Ionic Charge States of High Energy Solar Energetic Particles in Large Events

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Abstract

We present a novel technique to infer average ionic charge states of high energy ($\geq$ 10 MeV/nuc) solar energetic particles (SEPs) in large solar events. In some large SEP events, it is observed that higher energy SEPs decay in intensity more rapidly than at lower energies. Furthermore, this energy dependence varies with particle species, as would be expected if the decay timescale depended on a rigidity-dependent diffusive mean free path. By comparing the decay timescales of nitrogen, oxygen, neon, magnesium, silicon, sulfur, and iron to a reference element, such as carbon, charge states are inferred for these elements in several SEP events between 1997 and 2002. There is considerable variation in the inferred charge state of iron from event to event. For the November 6, 1997 event, charge states are also inferred for sodium, calcium, and nickel.

1. Introduction

Solar energetic particle (SEP) events are commonly divided into two categories: gradual and impulsive [14]. An impulsive event is one in which solar particles are accelerated in association with a solar flare. The temperature of the material can be as high as 10 MK [7]. These events typically last less than a day. In a gradual event, a coronal mass ejection drives a shockwave through the corona and solar wind, accelerating ambient material. The source temperature for particles in gradual events is found to be 2 MK, consistent with coronal material [13]. Gradual events typically last for several days.

2. Finding Charge States: a New Method

SEPs are thought to diffuse in the inner heliosphere through pitch-angle scatterings off turbulence in the interplanetary magnetic field (IMF). At some outer boundary, the scattering mean free path becomes very large and the particles escape [8]. The time intensity profiles for large gradual SEP events all

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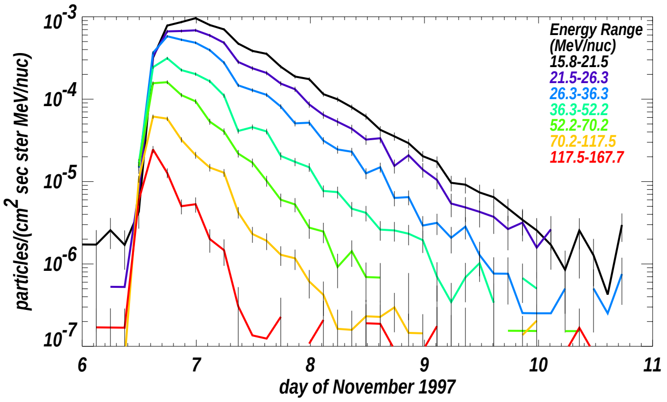

Fig. 1. Time intensity profiles for iron in the 11/6/97 event.

have roughly the same structure, as shown in Figure 1: an hours-long rise from background, followed by a days-long exponential decay. This rise and decay corresponds to the filling of a diffusive cavity in the inner heliosphere, followed by slow leakage from this cavity. It can be seen that at higher energies, iron decays more quickly than at lower energies. In the theory, this follows from the form of the solution for a Fokker-Planck equation that describes SEP propagation. The characteristic decay time scale for a particle population will depend on that population's charge to mass ratio and energy per nucleon.

Two separate solutions to the Fokker-Planck equation, by Forman [5] and Lupton and Stone [8,9], give reasonably accurate and consistent behavior for the decay phase of a solar particle event. In the decay phase for any given particle species, both solutions can be reasonably parameterized by an exponential decay of the particle flux f of the form $f = Ce^{t/\tau}$, where C is a constant, and the decay constant $1/\tau$ is given by:

$$\frac{1}{\tau} = \frac{1}{\tau_C} + W(\alpha_X E)^\gamma \tag{1}$$

For this equation, W is a normalization that is common to all particle species, γ is a power law index that is set by the power spectrum of the turbulence in the IMF, τ_C is a constant, and α_X is a second normalization that changes from species to species and depends on the charge state. This relationship is plotted with data from the Solar Isotope Spectrometer aboard the Advanced Composition Explorer for the November 6, 1997 event for carbon with $Q_C = 5.9$, and for several charge states of iron in Figure 2. For a given SEP event, decay timescales are found for as many elements as possible, and those decay timescales are fit to (2), allowing W, γ, τ_C, and α_X to float. Note that W, γ and τ_C are the same for all species in a given event. In order to find the charge state for a given element, a comparison is made to a reference element, for which $\alpha_X = 1$ is assumed, and

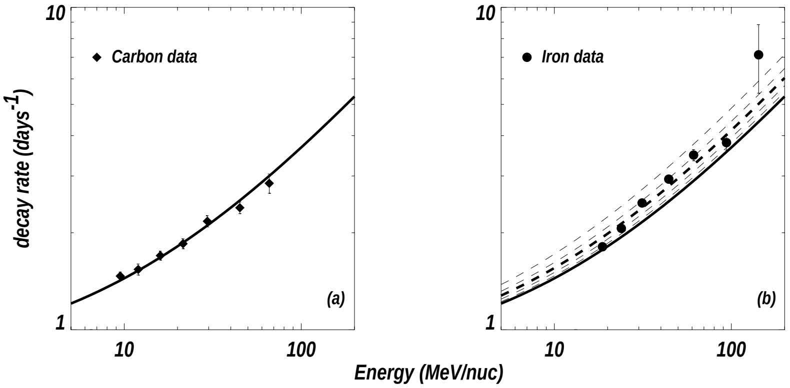

Fig. 2. Decay rates vs. energy for carbon and iron. (See text)

whose charge state is already known or estimated. For this analysis the reference element is carbon. Then in terms of the charge state Q_C and atomic mass A_C of carbon, the charge state Q_X of a given element of atomic mass A_X is given by:

$$Q_X = \alpha_X^{\gamma/(1-2\gamma)} \frac{Q_C}{A_C} A_X \tag{2}$$

Figure 2, panel (a) shows the reference element, carbon. The solid line is the curve for carbon based on the W, γ and τ_C fit for all the elements in the event. Note that $Q_C = 5.9$ is assumed. In panel (b), the same solid line is shown, along with data and calculations for iron. The dashed lines are calculations based on the fit for (from the top) $Q = 8, 12, 16, 20$, and 24. The curve fit for iron in this event is plotted as a bold dashed line. It can be seen to fall almost exactly over the line for $Q = 16$. It is assumed that particle charge states do not change with time or energy; also, only an average charge state is calculated.

3. Results and Conclusions

Figure 3 shows charge states inferred with this method for five different solar particle events between 1997 and 2002. Superposed over those measurements are the model calculations from [1] and [2] for equilibrium charge states at various temperatures. It can be seen in the figure that most of the events are consistent with temperatures of roughly 1-2 MK, which would be consistent with a coronal source. However, the November 6, 1997 is more consistent with a source temperature of 4 MK. This might indicate a mixed source, with some material coming from a hot flare region.

In the November 6, 1997 event, SAMPEX measures a charge state for iron of 19.6 ± 2.4 in the energy range 15 - 70 MeV/nuc [11]. Our measurement is 1.5 σ away from this value. For the November 2001 and April 2002 events, the charge

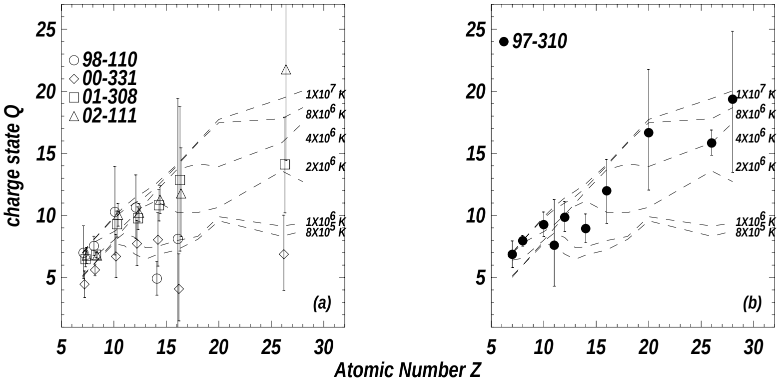

Fig. 3. Inferred charge states for five different events.

states measured by Labrador et al. [6] with SAMPEX are statistically consistent with those measured here.

The presence of flare source material in the large gradual solar event of November 6, 1997 has been suggested by other authors [4,11,12], and would seem to be more reason to question [3] the earlier division of impulsive and gradual events. On the other hand, that material could also have been accelerated from a remnant interplanetary population of solar flare particles [10].

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4. References

1. Arnaud, M. and Raymond, J. 1992, ApJ 398, 394
2. Arnaud, M. and Rothenflug, R. 1985, A&AS 60, 425
3. Cane, H.V. et al. 2003, GRL (submitted)
4. Cohen, C.M.S. et al. 1999, GRL 26, 149
5. Forman, M. 1971, JGR 76, 759
6. Labrador, A.W. et al. 2003, Proc. 28th ICRC, Tsukuba
7. Luhn, A. et al. 1987, ApJ 317, 951
8. Lupton, J.E. 1973, PhD Thesis, Caltech
9. Lupton, J.E. and Stone, E.C. 1973, JGR 78, 1007
10. Mason, G.M. et al. 1999, ApJL 525, L133
11. Mazur, J.E. et al. 1999, GRL 26, 173
12. Möbius, E. et al. 1999, GRL 26, 145
13. Möbius, E. et al. 2000, AIP Conf. Proc. 528, 131
14. Reames, D.V. 1995, Rev. Geophys. 33, 585