Two components in major solar particle events

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Received 8 November 2002; revised 31 January 2003; accepted 6 February 2003; published 24 May 2003.

[1] A study has been made of 29 intense, solar particle events observed in the energy range 25–80 MeV/nuc near Earth in the years 1997 through 2001. It is found that the majority of the events (19/29) had Fe/O ratios that were reasonably constant with time and energy, and with values above coronal. These all originated on the Sun's western hemisphere and most had intensities that rose rapidly at the time of an associated flare (and coronal mass ejection). Interplanetary shocks observed near Earth had little effect on particle intensities during these events. The remaining 10 events had different intensity-time profiles and Fe/O ratios that varied with time and energy with event-averaged values at or below coronal. Most of these originated near central meridian and 6 had strong interplanetary shocks that were observed near Earth. There were four events with two peaks in the intensity-time profiles, the first near the time of the associated flare (with high Fe/O) and the other at shock passage (with a lower Fe/O) suggesting that solar particle events have two components. At high rigidities the first component (probably flare generated) usually dominates and interplanetary shock-accelerated particles (forming the second component) make a minor contribution except in the case of unusually fast shocks. *INDEX TERMS:* 7514 Solar Physics, Astrophysics, and Astronomy: Energetic particles (2114); 7519 Solar Physics, Astrophysics, and Astronomy: Flares; 2139 Interplanetary Physics: Interplanetary shocks. **Citation:** Cane, H. V., T. T. von Rosenvinge, C. M. S. Cohen, and R. A. Mewaldt, Two components in major solar particle events, *Geophys. Res. Lett.*, *30*(12), 8017, doi:10.1029/2002GL016580, 2003.

1. Introduction

[2] In recent years there has been much debate about the relationship between flares and coronal mass ejections (CMEs). In the solar energetic particle (SEP) community a key problem has been to determine whether there are 'flare particles' in the largest particle events. Such particle events always occur in association with large, fast CMEs that drive shocks capable of accelerating any particles they encounter. However, the fastest CMEs are also well-associated with flares and flares are known to accelerate particles. Thus the question is whether there are two source populations in major events and whether they can be separated. In space, electrons and ions are unambiguously detected in association with some short duration flares. The enhancements in heavy ions, high electron to proton ratio, unusually high $^3He/^4He$, and charge states of Fe >+16 (indicating a source plasma of some 10 MK) identify the particles as 'flare particles'. It seems likely that flare particles are accelerated by stochastic processes involving resonant wave-particle interactions. The enhancement of Fe has a natural explanation in terms of the production of long wavelength turbulence that resonates first with Fe ions, with large gyro radii, and then cascades to shorter wavelengths to resonate with lighter ions [*Reames*, 1999]. The enhancement of ^3He also arises from resonant wave processes. However, the heavy ion enhancements are not correlated with the ^3He to ^4He ratio [*Reames*, 1999] and the lower limit to $^3He/^4He$ in flare events has not yet been determined.

[3] In the current paradigm [e.g., *Reames*, 1999] there are no flare particles in major particle events because it is believed that the particle abundances and charge states are more typical of the ambient corona. *Reames* [1998] added together all the particles counted in 49 large solar particle increases in the range 5–12 MeV/nuc and found an Fe/O ratio of 0.134. (This value is now commonly taken as the reference for coronal Fe/O.) In contrast, *Reames* [1999] found higher ratios (0.3–5) in flare ("impulsive") particle events. It is important to note that the *Reames* [1998] observations were made at energies below ~20 MeV/nuc where the largest particle events are those in which the intensities are dominated by interplanetary shock accelerated particles [*Cane et al.*, 1988]. Thus the agreement of the *Reames* [1998] Fe/O value with that of the solar wind is not surprising. Considering charge states, the belief that large SEP events have a mean Fe charge state well below that for flare particles was based on 0.3–1 MeV/nuc observations from the 1980's also dominated by interplanetary shock accelerated particles. More recent SAMPEX measurements at 28–65 MeV/nuc, [*Leske et al.*, 2001], have found that events dominated by particles accelerated near the Sun, and therefore possibly in flares, have high charge states (Fe ~+20).

[4] Another argument against a flare particle component in major particle events is the belief that all flare particles produced at the time of a major CME are trapped on closed field lines and cannot escape to the interplanetary medium [*Reames*, 2002]. Recently *Cane et al.* [2002] [see, also *Cane and Erickson*, 2003] have shown that this is incorrect. They found that major SEP events are accompanied by low frequency (<1 MHz), long lasting radio bursts generated by flare electrons as they propagate away from the Sun. The existence of type III radio emission (in which the emission

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Table 1. High Energy SEP Events in 1997–2001

Onset Time[a]	Flare Xray. Peak	Flare Long.	Group	Fe/O[b]	Speed[c] (km/s)
1997					
Nov. 04 0600	X2	W33	1	3.1	640
Nov. 06 1200	X9	W63	1	6.4	500
1998					
April 20 1000	M1	W90	2	0.03	520
May 02 1400	X1	W15	1	5.2	1120
May 06 0800	X3	W65	1	3.6	. . .
May 09 0330	M8	W100	1	3.0	. . .
Aug. 24 2230	X1	E09	3	0.9	1260
Sept. 30 1330	M3	W85	1	2.0	1010
Nov. 14 0500	. . .	W120	1	5.0	. . .
1999					
June 01 1900	. . .	W120	1	4.9	. . .
June 04 0700	M4	W69	1	2.9	. . .
2000					
June 10 1700	M5	W40	1	5.9	780
July 14 1030	X6	W07	3	0.6	1600
Sept. 12 1200	M1	W09	1	3.1	640
Oct. 16 0700	M2	W95	1	4.9	. . .
Nov. 08 2300	M7	W75	. . .	0.05	?
Nov. 24 1500	X2	W07	1	2.6	?
Nov. 25 0100	M8	E50	2	0.8	1000
2001					
Jan. 28 1600	M2	W59	1	4.5	630
Mar. 29 1000	X2	W12	1	3.3	690
April 02 2200	X20	W78	1	2.3	1020
April 10 0500	X2	W09	2	0.9	1220
April 15 1400	X14	W84	1	5.8	700
April 18 0230	C2	W120	1	3.3	. . .
Aug. 16 0000	. . .	W140?	. . .	0.9	. . .
Sept. 24 1030	X3	E23	2	0.1	1220
Nov. 04 1630	X1	W18	3	0.4	1240
Nov. 22 2300	X1	W34	3	0.4	1300
Dec. 26 0530	M7	W54	1	4.9	570

[a]Type III start time to nearest 30 mins.
[b]Event average at 25–80 MeV/nuc (relative to coronal).
[c]Transit speed of associated shock to Earth. "…" indicates no shock at Earth. "?" indicates shocks seen but indefinite association.

frequency is determined by the ambient electron density) at frequencies less than a few MHz proves that there must be open field lines from beneath CMEs. In the present paper, using Fe and O data at energies above 25 MeV/nuc, it is found that most major particle events have enhanced Fe/O [see, also *Cohen et al.*, 1999; *von Rosenvinge et al.*, 2001]. Those events or periods during an event when the Fe/O ratio was not enhanced occurred when there was interplanetary shock acceleration usually evidenced by low energy particles peaking at the passages of shocks. These observations suggest the presence of flare particles (characterized by high Fe/O) in major events and that flare particles make the dominant contribution at high energies except in the presence of very strong interplanetary shocks.

2. The Observations

[5] Intensity profiles for O and Fe in the range ~10–100 MeV/nuc have been examined for 29 high energy events in the period 1997–2001. The SEP events considered were those with an Fe intensity at ~25 MeV/nuc above 3×10^{-6} particles/(cm^2-ster-sec-MeV/nuc). The data were obtained from the SIS experiment on ACE [*Stone et al.*, 1998]. Table 1 provides a list of the events and their characteristics. Evidence of strong interplanetary shocks has been obtained by examining data from the WAVES experiment on Wind. These data are available from the internet site (http://lep694.gsfc.nasa.gov/waves/waves.html) maintained by M. L. Kaiser. *Cane* [1985] found that shocks with high transit speeds produce "IP type II events" in which broadband emission is seen during the time that these shocks travel from the Sun to the Earth.

[6] The SEP events can be divided into 3 groups. Figure 1 shows Fe and O intensity profiles at three energies for an event from each of the three groups. The first group had intensity profiles that rose rapidly and then decayed more slowly. The example shown in Figure 1a, on December 26, 2001, was associated with an M7 flare at 08°N 54°W. At the two lower energies Fe/O was about 0.5, meaning that it was enhanced over the coronal value by a factor of about 4. From the profiles it can be seen that the ratio did not change significantly after the first few hours of the event. Earlier in the event, because of propagation effects, Fe reaches peak intensity before O. Such effects do not influence the event integrated abundances. The mean enhancement of Fe/O above coronal for all similar events (19 in total) in the energy range 25–80 MeV/nuc was 3.8 ± 0.3. The mean longitude of the flares associated with the 14 on-disk events was 48°W; the remaining events originated beyond W90° [*Cane et al.*, 2002]. No shocks passed near Earth during the period illustrated in Figure 1a. In 7 of the 19 events, a shock passed Earth within 48 hours of the flare (implying a transit speed >860 km/s) but in all but one case the Fe intensities at >25 MeV/nuc had already decayed to background levels at the time of shock passage.

[7] The second group of events are exemplified by the event of September 24, 2001 that was associated with an X3 flare at ~1000 UT and 16°S 23°E. The profiles were more rounded than those in the first group of events and reached maximum intensities about 24 hours after the flare. These particles were clearly related to the strong shock that passed at ~2000 UT on September 25 as may be seen in Figure 1b. At 30 MeV/nuc the Fe profile reached a peak value that was two orders of magnitude below that of O corresponding to Fe/O relative to coronal of 0.09. At the highest energy, little Fe was detected, meaning that the event-averaged spectrum steepened at high energies. Similar events occurred on April 20, 1998, November 25, 2000, and April 10, 2001. The associated flares occurred at 90°W, 50°E, and 9°W, respectively. For both the November 2000 and April 2001 events, shocks passed Earth near the time of peak intensity. The event of April 20, 1998 was very unusual because it originated near the west limb of the Sun but did not have a profile typical for events from this location.

[8] The November 4, 2001 event (associated with an X1 flare at 6°N 18°W) typifies the four events in the third grouping. The profiles are basically a combination of those of the previous two groupings i.e. an Fe-rich component at the time of the flare and later, a shock-associated component with a lower Fe/O ratio. The other events occurred on August 24, 1998, July 14, 2000, and November 22, 2001 and were associated with flares at 9°E, 7°W, and 34°W, respectively. There were fast shocks seen at Earth less than 36 hours after all four flares. For the August 1998 and July 2000 events the first component was dominant above ~50 MeV/nuc in Fe whereas the shock component was dominant for the November 22, 2001 event. These events all origi-

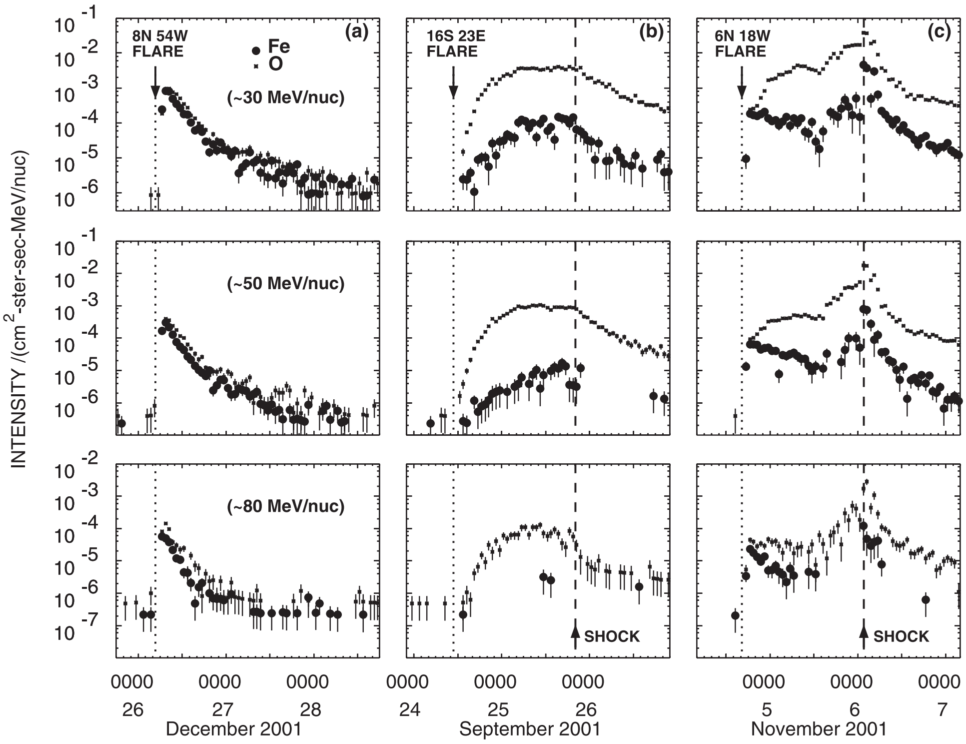

Figure 1. Three-day plots of Fe (filled circles) and O (asterisks) intensities (1 hour averages) at ~30 MeV/nuc (upper panels), ~50 MeV/nuc (middle panels), and 80 MeV/nuc (lower panels) showing examples of the three groups of events at these energies, differentiated by their intensity-time profiles. The vertical dotted lines indicate the times of the flares and the dashed lines indicate the times of shock passages. The periods illustrated start at (a) 1800 UT December 25, 2001, (b) 2200 UT September 23, 2001, and (c) 0400 UT November 4, 2001.

nated near central meridian so that the strongest part of the shocks propagated towards Earth.

[9] There were two events that did not fit into any group. These occurred on November 8, 2000 and August 15, 2001. It is likely that the November 8, 2000 event was affected by the occurrence of another major solar event on November 9 as evidenced by radio observations. The November 8 event was very intense at low energies but no Fe was detected above ~50 MeV/nuc. The event of August 16, 2001 originated behind the west limb of the Sun, possibly as distant as 140°W. The profiles were like those of the first group but Fe/O was slightly below coronal. A relatively fast shock passed Earth on August 17 (unrelated to the solar event responsible for the SEP event) causing an enhancement in the O intensities above 40 MeV/nuc. Thus, in both events, Fe/O was probably influenced by additional shock acceleration.

[10] As a further illustration of the influence of interplanetary shock acceleration on relative abundances, Figure 2 shows event-averaged Fe/O as a function of shock transit speed to 1AU for those events where the shock passed the spacecraft. For the two-component events Fe/O ratios at the beginning of the events are higher than the values shown. It is clear that Fe tends to be enhanced in events where the shock speed is lower and there are no interplanetary shock-accelerated particles.

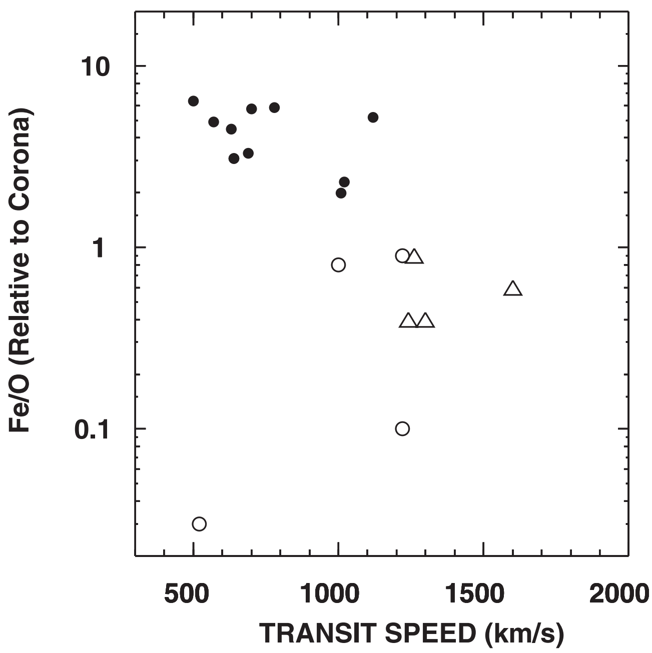

Figure 2. Event-averaged Fe/O at 25–80 MeV/nuc as a function of shock transit speed (filled circles- events like that in Figure 1a, open circles–events like that in Figure 1b, open triangles–events like that in Figure 1c). The peculiar event of April 20, 1998 is in the lower left corner of the plot.

3. Discussion and Conclusions

[11] The events of the first group were the most common and had Fe/O above coronal. Since this was true throughout

the several days duration of the events it is hard to explain this in terms of any transport effect [e.g., *Reames et al.*, 2000], which should only affect the earliest particles. It has also been suggested that enrichments in ^{3}He (and Fe) in large events could result from shock acceleration of remnant suprathermal particles in the interplanetary medium from previous small flares [*Mason et al.*, 1999]. However, since it has now been shown that flare particles escape directly in all SEP events [*Cane et al.*, 2002], we see no need to invoke a population from earlier, smaller flares. Furthermore it is hard to understand how shock acceleration could cause a long-lasting enhancement of Fe since Fe ions are the least likely ions to resonate with the proton-generated, relatively short wavelength, waves that scatter particles back to the shock during the acceleration process. This is the opposite situation to that in flares where the initial waves are likely to have long wavelengths. Thus it seems reasonable that enhanced Fe/O can be used to identify flare particles and that reduced Fe/O can be used as an identifier for strong shock acceleration. Indeed *Cane et al.* [1990] found that periods of low Fe/O at 2–3 MeV/nuc usually occurred when strong shocks were passing the spacecraft. Note that shock acceleration of an Fe-rich seed population can, under some conditions, produce a population with a high Fe/O ratio. At low energies an equilibrium situation, in which spectral shapes are maintained, may be reached in the time it takes a shock to travel from the Sun to 1 AU leading to shock populations with high Fe/O [e.g., *Tan et al.*, 1989]. At high energies it is likely that some re-acceleration of the flare particles may occur close to the Sun.

[12] As mentioned above, a high ^{3}He/^{4}He ratio is a robust signature of flare particles. A lower limit for flare particles has not been established, but there are clear flare events (electron-rich, associated with flares and Type III bursts) that have ^{3}He/^{4}He < 0.01. The solar wind value is $\sim 5 \times 10^{-4}$ so measurements of small enhancements are difficult. There are ^{3}He/^{4}He data from SIS at 7–14 MeV/nuc for 18 Group 1 events and 7 Group 2 and 3 events. (see examples in *Cohen et al.* [1999] and *Wiedenbeck et al.* [2000]). We find finite ^{3}He/^{4}He ratios ranging from 0.002 to 0.03 in 12 of the 18 Group 1 events and upper limits for the other six. However, for the seven Group 2 and Group 3 events there are only limits to the 3He/4He ratio ranging from <0.004 to <0.012. Thus, the available high-energy 3He data are consistent with the proposal that flare particles are being observed in Group 1 events, while shock-accelerated particles dominate Group 2 and Group 3 events.

[13] Shock speed is clearly important in determining the presence of a shock-associated component at high energies. The mean transit speeds for the four shocks in the two component events was 1350 km/s and for the three "rounded" events with shocks the mean speed was 1150 km/s. All but one of these 7 shocks produced strong broadband radio emission in the interplanetary medium. Such high speed interplanetary shocks are uncommon, with less than 10 occurrences per solar cycle [*Cane*, 1985]. Particle events associated with fast shocks have the highest intensities below about 20 MeV/nuc and the steepest spectra [*Cane et al.*, 1988]. Because the high energy end of the spectra steepen at a lower energy for Fe than for O (presumably because of rigidity-dependent effects) the Fe/O ratio decreases rapidly with increasing energy.

[14] In conclusion, the observations above 25 MeV/nuc are consistent with a population of flare particles in most major solar particle events. Given that the abundances are organized by the longitude of the flare [*Cane et al.*, 1991; *von Rosenvinge et al.*, 2001] it is likely that those events without a first, Fe-rich, component (i.e. events like those in Group 2) would have one if sampled at an appropriate location.

[15] **Acknowledgments.** This research was partially supported by NASA under grant NAG5-6912. HVC was partially funded by a NASA contract with USRA.

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