Two components in major solar particle events

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Abstract. A study has been made of 29 intense, solar particle events observed in the energy range 25–100 MeV/nuc near Earth in the years 1997 through 2001. It is found that the majority of the events (19/29) had Fe to O ratios which 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 (CME), and then decayed more gradually. Few interplanetary shocks were observed during these increases. The spectra were mainly power laws. The remaining 10 events had different intensity–time profiles and Fe to O ratios that varied with time and energy with values at or below coronal. Most of these originated near central meridian and 6 had strong interplanetary shocks that were observed near Earth. In general the spectra were not power laws but steepened at high energies, particularly for Fe. There were four events with two peaks in the intensity–time profiles, the first near the time of the associated flare and the other at shock passage. The results, considered in the light of other recent work, suggest that the high energy particles that occur shortly after flares are indeed flare particles. At the highest rigidities considered here shock–accelerated particles are uncommon and are observed only in association with unusually fast shocks.

1. Introduction

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 the 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, in particular, the ambient coronal and solar wind material. 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 ^{3}He/^{4}He, 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 ^{3}He also arises from resonant wave processes. Note, however, that heavy ion enhancements are not correlated with the ^{3}He to ^{4}He ratio [*Reames*, 1999] and that, to date, the lower limit to ^{3}He/^{4}He in flare events has not been determined.

In the current paradigm as espoused by Reames [1999] there are no flare particles in major particle events because it is claimed 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 a 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 particle events. However it is important to note that the *Reames* [1998] observations were made at energies below ~20 MeV 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 cornerstone for the argument that large SEP events have a mean Fe charge state well below that for flare particles are the ISEE-3 observations of *Luhn et al* [1985] for a period in September 1978. These observations (at energies of 0.3–1 MeV/nuc) were also dominated by interplanetary shock accelerated particles. Nevertheless the *Luhn et al.* [1985] value of +14 is above the mean value of +11 for the slow solar wind [*Lepri et al.*, 2001]. More recent measurements at 28-65 MeV/nuc from SAMPEX have found some increases with relatively high charge states (Fe ~+20) and others with ones closer to coronal/solar wind values [*Leske et al.*, 2001]. Clearly the role of flare acceleration requires further investigation and in particular at higher energies where interplanetary shock acceleration is less efficient.

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] have shown that this is incorrect. They found that major SEP events are accompanied by long lasting radio bursts (that they call type III-*l*) generated by flare electrons as they propagate away from the Sun. This proves that there must be open field lines from beneath CMEs. In a separate paper *Cane and Erickson* [2002] show that these flare particles can reach observers over an extensive longitude range. 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. Those events or periods during an event when the Fe to O ratio was not enhanced relative to values for the solar wind 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

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 $3\text{x}10^{-6}$ particles/(cm^2-ster-sec-MeV/nuc). The data were obtained from the SIS experiment on ACE [*Stone et al.*, 1998]. The presence of shocks was determined from geomagnetic storm sudden commencements (SCs) and from the list prepared by *Berdichevsky et al.* (D. B. Berdichevsky, private communication, 2002). Solar wind plasma and field data available from NSSDC were also examined. Further evidence of strong interplanetary shocks has been obtained by examining data from the WAVES experiment on Wind. These data are available at NSSDC and on 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 broad-band emission is seen during the time that these shocks travel from the Sun to the Earth.

The events can be divided into 3 groups which have similar properties. Figure 1 shows Fe and O intensity profiles (one-hour averages) at three energies (~30, ~ 50, and ~80 Mev/nuc) 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 coronal 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. To determine a value for Fe/O that is not influenced by propagation therefore, observations following the O peak must be considered. Thus, the mean enhancement of Fe/O above coronal for all similar events (19 in total) at 30 MeV/nuc was 3.6±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 i.e. within approximately 60 hours after the flare. In 7 of the 19 events, a shock did pass Earth within 48 hours of the flare 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.

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. There was no shock at Earth within three days of the solar event. The shock that passed Earth on April 23 may have been corotating.

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. a component at the time of the flare and later, a shock–associated component. 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 originated near central meridian so that the strongest part of the shocks propagated towards Earth.

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 2001 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 about 50 MeV/nuc. The event of August 16 2001 originated behind the west limb of the Sun, probably 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.

As a further illustration of the influence of interplanetary shock acceleration on relative abundances Figure 2 shows Fe/O at ~30 MeV/nuc as a function of shock transit speed to 1AU for those events where the shock passed the spacecraft. The symbols differentiate events in the different groupings; filled circles for the first group, open circles for the second, and open squares for the two component events. For the two component events Fe/O near shock passage is shown. It is clear that Fe tends to be enhanced in those events where the shock speed is lower, in which case shock acceleration should be less efficient.

3. Discussion and Conclusions

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 for this two-stage process to explain the observed enrichment of flare material in major SEP events. Furthermore it is hard to understand how shock acceleration of ambient coronal/solar wind material 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 usually occurred when strong shocks were passing the spacecraft. That the events with high Fe/O originate in the western hemisphere (see also *von Rosenvinge et al.*, [2000]) is consistent with the fact that shocks from such regions usually do not reach the Earth or are relatively slow [*Cane*, 1988].

As mentioned in the Introduction, a high ^{3}He/^{4}He ratio is a robust signature of flare particles. However a lower limit for flare particles has not been established mainly because previous instruments could not measure values <0.1. The solar wind value is $\sim 5\times 10^{-4}$ so those flare events with ^{3}He/^{4}He ~ 1 are very ^{3}He–rich. However there are clear flare events (electron–rich, associated with short duration flares and with type III radio bursts) that have ^{3}He/^{4}He<0.01. We have not made a systematic determination of ^{3}He/^{4}He but note that all of the events in our first group in the period 1997-1999 had reported values in the range 2×10^{-3} - 6×10^{-2} at various energies [e.g. *Cohen et al.*, 1999; *Mason et al.*, 2002] i.e. enhanced above the value in the solar wind.

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 broad–band radio emission in the interplanetary medium. Such high speed shocks are uncommon with less than 10 per solar cycle [*Cane*, 1985; 1988]. 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.

Shock speed must also be important for understanding charge state observations. [*Leske et al.*, 2001] found that the charge states increased with energy and were higher for events with higher Fe/O. The three events in that study without shock effects all had Q(Fe) near 20. Note that the October 30 1992 event had an associated shock with the very high transit speed of 1470 km/s.

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.*, 2000] it is likely that those events without a first, Fe–rich, component would actually have had one if viewed from an appropriate location. For those events in which there is a fast shock present there are particles accelerated out of the ambient corona and solar wind that dominate over any flare particles at most locations and at lower rigidities than considered in this work.

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References

Cane, H. V., The evolution of interplanetary shocks, *J. Geophys. Res., 93*, 1, 1988.

Cane, H. V., The large–scale structure of flare–associated interplanetary shocks, *J. Geophys. Res., 90*, 1, 1988.

Cane, H. V. and W. C. Erickson, Low frequency (<100 kHz) observations of type III radio bursts and their implication for particle propagation in the inner heliosphere, submitted to *J. Geophys. Res.*, 2002.

Cane, H. V., D. V. Reames and T. T. von Rosenvinge, The role of interplanetary shocks in the longitude distribution of solar energetic particles, *J. Geophys. Res., 93*, 9555, 1988.

Cane, H. V., D. V. Reames and T. T. von Rosenvinge, The origin of solar particle events with low Fe/O, *Proc. 21st Int. Cosmic Ray Conf., 5,* 370, 1990.

Cane, H. V., D. V. Reames and T. T. von Rosenvinge, Solar particle abundances at energies greater than 1 MeV per nucleon and the role of interplanetary shocks, *Astrophys. J., 373*, 675, 1991.

Cane, H. V., W. C. Erickson, and N. P. Prestage, Solar flares, type III radio bursts, coronal mass ejections and energetic particles, *J. Geophys. Res., 107(A10)*, 1315, DOI 10.1029/2001JA000320,, 2002.

Cohen, C. M. S. et al., New observations of heavy-ion-rich solar particle events from ACE, *Geophys. Res. Lett., 26*, 2697, 1999.

Lepri, S. T. , Zurbuchen, T. H., Fisk, L. A., Richardson, I. G. , Cane,H. V., Gloeckler, G., Iron charge distribution as an identifier of interplanetary coronal mass ejections, *J. Geophys. Res., 106* , 29,231, 2001.

Leske, R. A., R. A. Mewaldt, A. C. Cummings, E. C. Stone and T. T. von Rosenvinge, The ionic charge state composition at high energies in large solar energetic particle events in solar cycle 23, in *Solar and Galactic Composition*, ed. R. F. Wimmer–Schweingruber, pp. 171–176, American Institute of Physics, Woodbury, NY, 2001.

Luhn, A. et al., The mean ionic charges of N, Ne, Mg, Si, and S in solar energetic particle events, *Proc.*

19th. Internat. Cosmic Ray Conf. (La Jolla), 4, 241, 1985.

Mason, G. M., J. E. Mazur, and J. R. Dwyer, ^{3}He Enhancements in large solar energetic particle events, *Astrophys. J., 525*, L133, 1999.

Mason, G. M. et al. Spectral properties of He and heavy ions in ^{3}He–rich solar flares, *Astrophys. J., 574*, 1039, 2002.

Reames, D. V., Solar energetic particles: Sampling coronal abundances, *Space Sci. Rev., 85*, 327, 1998.

Reames, D. V., Particle acceleration at the sun and in the heliosphere, *Space Sci. Rev., 90*, 413, 1999.

Reames, D. V., Magnetic topology of impulsive and gradual solar energetic particle events, *Astrophys. J., 571*, L63, 2002.

Reames, D. V., C. K. Ng, and A. J. Tylka, Initial time dependence of abundances in solar energetic particle events, *Astrophys. J., 531*, L83, 2000.

Stone, E. C. et al., The Solar Isotope Spectrometer for the Advanced Composition Explorer, *Space Sci. Rev., 86*, 357, 1998.

von Rosenvinge, T. T., et al., Time variations in elemental abundances in solar energetic particle events, in *Solar and Galactic Composition*, ed. R. F. Wimmer–Schweingruber, pp. 343–348, American Institute of Physics, Woodbury, NY, 2001.

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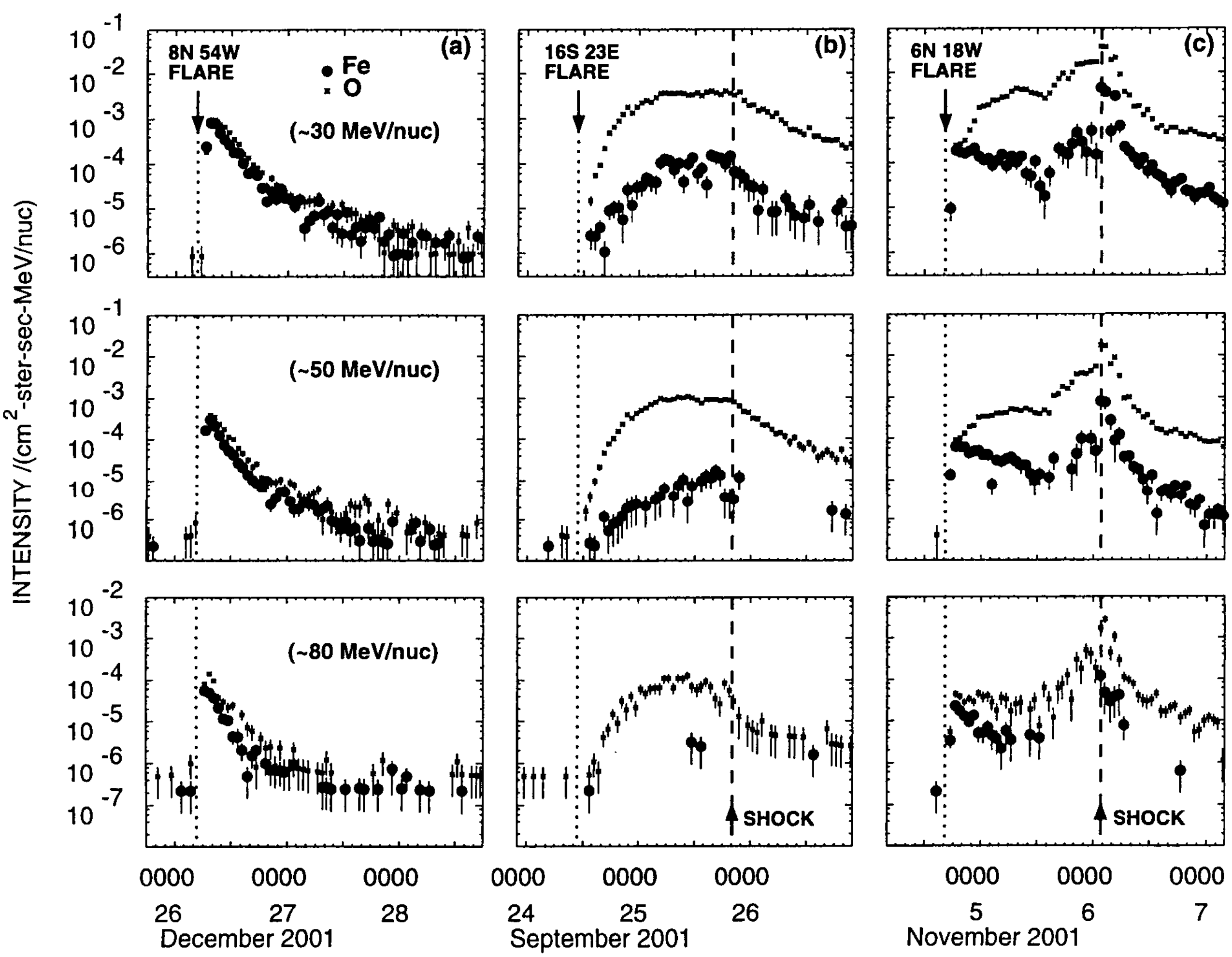
Figure 1. Three–day plots of Fe (filled circles) and O (asterisks) intensities (1 hour averages) at ~30 MeV/nuc (upper panels), ~50 MeV/nuc (middle panels), and ~80 MeV/nuc (lower panels) showing examples of the three groups of events at these energies, differentiated by their intensity–time profiles. 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.

Figure 2. Fe/O at ~30 MeV/nuc as a function of shock transit speed (• – events like that in Fig.1a, ○ – events like that in Fig. 1b, □ – events like that in Fig. 1c, second component)


8N 54W
FLARE
Fe
O
(a)
(~30 MeV/nuc)
16S 23E
FLARE
(b)
6N 18W
FLARE
(c)
(~50 MeV/nuc)
(~80 MeV/nuc)
SHOCK
SHOCK
INTENSITY /(cm^2-ster-sec-MeV/nuc)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
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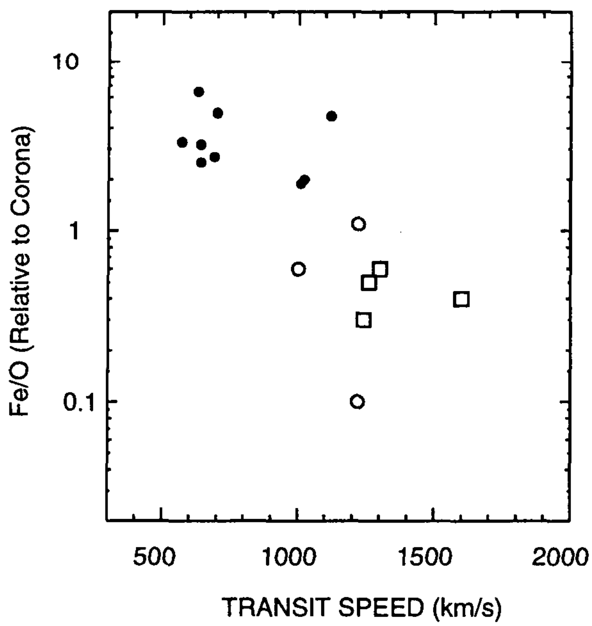
September 2001
5
6
7
November 2001


10
1
0.1
Fe/O (Relative to Corona)
500
1000
1500
2000
TRANSIT SPEED (km/s)