

energy Spectra of Very Large Gradual Solar Particle Events

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Abstract. Energy spectra provide a powerful tool in understanding solar energetic particle (SEP) events, in that spectra contain information on all aspects of SEP production, including source plasma, interplanetary transport effects, and characteristics of the accelerator. We compare energy spectra of two very large gradual events (1998 April 20 and 2000 July 14), produced by shocks driven by fast coronal mass ejections (CMEs). We show that differences in their Fe spectra can be understood in terms of a small, variable admixture of remnant flare suprathermals in the SEP source population.

1 Introduction

The suprathermal tail of the solar wind (SW) is generally believed to comprise the source population of gradual SEP events. On the basis of measured $^3\text{He}/^4\text{He}$ on the order of a few percent in some gradual SEP events, Mason *et al.* (1999) suggested that, at least at some times, the SW suprathermals could be augmented by suprathermals from impulsive SEP events. These suprathermals would have been originally accelerated at a flare site, and hence bear distinctive compositional and charge-state characteristics. Since suprathermal particles take several days to move through the inner heliosphere, they constitute a remnant population, replenished nearly continuously by flare activity. A shock would then accelerate particles from both solar-wind and flare suprathermals in a more or less democratic fashion. Other studies have further bolstered the remnant-flare hypothesis (Richardson *et al.* 1993; Desai *et al.* 2001).

The connection between spectra and source population manifests itself at high energies: as energy and gyroradius increase, it becomes less probable that a particle can be contained within the shock region. Ellison & Ramaty (1985) suggested that this escape would cause the spectra of shock-accelerated particles to roll over more or less exponentially,

with e-folding energy directly proportional to the ion's charge to mass (Q/A) ratio. Thus, SEP ionic charge states can be inferred by comparing spectra of various elements, as first demonstrated by Tylka *et al.* (2000).

The two events considered here (1998 April 20 and 2000 July 14) were both produced by very fast CMEs, with initial speeds of ~ 1600 km/s and ~ 1800 km/s, respectively. In both events the associated flares were at heliolongitudes far from the footpoint of the Sun-Earth magnetic field line (W90 and W07, respectively). It is thus unlikely that in either case we saw particles *directly* accelerated in the flare. For the same reason, both events are also probably free of complications caused by concurrent acceleration and ion-stripping in the low corona, which affected the well-connected (W63) event of 1997 November 6 (Reames *et al.* 1999; Barghouty & Mewaldt 1999, 2000; Stovpyuk & Ostryakov 2001).

A major difference between these two events is the level of preceding solar activity. The 1998 April 20 SEP event marked the end of a period of very low solar activity, with no C-, M-, or X-class x-ray flares in the preceding 4 days. The 2000 July 14 event, on the other hand, followed an extended period of very high flare activity, with 40 x-ray flares (2 X, 17 M, 21 C) in the preceding four days.

2 Observations

Fig. 1 shows sample heavy-ion spectra in the 2000 July 14 (Bastille Day) event from two intervals covering 6–14 and 22–26 hours after the flare (Tylka *et al.* 2001). The spectra clearly evolve, with e-folding energies decreasing with time (Tylka *et al.* 2000), as generally expected as a fast CME-driven shock moves outward from the Sun (Zank *et al.* 2000).

Reames, Ng, & Tylka (2001) also examined the time intervals in Fig. 1, using only *Wind/LEMT* data at $\sim 4\text{--}20$ MeV/nuc. The dashed curves are their exponential fits. These fits show that Fe has smaller e-folding energies than other species, corresponding to lower Q/A , at least at LEMT energies. In fact, Reames *et al.* (2001) assumed e-folding energies to

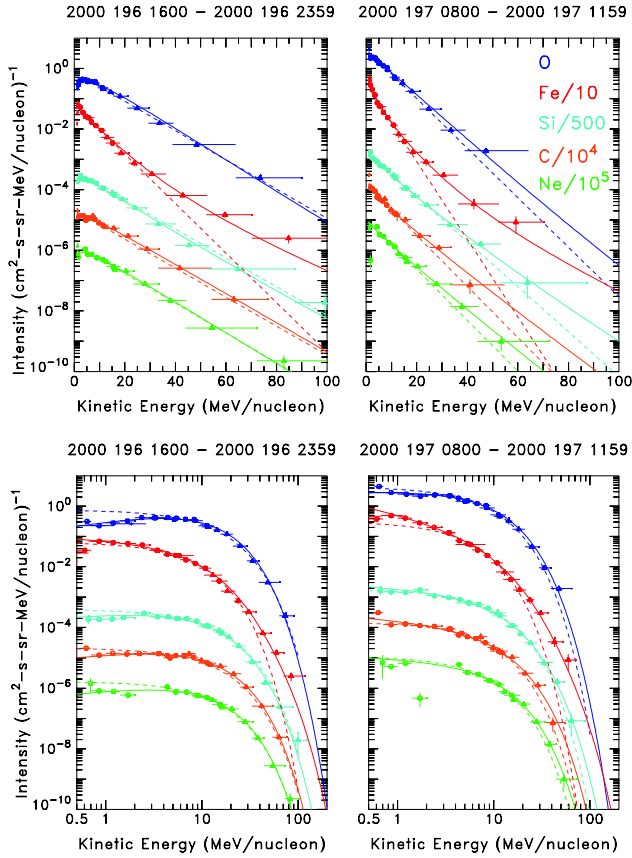


Fig. 1. (from Tylka *et al.* 2001): Heavy-ion spectra in the 2000 July 14 (DOY 196) event in two time intervals. Top row shows log-linear plots, while bottom shows the same spectra in log-log plots. Data come from *Wind*/LEMT (von Rosenvinge *et al.* 1995; filled circles), *ACE*/EPAM (Gold *et al.* 1998; half-filled circles), and *ACE*/SIS (Stone *et al.* 1998; filled triangles). Modest adjustments (less than a factor of two) have been used to remove normalization discrepancies, without altering the spectral shape reported by any instrument. Dashed curves are exponential fits to LEMT only (Reames *et al.* 2001). Solid curves are model fits, as described in the text.

be directly proportional to Q/A and that the e-folding energy of carbon corresponded to $\langle Q_C \rangle = 5.5$, a typical value in gradual events and the solar wind. From ratios of fitted e-folding energies, they then derived reasonable mean ionic charge states for other species, including $\langle Q_{Fe} \rangle \sim 10$. This value agrees with measurements from SEPICA (Möbius *et al.* 1998) on *ACE* (Smith *et al.* 2001).

Except for Fe, these LEMT exponentials account reasonably well for higher-energy data from SIS. However, Fe spectra above ~ 20 MeV/nuc are nearly power laws. Similar spectral differences between Fe and lighter species have been previously noted at high energies in large SEP events in earlier solar cycles (Tylka and Dietrich 1999). Also, although the spectra soften as time increases, the unique character of Fe persists long into the event. This is another indication that the high-energy Fe cannot be attributed to a direct flare origin.

Fig. 2 shows comparable spectra for the 1998 April 20 event. Unlike in the Bastille Day event, the Fe spectrum here

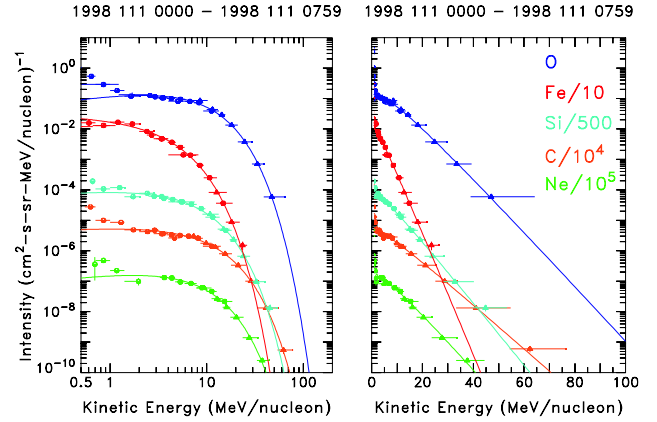


Fig. 2. Sample heavy-ion spectra from the 1998 April 20 (DOY 110) event, as in Fig. 1. (Additional intervals are shown in Tylka 2001.) Left panel is log-log; right panel is log-linear. Curves are fits consistent with a pure SW source population, without remnant-flare suprathermals.

does not harden with increasing energy. Instead, it falls much more steeply than the others throughout the observed energy range. Tylka *et al.* (2000) used the fitted e-folding energies in this event to infer mean ionic charge states. These values were similar to slow solar wind (von Steiger & Schwadron 1998) and in excellent agreement with SEPICA measurements at ~ 0.3 MeV/nuc (Klecker *et al.* 1999), implying virtually no energy dependence in charge states in this event.

3 Modeling

For the spectra in Figure 1, we consider a two-component source, with 95% of the Fe ions coming from solar wind suprathermals and 5% from flare suprathermals. To specify the SW component, we used the in-ecliptic, slow solar-wind Q_{Fe} distribution from *Ulysses* (von Steiger & Schwadron 1998). This distribution extends from $Q_{Fe} = 6$ to $Q_{Fe} = 16$, with mean $\langle Q_{Fe} \rangle \sim 10$ and rms width ~ 2 . For the flare suprathermals, we used the Q_{Fe} distribution observed in a typical impulsive SEP event by SEPICA (Mewaldt 1999). This distribution has $\langle Q_{Fe} \rangle \sim 17$ and rms width ~ 4 . With this 5% flare component, 3% of the resulting Fe-ion source population have $Q_{Fe} > 16$ and less than 0.5% have $Q_{Fe} > 22$. Note that a flare component much larger than 5% is excluded by $\langle Q_{Fe} \rangle \sim 10$ from SEPICA in the Bastille Day event.

To model the Fe spectra, we first fit the spectra below 20 MeV/nuc, using the full Ellison-Ramaty (1985) form of $F(E) \sim E^{-\gamma} \exp(-E/E_0)$. We then assumed that the e-folding energy (E_0) derived from the < 20 MeV/nuc data corresponds to $\langle Q_{Fe} \rangle = 10$. The e-folding energies of other Fe ions were then scaled from this value, proportionally to Q_{Fe} . The contribution of each charge state to the spectrum was weighted by its fraction in the two-component mixture. Solid curves in Fig. 1 show the results of this superposition.

This small admixture of remnant-flare suprathermals does remarkably well in accounting for the additional high-energy

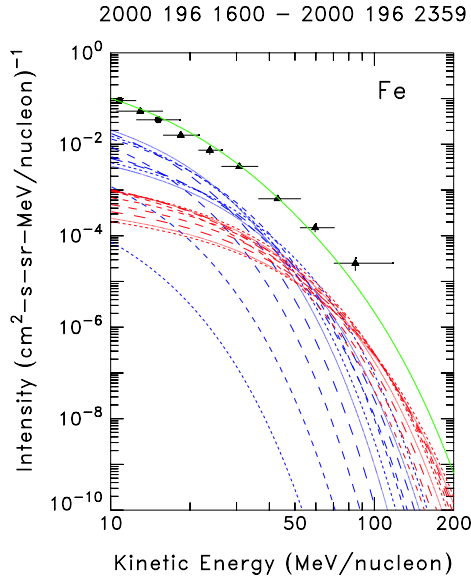


Fig. 3. (from Tylka *et al.* 2001): Contributions of various charge states to the Fe spectrum. Blue curves are $Q_{Fe} = 6-16$ that arise primarily from the SW component; red curves are $Q_{Fe} > 16$, from the remnant flare-suprathermals. The green curve is the sum.

Fe. Agreement could be further improved by massaging the assumed flare- Q_{Fe} distribution. For example, the slight deficit in the highest-energy Fe can be removed by increasing the proportion of ions with $Q_{Fe} > 22$. A larger fraction of very highly-ionized Fe ions may not be unreasonable: the assumed flare- Q_{Fe} distribution came from a C1.0 x-ray flare, whereas the Bastille Day event was preceded by much larger flares.

We similarly modeled other species' spectra, using SW Q distributions (von Steiger & Schwadron 1998) and assuming the flare-component to be fully ionized. However, in that impulsive SEP events are Fe-rich (Reames 1995), the assumed flare component for other species was smaller ($\sim 1.8\%$ for Si and Ne, $\sim 0.6\%$ for O and C.) As shown by the solid curves in Figure 1, these refinements had little impact.

4 Other Implications

Fig. 3 illustrates how various Fe charge states contribute to the overall spectrum in the Bastille Day event. Solar-wind charge states dominate at low energies. The remnant-flare component becomes more important as energy increases. This modeling implies energy dependence in the mean Fe charge state, which is shown by the solid curve in Fig. 4. This curve is consistent with measured $\langle Q_{Fe} \rangle$ values from SEPICA (Smith *et al.* 2001) and SAMPEX (Leske *et al.* 2001) for the Bastille Day event.

For comparison, Fig. 4 also shows observed $\langle Q_{Fe} \rangle$ for the 1992 November (Leske *et al.* 1995; Mason *et al.* 1995; Oetliker *et al.* 1997) and 1997 November (Mazur *et al.* 1999) events. The 1992 event shows energy dependence remarkably similar to that derived here for the Bastille Day event.

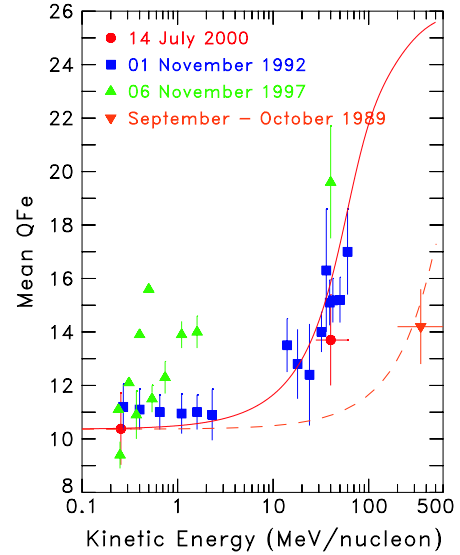


Fig. 4. (from Tylka *et al.* 2001): Energy dependence of the mean ionic charge state of Fe. Solid curve is evaluated from the spectra in Fig. 3. Dashed curve is calculated with the same source mixture but subjected to a shock with e-folding energies an order of magnitude larger. Measurements are from various sources, as noted in the text.

The 1997 November 6 event, on the other hand, exhibits stronger energy dependence, particularly below 2 MeV/nuc, which cannot be re-produced by the two-component model discussed here. The 1997 November 6 event has been explained as concurrent shock acceleration and stripping in the low corona (Reames *et al.* 1999; Barghouty & Mewaldt 1999, 2000; Stovskyuk & Ostryakov 2001).

The solid curve in Fig. 4 might suggest that high-energy solar Fe ions must always be nearly fully-stripped. This impression would be incorrect. The dashed curve in Fig. 4 shows another calculation, again using the same source mixture but subjected to a shock with e-folding energies an order of magnitude larger. The 1989 September 29 event is an example of such a shock: proton e-folding energies were greater than 500 MeV (Lovell *et al.* 1998), and Fe ions were observed up to nearly 1 GeV/nuc (Tylka & Dietrich 1999). In this and the other very large events of 1989, Tylka *et al.* (1995) measured $\langle Q_{Fe} \rangle \sim 14$ at 200–600 MeV/nuc.

Figs. 1 and 2 clearly indicate energy-dependent abundance ratios. Fig. 5 shows the Fe/C ratio vs. energy. The enhanced Fe/C below ~ 10 MeV/nuc in both events is probably caused by Q/A -dependent transport (Ng *et al.* 1999, 2001). The increase in Fe/C above ~ 30 MeV/nuc in the Bastille Day event appears to be due to the remnant flare-suprathermal component. Fine-tuning the assumed flare- Q_{Fe} distribution can improve the curve's agreement with data. The statistical significance of this increase is modest here. However, very similar, complicated energy-dependent Fe/O ratios have been previously noted in other large SEP events (Tylka & Dietrich 1999). Remnant flare suprathermals may also account for reported association between Fe enhancements above ~ 40

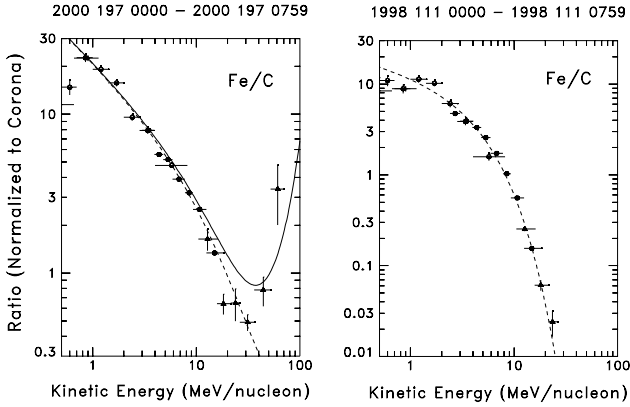


Fig. 5. Fe/C vs. energy in the 2000 July 14 and 1998 April 20 events, normalized to coronal value of 0.288 (Reames 1995). Dashed curves are calculations using SW-component Fe only; solid curves also include flare suprathermals. Note the different y-axis scales.

MeV/nuc and ground-level neutron-monitor events (Dietrich & Lopate 1999), which almost always occur during periods of high flare activity.

5 Discussion and Summary

The foregoing analysis assumed that e-folding energies are directly proportional to Q/A . This assumption can be checked with H and He (Tylka *et al.* 2000). For a variety of reasons, H and He data in the Bastille Day event are limited and of poor quality. Nevertheless, as a consistency check, Fig. 6 compares H and He data to exponentials, with e-folding energy scaled by Q/A from that of carbon in Fig. 1, again assuming $<Q_C>=5.5$. The comparison appears reasonable.

The observations and modeling discussed here touch upon several previously unexplained features of Fe spectra in large SEP events: (1) spectral hardness of Fe relative to other species at high energies; (2) energy-dependent Fe charge states at high energies; and (3) enhanced Fe/C (and Fe/O) at high energies. These effects have sometimes been interpreted as evidence for flare-accelerated particles becoming dominant over shock-accelerated particles at high energies.

However, we have shown that these effects are natural consequences of shock acceleration acting upon a source population containing a small admixture of remnant flare suprathermals. Preceding flare activity thus plays a highly significant role in generating SEP event-to-event variability.

The conditions at the accelerator are apparently quite different in some events, such as 1997 November 6. Nevertheless, this analysis strongly suggests that the hypothesis of remnant flare suprathermals may make it possible to understand a large body of SEP heavy-ion data, extending to at least several hundred MeV/nuc, in terms of CME-driven shocks, without appeal to other acceleration mechanisms.

Acknowledgements. NOAA provided flare and GOES proton data. AJT was supported by the ACE Guest Investigator Program (NASA

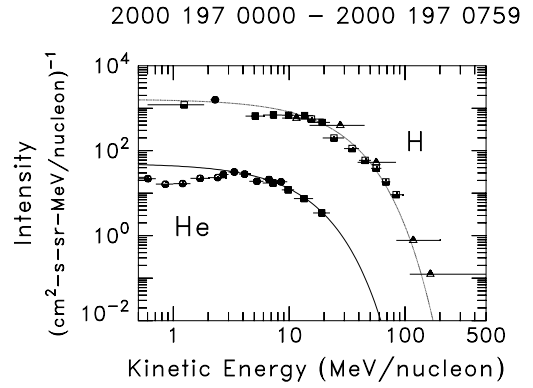


Fig. 6. (from Tylka *et al.* 2001): H and He in the Bastille Day event from GOES (half-filled triangles, H only), Wind/LEMT (filled circles), IMP8/GME (filled squares), IMP8/CRNC (half-filled squares, H only), and ACE/EPAM (half-filled circles, He only). Curves are exponentials, with e-folding energies scaled from that of carbon in Fig. 1, as described in the text.

DPR W19,501), ISTP Solar Max Extended Science Program (NASA DPR S92662F), and the Office of Naval Research. WFD was supported by the SEC Guest Investigator Program (NASA DPR 19,493).

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