Impulsive Flare Material: A Seed Population for Large Solar Particle Events?

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Abstract

It has been suggested that gradual solar energetic particle (SEP) events enriched in ^{3}He and Fe result from the shock acceleration of remnant interplanetary material from previous impulsive flares. We test this hypothesis by comparing the number densities of Fe ions during quiet periods, ^{3}He-rich periods, and Fe-rich SEP events. We find that there is not a sufficient density of suprathermal Fe during typical quiet periods (or ^{3}He-rich periods) to account for the overall enrichment of Fe in and suggest other possibilities for interpreting these events.

1. Introduction

In the current two-class paradigm (e.g., [10]) gradual SEP events are accelerated by CME-driven shocks and characterized by roughly coronal abundances and charge states. Impulsive events are generally smaller events associated with impulsive x-ray flares and characterized by enrichments in ^{3}He and heavy ions such as Fe, with charge states characteristic of ∼5 to 10 MK. It was therefore surprising when >10 MeV/nuc observations by the SIS instrument on ACE revealed that a large fraction of gradual events are enriched in Fe and other heavy elements [3], with significant overabundances of ^{3}He [3,6,11]. Other impulsive-event properties in some of these events include highly-ionized charge states (e.g., Q(Fe) ∼ 20; [8,5,4]). For lack of a better term, we call these "hybrid" events [2].

In the same time frame Mason et al. [6] discovered that ^{3}He and Fe are present a majority of the time in the interplanetary medium (IPM; see also [12]), and suggested that the ^{3}He and Fe enrichments in gradual events result from shock acceleration of remnant interplanetary material from earlier impulsive events. Other suggestions include direct contributions from high-energy flare-accelerated particles [2,1]. Both possibilities mix impulsive-flare material with coronal-like material. Given the presence of impulsive material in the IPM, it is

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important to ask if the amount is sufficient to explain the large intensity of Fe ions in gradual events. We test the hypothesis of Mason et al. [6] using data from the SIS and ULEIS instruments on ACE to compare the density of suprathermal Fe ions in the IPM with the densities of Fe in hybrid SEP events.

2. Approach and Observations

To relate densities of seed and accelerated particles we consider a "cone" of solid angle Ω (Figure 1) and assume particles are confined to field lines. As the shock moves out it accelerates a number of ions $dN_{inj} = \varepsilon n_{seed} \Omega r^2 dr$, where ε is the injection efficiency and n_{seed} is the density of seed particles, given by $n_{seed} = n_o[r_1/r]^2$, where n_o is the density at $r_1 = 1$ AU. If the shock injects and accelerate particles out to a radius R_{shock}, the number of injected ions is given by integrating from the solar surface to R_{shock}, giving $N_{inj} = \varepsilon n_o \Omega r_1^2 R_{shock}$.

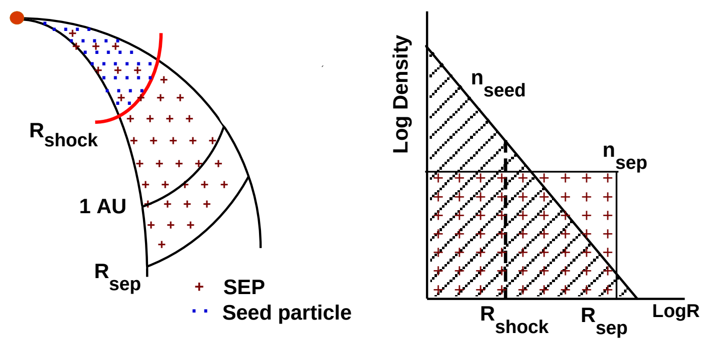

Fig. 1. (left): Illustration of the geometry for comparing SEP and seed-particle densities. (right): The shock accelerates particles (which fall off as r^{-2}) out to radius R_{shock}. Accelerated SEPs are assumed to have constant density out to radius R_{sep}.

To estimate the total number of SEP ions (N_{sep}) we assume that after reaching equilibrium SEPs fill a volume V_{sep} with a uniform number density of n_{sep} (Figure 1). Then $N_{sep} = n_{sep}\Omega R_{sep}^3/3$. Setting $N_{sep} = N_{inj}$, we find $n_{sep}/n_o = 3\varepsilon r_1^2 R_{shock}/R_{sep}^3$. As a conservative estimate, we take $\varepsilon = 1$, $R_{shock} = 0.5$ AU, and $R_{sep} = 1$ AU, which gives $n_{sep}/n_o = 1.5$ ($\approx$1). Thus, for these assumptions, one expects the average SEP number density to be comparable to the seed-particle number density, where both are evaluated at 1 AU. Our approach is to measure n_o at 1 AU for various quiet-time selection criteria and see if it is adequate to explain the observed number density (n_{sep}) measured in hybrid SEP events. In both cases we use $n(E) = 4\pi(dJ/dE)/v$, where v is velocity, and the observed spectrum is integrated from 40 keV/nuc to $\sim$120 MeV/nuc, and then extrapolated to 10 keV/nuc using the observed low-energy slope.

The quiet-time densities of suprathermal Fe ions were investigated using daily-average intensities from February 19, 1998 to March 14, 2002. Daily intensities were ordered by the >0.04 MeV/nuc Fe intensity. Figure 2 shows integral density spectra averaged over the quietest 10%, 25%, 50% and 75% of the days.

Also shown are density spectra averaged over 331 days with $^3He/^4He > 0.1$ and five ^3He-rich events (e.g., [7]). It is not known if these ^3He-rich events are typical.

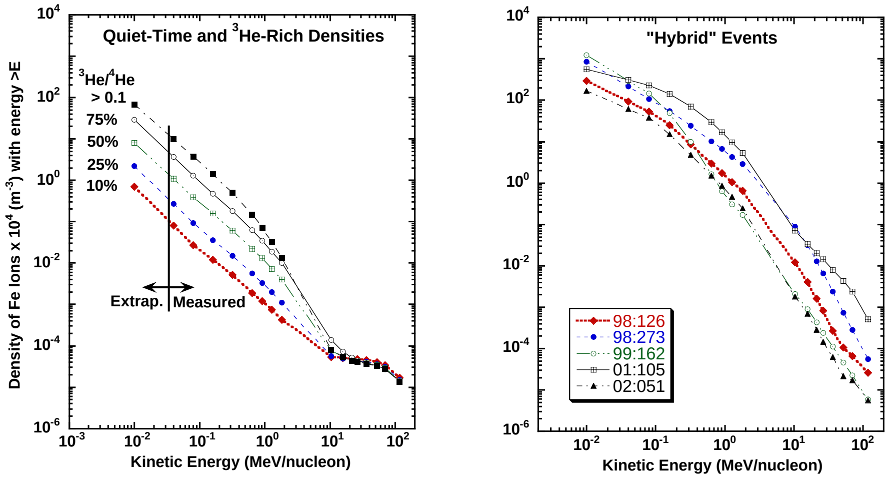

Fig. 2. (left): Integral density spectra of Fe averaged over the quietest 10%, 25%, 50%, and 75% of the days and for 331 days with $^3He/^4He > 0.1$; (right): Integral density spectra of Fe for 5 hybrid events.

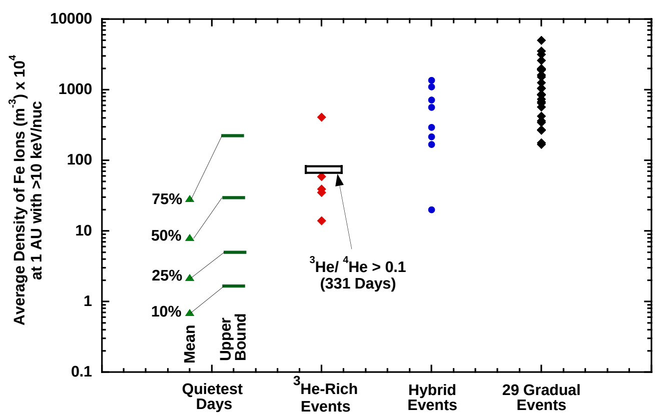

Fig. 3. Summary of the integral density of Fe for quiet-time periods, five ^3He-rich events, the average of 331 ^3He-rich days, hybrid events, and 29 other gradual events.

Hybrid events were selected from gradual SEP events during September 1997 to April 2002, by requiring an event-average Fe/O ratio >0.4 (≈3 times coronal) at 12-40 MeV/nuc, and $^3He/^4He$ >0.002 for either 0.02 to 0.06 or 5 to 13 MeV/nuc (in some events only upper limits are obtained). Figure 2 shows 5 of 8 resulting events. In these events the >12 MeV/nuc Fe enrichments (relative to coronal [10]) ranged from 3 to 8 and the 0.04 to 1.28 MeV/nuc Fe enrichments ranged from 2.5 to 13. In the large events density spectra were averaged over several days (~4). Figure 3 summarizes integral densities measured in this way.

3. Discussion

All 8 hybrid events are Fe-rich at both low energies (0.04 to 1.3 MeV/nuc) and high energies (>12 MeV/nuc). Inspection of Figure 3 shows that in all but one hybrid event the Fe density is ∼10 to 100 times greater than the quietest 50% of the days. The Fe density in typical hybrid events is also greater than all but one ^{3}He-rich event. Following the reasoning in Section 2, we conclude that there is not enough Fe available from any but the most solar-active periods to account for the Fe enrichment in hybrid events. There are several possibilities: (1) Perhaps hybrid events occur when there is an above-average source of Fe in the IPM (during solar active days). However, Fe-rich events are very common; a majority of gradual events are enriched in Fe by x2 or more. (2) Perhaps the shock accelerates impulsive flare material from the same event as well as remnant ions. Since the associated x-ray flares range from M2 to X14, many more flare-accelerated ions may be available than in impulsive events (generally not associated with large x-ray flares). (3) Perhaps most remnant Fe is accelerated to high energies (e.g., >1 MeV/nuc). In this case there is sufficient interplanetary Fe during quiet days (see Figure 2). This possibility is consistent with observations in some events of highly-ionized Fe at higher energies [8,9]. However, then low-energy Fe-enrichments in these hybrid events must have a different origin.

Finally, it is important to consider ^{3}He. In the quiet-time IPM ^{3}He/Fe ∼20 at ∼0.1 MeV/nuc [6], while in typical ^{3}He-rich events ^{3}He/Fe ∼10 [7]. In hybrid events (and other gradual events with detectable ^{3}He), ^{3}He/Fe ∼1 on average. This comparison suggests that if the remnant source is responsible for ^{3}He in gradual events (as seems reasonable), then the remnant contribution of Fe would fall short by a factor of ∼10, in agreement with the analysis presented here.

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4. References

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