The ^{3}He-Rich SEP Events of August 2002: Exceptional Elemental and Isotopic Composition Patterns at Energies above 10 MeV/nucleon

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Abstract

Heavy-ion composition observations from the Solar Isotope Spectrometer on ACE are reported for four ^{3}He-rich solar-energetic-particle (SEP) events that occurred in August 2002. The abundance enhancement patterns are not monotonic functions of atomic number (or mass), such as is commonly found in ^{3}He-rich events, but have large enhancements of abundance ratios between some neighboring elements (e.g., N/O) and between isotopes of some elements (e.g., ^{26}Mg/^{24}Mg). The possibility that these patterns could be indicative resonant acceleration of particles within a narrow range of charge-to-mass ratios is considered.

1. Introduction

Solar energetic particle (SEP) events that exhibit large enhancements of the ^{3}He/^{4}He ratio relative to the solar coronal value of $\sim 5 \times 10^{-4}$ are very common [5,7]. Such events, which are classified as "impulsive", are believed to involve particle acceleration at the site of a solar flare. It is commonly thought that an acceleration process capable of enhancing ^{3}He/^{4}He by $\sim 10^3$ or more must involve a resonant process that can selectively enhance ion abundances within a narrow range of charge-to-mass ratios, Q/M.

Heavy-ion composition in "typical" impulsive SEP events is characterized by minimal fractionation of CNO abundances relative to the solar corona, enhancements of Ne, Mg, and Si (relative to O) by $\sim 3\times$, and of Fe/O by $\sim 7\times$ [5,6]. In this pattern, which has been attributed to the charge-state distribution expected in a plasma with a temperature $\sim$ 3–5 MK [5], abundance enhancements for elements heavier than He are generally an increasing function of mass and do not indicate preferential acceleration of ions within a narrow range of Q/M.

Several individual impulsive events recently observed below 0.5 MeV/nuc

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had large enhancements of nearby element ratios such as N/O, Si/Ne, and S/Ne [3]. Such a pattern could be indicating a resonant Q/M fractionation, and a subsequent theoretical study [8] attributed the high N/O ratio to resonant heating by H cyclotron waves in a plasma at $\sim$ 2–3.2 MK.

In this paper we report observations of heavy element and isotope abundances in the energy range 12–60 MeV/nuc made in four impulsive SEP events in August 2002 by the SIS instrument on the Advanced Composition Explorer mission. In addition to being ^{3}He-rich (^{3}He/^{4}He > 0.1) and Fe-rich (Fe/O > 1), these events have characteristics commonly ascribed to impulsive events [2].

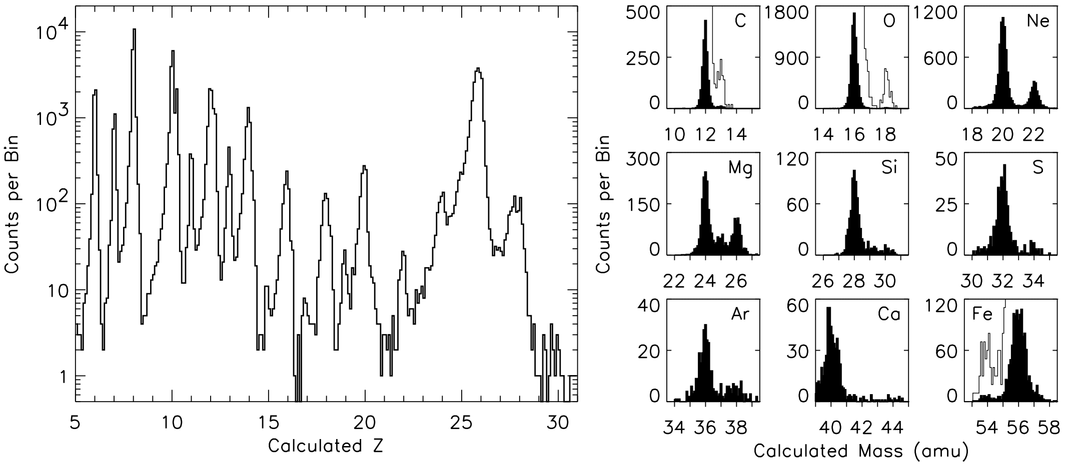

Fig. 1. ACE/SIS observations in the 20 Aug 2002 ^{3}He-rich SEP event. Left: charge histogram. Right: mass histograms for selected elements. For C, O, and Fe the unfilled histograms show the data with vertical scales expanded by factors of 20, 50, and 10, respectively, to better show the rare isotopes.

2. Observations

Time–intensity profiles for the four events considered in this paper (3 Aug 21:00 to 4 Aug 15:00; 5 Aug 6:00 to 6 Aug 12:00; 19 Aug 10:00 to 21:00; 20 Aug 8:00 to 21 Aug 12:00) are shown in [2]. The fluxes of heavy ions at SIS energies were much larger than in typical impulsive SEP events, although smaller than in many “gradual” (shock acceleration) events. This allowed abundance measurements for an unusually large set of elements and isotopes. Figure 1 shows a charge histogram for the 20 August event, which had the highest heavy-ion fluences. Also shown are mass histograms for selected elements in this event.

Relative abundances measured in the four events are summarized in Figure 2. The measured abundance patterns (filled points) exhibit some distinct differences from typical impulsive SEP composition (shaded bands, [6]). For example, in the 3 August event (squares) C, Ne, and Fe are close to normal values, but N, Mg, and Si are significantly enhanced, somewhat reminiscent of the composition reported in [3]. In the 20 August event (circles), deficits of C, N, Si, and S are accompanied by enhancements of Ne, Fe, and Ni, while Al and Ca have abundances close to normal values. In all four events, the elements Ne and Mg have large enhancements of heavy isotope abundances.

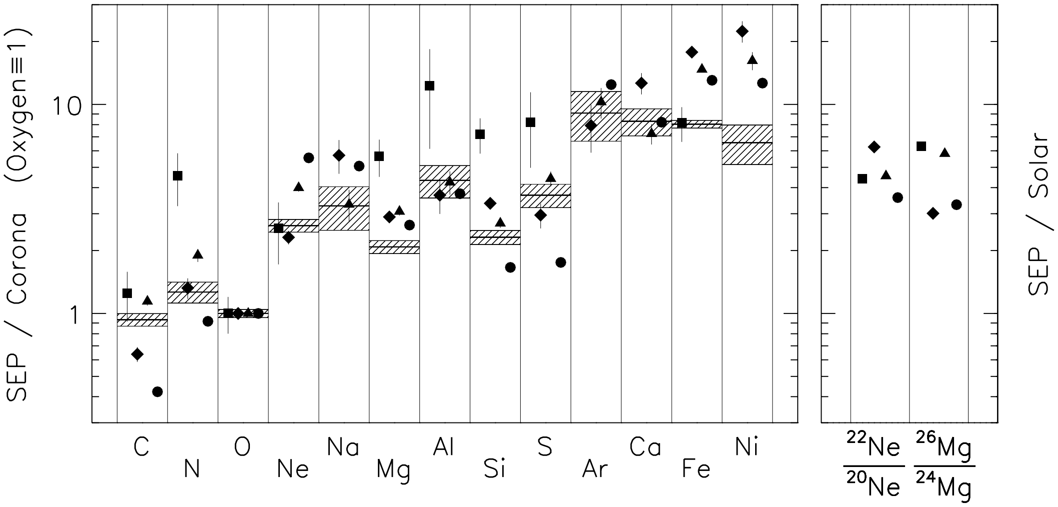

Fig. 2. Composition in the ^{3}He-rich events of August 2002 (square, 3 Aug; diamond, 5 Aug; triangle, 19 Aug; circle, 20 Aug). Left panel shows abundances of major elements relative to coronal values [6]. Shaded bands are "typical" impulsive SEP composition [6]. Right panel shows Ne and Mg isotope ratios relative to solar [1].

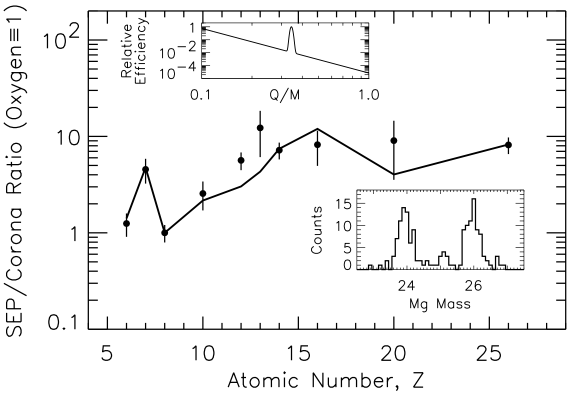

Fig. 3. Comparison of observed elemental composition in the 3 Aug SEP event (points) with model calculation (solid line) described in the text. Insets show assumed acceleration efficiency (upper left) and measured Mg isotope distribution (lower right).

3. Discussion

We have investigated the possibility that the fractionation patterns in the August 2002 events could be related to resonance effects causing preferential acceleration of ions within a narrow range of Q/M. Assuming an isothermal source population of temperature T (which determines the ionic charge states [4], Q) and coronal composition [6,1] we fit a fractionation function, $f(Q/M)$, representing the relative acceleration probabilities for ions with different Q/M values. We assume that f has the form of a power law plus a narrow Gaussian (illustrated in the inset in Fig. 3) and fit the shapes and relative contributions of these components. Fits over a wide range of temperatures are examined to find the best overall fit.

To account for a large enhancement of N relative to both C and O as seen in the August 3 event (Figure 3) it is necessary not only to have a narrow peak in the efficiency function near the Q/M value of N, but also to have source material at low enough temperature so that C, N, and O are not fully ionized and thus can be distinguished from one another by their Q/M values. In this example we have assumed T = 1.66 MK. The resonance is selectively enhancing $^{14}\mathrm{N}^{+5}$ ($Q/M = 0.357$), $^{26}\mathrm{Mg}^{+9}$ (0.346), and $^{32}\mathrm{S}^{+11}$ (0.344) relative to $^{12}\mathrm{C}^{+4}$ and $^{24}\mathrm{Mg}^{+8}$ (both 0.333) and to $^{16}\mathrm{O}^{+6}$ and $^{24}\mathrm{Mg}^{+9}$ (both 0.375). SIS isotopic composition measurements (Fig. 3 inset) confirm the presence of a large enhancement of the $^{26}\mathrm{Mg}/^{24}\mathrm{Mg}$ ratio (Fig. 2).

While the simple, empirical model we have used can account for some features of the observed abundance patterns, the agreement is only approximate (Fig. 3). Examination of events such as August 20 where the composition data are more numerous and more precise, makes it clear that the model is, at best, a first approximation. In a resonance model, abundance enhancements might occur at several harmonics of a fundamental frequency. However, in the absence of theoretical guidance as to the relative strengths and widths of the various enhancements, introduction of additional parameters in the model appears unjustified.

The prediction that impulsive events with large relative fractionation of C, N and O must be indicative of a relatively low-temperature source population stems from the requirement that these elements have distinguishable Q/M values. It will be of great interest to find events of this type in which the source temperature can be directly determined, as should be possible from x-ray spectral observations such as those now being made by RHESSI.

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4. References

1. Anders, E. and Grevesse, N. 1989, Geoch. Cosmoch. Acta, 53, 197.
2. Leske, R.A. et al. 2003, Proc. 28th ICRC (Tsukuba), this conference.
3. Mason, G.M., Mazur, J.E., and Dwyer, J.R. 2002, ApJL, 565, L51.
4. Mazzotta, P. et al. 1998, A&A Supp. 133, 403.
5. Reames, D.V., Meyer, J.-P., and von Rosenvinge, T.T. 1994, ApJS, 90, 649.
6. Reames, D.V. 1999, Sp. Sci. Rev., 90, 413.
7. Wiedenbeck, M.E. et al. 2003, Solar Wind 10 Conf. Proc., in press.
8. Zhang, T.X., and Wang, J.X. 2003, ApJL, 588, L57.