplanetary medium, energy-dependent charge states may be produced instead by rigidity-dependent shock acceleration. This selective acceleration may create a 1-2 unit increase of the average Fe charge state over the source population (Klecker et al., 2000, 2001). In the three large events presented here, all of these mechanisms may have contributed to the observed energy dependence. Close to the Sun, a CME-driven shock may accelerate ions in a collisional environment. Flare acceleration may contribute in a similar way. After the shock leaves the corona, it may weaken but still be capable of accelerating ions in the interplanetary medium. During the transit from the corona to 1 A.U., only rigidity-dependent acceleration will create new energy dependence. A complete model of the observations must integrate all of these effects with appropriate timescales. The observed gradients in charge state with energy may then place limits on the relative contribution of each mechanism.

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