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The Dependence of Solar Energetic Particle Fluences on Suprathermal Seed-Particle Densities

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Abstract. Measurements during solar cycle 23 showed that most solar energetic particles (SEPs) are accelerated from a seed-population of suprathermal ions (e.g., >10 keV/nuc) rather than from the bulk solar wind. In this case the SEP fluence should depend on the pre-existing density of suprathermal ions. Lacking near-Sun measurements of suprathermal ion densities we have used ACE/ULEIS daily-average densities of suprathermal Fe at 1 AU during 1998-2005 as a proxy. We find that the maximum Fe daily-average SEP fluences measured by ACE/SIS are apparently limited by the pre-existing suprathermal number density. Similarly, large fluences of Fe in solar energetic particle events only occurred when there was a pre-existing high density of suprathermal Fe. We conclude that *in situ* suprathermal ion data can play a key role in estimating the probability of large SEP events, or in forecasting all-clear periods.

Keywords: Solar energetic particles, solar wind, energetic particle acceleration, coronal mass ejections
PACS: 96.50.Vg, 96.50.Pw, 96.60.Vg, 96.50.sb, 94.20.wq, 94.50.Sd, 96.60.Q-

INTRODUCTION

Several lines of evidence show that large solar energetic particles (SEPs) are accelerated primarily from suprathermal ions (e.g., ions with 10s of keV/nuc to ~1 MeV/nuc) rather than from the bulk solar wind (e.g., [1-3]). This conclusion is supported by the differences in composition between solar wind and SEPs [2], by the presence of excess ^{3}He, He$^+$, and Fe in many or most SEP events [1,3,4], and by estimated injection energies for shock acceleration due to fast coronal mass ejections (CMEs) [5]. If suprathermal ions are the primary seed population for CME-driven shocks, we would expect that SEP fluences should be correlated with the pre-existing density of suprathermal ions, which varies by orders of magnitude more than does the density of solar wind ions. Although it is not yet possible to monitor suprathermal seed-particle densities close to the Sun, the 1-AU density of suprathermal ions from H to Fe has been measured at the L1 Lagrangian point from 1998 to the present by the ACE/ULEIS instrument [6].

Sources of suprathermal seed particles include suprathermal solar wind; interstellar and "inner-source" pickup ions; ions accelerated by ^{3}He-rich flares, CME

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driven shocks, shocks associated with co-rotating interaction regions (CIRs) and by stochastic interplanetary acceleration processes; energetic neutral atoms (ENAs) from the heliosheath; and ions from Sun-grazing comets (e.g. [2], [7]).

In this paper we compare daily averages of the Suprathermal Fe number density at 1 AU with SEP Fe fluences measured by ACE/SIS one to two days later. We find that SEP fluences accelerated by CME-driven shocks appear to be limited by the pre-existing suprathermal number density. For example, days with >1000 Fe/cm^{2}sr with energies >12 MeV/nuc did not occur if the number density of suprathermal Fe on the previous day was <0.1 per cubic decameter (Dm^3). This paper will demonstrate how suprathermal ion densities are apparently related to SEP fluences and also discuss how real-time measurements of suprathermal ion densities can play a key role in estimating the probability of a large SEP event and in forecasting "all-clear" periods.

OBSERVATIONS

We investigate how the intensities of 12-80 MeV/nuc Fe are related to the density of preexisting suprathermal Fe ions. To simplify the analysis we consider daily averages. The >12 MeV/nuc Fe fluences are based on data from the ACE/SIS instrument [8], which measures Fe from ~10 to ~140 MeV/nuc. A nominal geometry factor of ~32 cm^{2}sr provides excellent statistical accuracy. Figure 1 shows daily 10 to 140 MeV/nuc Fe fluences from 1998 through 2005, including essentially all large SEP events from the cycle-23 solar maximum except for three events in December 2006. About 10% of the days during 1998-2005 had >12 MeV/nuc fluences elevated above the galactic cosmic ray (GCR) background level by a factor ≥10.

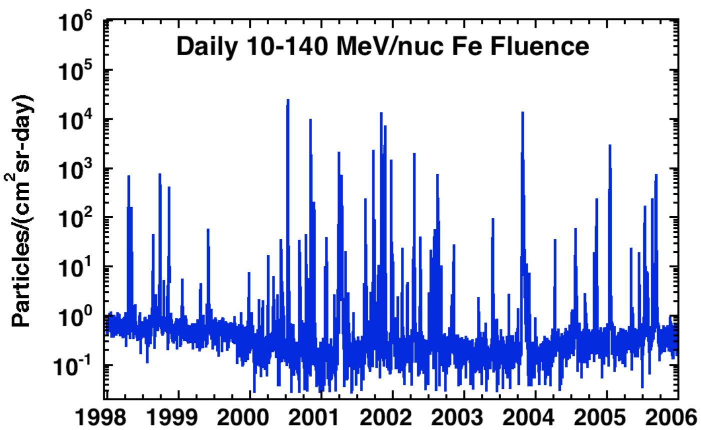

FIGURE 1: (a) Daily-average 10-140 MeV/nuc Fe fluences measured by the ACE/SIS instrument from early 1998 through 2005. The underlying background is due to galactic cosmic rays.

To evaluate the number density of suprathermal Fe we use daily-average ACE/ULEIS Level-2 data from the ACE Science Center [9], and include seven Fe energy intervals from 0.04 – 1.81 MeV/nuc. For a given energy interval (E_1 to E_2) the number density, n, is given by

$$n(E_1,E_2) = 4\pi\int[(dJ/dE)/v]dE \qquad (1)$$

where dJ/dE is the differential energy spectrum (assumed isotropic), v is the particle velocity, and the integral extends from E_1 to E_2. For convenience we assume a slope of dJ/dE ~ E^{-2} for each interval [10], and derive v from the mean kinetic energy, $(E_1 * E_2)^{0.5}$. Each energy interval is evaluated individually and the results are summed.

Figure 2 compares the number-density distribution of suprathermal protons with that for solar wind protons. Note that the solar wind densities typically only vary by 1-2 orders of magnitude, while the suprathermal ion densities commonly vary by ~5 orders of magnitude from 1998 through 2005, including solar maximum.

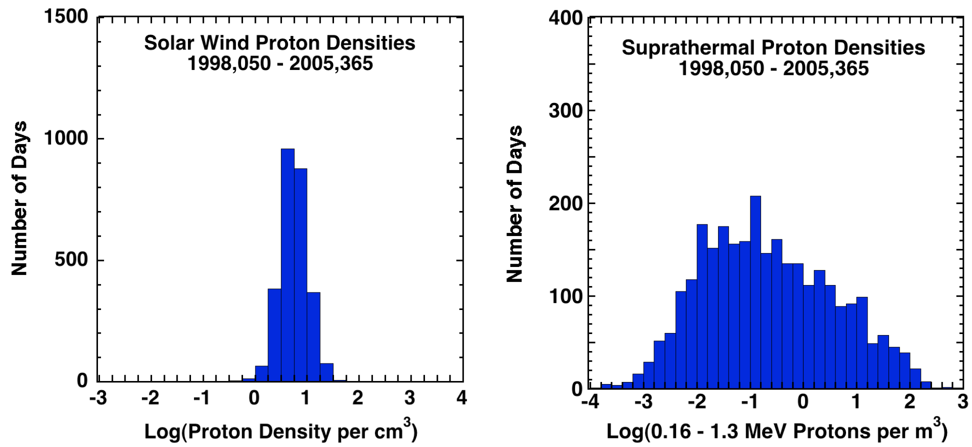

FIGURE 2: (left panel) Distribution of daily-average solar wind proton densities measured by ACE/SWEPAM from 1998 through 2005. (right panel) Distribution of daily-average number densities for 0.16 – 1.28 MeV protons from 1998 through 2005 measured by ACE/ULEIS. Note that suprathermal ion densities are highly variable. Distributions for Fe are similar to those for protons.

To investigate whether pre-existing suprathermal ion densities are related to SEP fluences, Figure 3 (left panel) compares the fluence of Fe in SEP events with the number density of suprathermal Fe at 1 AU on the day before the solar flare and CME eruption. Figure 3 (right panel) shows that suprathermal densities are, on average, significantly greater before SEP events than overall (including all large SEP events). While it would be more meaningful to compare to suprathermal ion densities near the Sun, where most SEPs are accelerated, near-Sun data are not available, so we use 1-AU densities as a proxy. This is reasonable because sub-MeV/nuc ions are not very mobile, so they tend to linger in the inner heliosphere following SEP events. Since it takes at least 2.7 hours for a 1.81 MeV/nuc heavy ion to reach 1 AU along the Parker spiral, we have used Fe densities on the day of the eruption if the flare onset is after 2230 UT. In this study we included essentially all 1998-2005 events tabulated in Cane et al. [11] that had >12 MeV/nuc Fe fluences >0.1/cm^{2}sr.

To carry this comparison further, Figure 4 (left panel) plots the daily-average 12-80 MeV/nuc Fe fluences versus the suprathermal densities one day earlier. The pattern is similar to that in Figure 3, suggesting that the pre-existing fluence may limit the maximum fluence the next day. The dotted line was drawn to guide the eye. The only day significantly above this line was 9 November 2000; from the "Election Day" event that originated at W75°. [The other two nearby points are 26 December

2001 (W54°) and September 25, 2001 (E28°)]. In Figure 4 (right panel) the suprathermal densities are from 2 days before the fluence measurements. The pattern is similar. The lone high-intensity day above the line is again 9 November 2000.

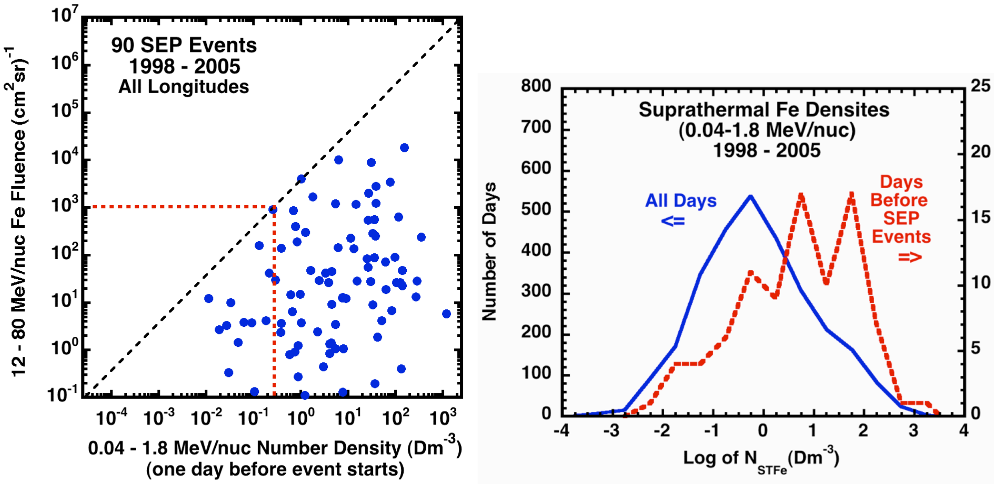

FIGURE 3: (left panel) Plot of the fluence of 12 – 80 MeV/nuc Fe in 90 large SEP events observed during 1998-2005 versus the suprathermal Fe density averaged over the day before the SEP event. The dashed black line is 3333 times the number-density scale. Note that days with high fluences (e.g., $>10^3$ Fe/cm^{2}sr; red dashed line) only occur when the pre-existing density of suprathermal Fe was >0.3 Dm^{-3}. (right panel) Histogram of daily-average suprathermal Fe densities for all days from March 1998 to December 2005 (left scale) compared to a histogram of suprathermal Fe densities on the day before SEP events (right scale).

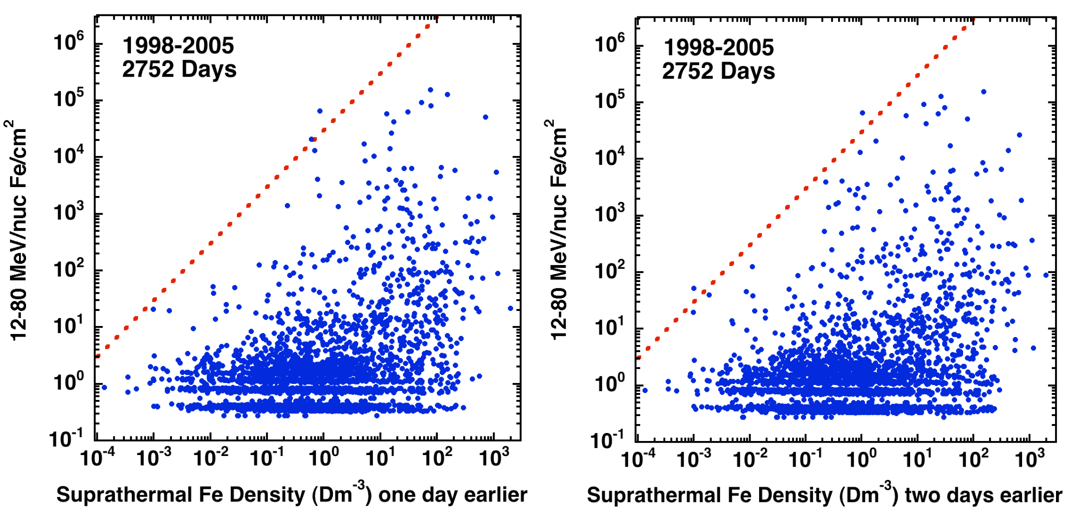

FIGURE 4: (left panel) Daily fluences of 12-80 MeV/nuc Fe measured by ACE/SIS are plotted versus the 0.04-1.81 MeV/nuc suprathermal Fe density measured one day earlier by ACE/ULEIS. The dotted line is 3×10^4 times the suprathermal ion density scale. (right panel) Same as on the left with the SEP Fe fluence from two days later. Note that days with large SEP fluences only occur when there is a large pre-existing pool of interplanetary suprathermal Fe. The only day significantly (2.7 times) above the dotted line in both plots is 8 November 2000. The bands at the bottom are due to small integer numbers of cosmic-ray Fe during the quietest days of solar maximum (9 days with no 12-80 MeV/nuc Fe are not plotted).

We have investigated the origin of points in Figure 4(left panel) with Fe-fluence to suprathermal-density ratios >3000 Dm^3/cm^2 (within 10% of the dotted line). Thirteen of the 17 points with fluences >1000/cm^2 represent the highest daily fluence of that SEP event (not always the first day). In six cases the 2nd or 3rd day of the event had ratios >3000 Dm^3/cm^2, including the 2nd day of the 14 July 2000 event, and the 2nd and 3rd days of the 4 November 2001 event. For such days the suprathermal density that is plotted can contain significant contributions from the early part of the event itself, and not just a pre-existing population.

DISCUSSION

It is reasonable to ask whether SEP ions from earlier small, ^{3}He-rich events and larger CME-shock events will remain in the inner heliosphere long enough to be accelerated by following CME shocks. Simulations by Giacalone et al. [12] showed that a substantial fraction of low-energy ions from ^{3}He-rich events remain inside 0.5 AU a day later. Mewaldt, Mason and Cohen [3] concluded that during solar maximum the largest source of suprathermal ions was from preceding CME-shock events (in the several-day decay-phase of these events ions are observed diffusing towards the Sun [13]). Indeed, following large SEP events a reservoir of energetic ions is often formed in the inner heliosphere that extends over a broad longitude range and lasts for days [14]. The properties of these reservoirs include essentially no radial gradient and a relatively small longitudinal gradient (see [15]). It is this reservoir that feeds the inward diffusion of low-energy energetic ions.

Gopalswamy et al. [15] found that the largest SEP events are usually preceded by an earlier CME from the same active region less than 24 hours earlier. Shock acceleration by this earlier CME can be a ready source of seed particles. In particular, Gloeckler et al. [17] find that suprathermal tails with $f(v) \sim v^{-5}$ distribution functions are essentially always formed in the wake of passing shocks. Finally, ions accelerated by CIR-shocks at ~2-3 AU also diffuse towards the Sun with a radial gradient of ~100 to 200 percent per AU [18-20].

The data in Figure 3 and 4 suggest that the size of an SEP event may be limited by the available pool of suprathermal ions. Two earlier papers [2, 21] considered this possibility and found that the suprathermal Fe density was not sufficient to provide enough Fe ions during solar quiet times for a large SEP event. In other words, if suprathermal seed particles are the main source of seed particles, only low-fluence events can occur during quiet interplanetary conditions.

The results shown in Figures 3 and 4 suggest that suprathermal ion intensities can serve as one of several inputs to forecasting the probability of large SEP events or of all-clear periods. For example, we see in Figure 3 that Fe fluences >10^3 per cm^{2}sr only occurred if the suprathermal Fe density on the preceding day was >0.3 Fe/Dm^3 (see also Figure 4). Of course, one reason this occurs is that SEP events occur in clusters when there is one or more very active regions that result in a series of fast CMEs, X-class flares, and a ready pool of suprathermal ions (e.g., the Halloween 2003 period). However, data like that in Figures 3 and 4 can also be used to generate the probability of a large SEP event as a function of the suprathermal ion density. Such data can also be used to help forecast "all-clear" periods if the suprathermal ion density is low (e.g., <0.1 per Dm^3 in Figure 4.)

SUMMARY AND FUTURE PROPECTS

The above work suggests that near-real-time monitoring of suprathermal ion densities can be one contributing factor in forecasting the probability of large SEP events and of all-clear periods. The next step in this work will be to extend this study to protons, which are generally of greater space weather concern. It is also interesting that with ACE and STEREO we presently have ~360° coverage of suprathermal ion densities – perhaps by combining these three spacecraft, or by choosing the best connected spacecraft, it is possible to provide improved capability to forecast the occurrence of large SEP events.

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