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SEP Fe charge states in 3He-rich interplanetary shock events

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Abstract. Recent work by Mason et al. (1999) and Desai et al. (2000) suggests that suprathermal ion populations from impulsive solar energetic particle events may be subsequently accelerated by interplanetary shocks. They have used 3He/4He abundance ratios from the ACE/ULEIS instrument to detect ion populations originating in impulsive events. Desai (2000) identified several interplanetary shock events in which the 3He/4He ratios were enhanced above the solar wind value.

Another tracer of impulsive events is the ionic charge state of solar energetic particles (SEPs). It has been shown that that SEPs accelerated in impulsive events are highly ionized. The ACE/SEPICA instrument measures ionic charge states of SEP ions, and it has detected highly ionized Fe in some of the He3-rich interplanetary shock events identified by Desai (2000). Observations for these events will be presented and discussed in the context of earlier observations of interplanetary shock events.

1. Introduction

3He/4He enhancement has often been observed in impulsive, flare-associated Solar Energetic Particle (SEP) events (Mason et al., 1999). Wave-particle resonance interactions have been suggested as a mechanism for creating the enhancement (Miller et al., 1998). Enhancements of other ion species such as Fe and Ne also occur in impulsive events (Reames et al. 1994, Moebius et al. 2000). However, recent observations from the ULEIS instrument aboard the Advanced Composition Explorer (ACE) have revealed significant 3He/4He enhancements during gradual SEP events driven by interplanetary shocks (Desai et al., 2000). Although these CME-related events are not expected to create the isotope enhancements themselves, Mason et al. (1999) suggested that interplanetary shocks may further accelerate 3He initially accelerated in flares.

Another tracer of impulsive events is the ionic charge state of SEPs. Luhn et al (1987) observed substantially higher charge states for Si and Fe in impulsive events than in gradual events. This is consistent with the higher temperature in the source region for impulsive events. Moebius et al (2000) found Fe charge states extending from $\langle Q\rangle=10$ to $\langle Q\rangle=18$ for SEP events in 1998. In gradual events, the mean Fe charge state is typically Q=10-12 (see examples in Moebius et al., 2000, Klecker et al., 2000 and Popecki et al., 2000), which is similar to what is found in the solar wind (Gloeckler et al., 1999). The ionic charge states of SEPs during periods of He3 enhancements can therefore be used as an additional identification of material originally accelerated in impulsive events. In this paper we will therefore study the ionic charge states in a sample of interplanetary shock events, for which Desai et al. (2000) have found substantial 3He enrichment. In particular, we will search for contributions of high charge state ($Q\geq14$) in these events.

2. Spacecraft and Instrumentation

The ACE spacecraft was launched in August, 1987 and is situated in a halo orbit around the L1 Lagrangian point. It carries instrumentation for elemental, isotopic and charge state composition, as well as magnetic field measurement (Stone et al, 1998). SEPICA consists of a ΔE-E_{res} telescope with a proportional counter for the energy loss measurement (ΔE), and a solid state detector for the residual energy (E_{res}) measurement. The element number Z is determined from the specific energy loss (ΔE) of the incoming ion. Combining the residual energy with the energy loss in the proportional counter gas and windows results in the total energy E. The energy per charge (E/Q) of the ions is

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determined in a collimator/electrostatic deflector assembly by measuring the impact position in the proportional counter. Finally, combining E/Q and E leads to the charge state Q. A complete description of the instrument may be found elsewhere (Möbius et al., 1998). The energy range for measurement is defined by requirements for element identification and deflection. For example, the Fe charge states presented here were measured at energies of 0.18-0.33 MeV/nuc.

3. Data Selection and Observational Results

Desai et al. (2000) have identified SEP events in which the 3He/4He ratio is enhanced during the passage of interplanetary shocks. The charge state distribution of Fe has been measured for five of the events with the largest He3 enhancement. A list of these events is presented in Table 1, including event times, the shock time, the 3He/4He ratio from ULEIS and the Fe mean charge state as obtained with SEPICA.

Table 1. 3He-rich Interplanetary Shock Events

Beginning	End	Shock	3He/4He Ratio	<QFe>
Sep 15, 1999 15:19 (99/258.64)	Sep 16 22:40 (259.94)	Sep 15 19:38 (258.82)	0.1585 ±0.0263	14.8 ±1.0
Jan 20, 2000 10:40 (00/0020.44)	Jan 24 11:20 (024.47)	Jan 22 00:23 (022.02)	0.0418 ±0.0060	11.9 ±0.3
Apr 23, 2000 06:57 (00/114.29)	Apr 24 17:55 (115.75)	Apr 24 08:50 (115.37)	0.2402 ±0.0119	16.4 ±0.3
Jul 11, 2000 02:04 (00/193.08)	Jul 12 05:55 (194.25)	Jul 11 11:24 (193.47)	0.0430 ±0.0037	16.5 ±0.3
Oct 11, 2000 05:37 (00/285.23)	Oct 13 19:06 (287.80)	Oct 12 21:45 (286.91)	0.0494 ±0.0035	10.6 ±0.2

As an example, the temporal evolution of the event that started on DOY 115 (Apr 24), 2000 is presented in Figure 1. From top to bottom are shown: the proton density and speed from the ACE/SWEPAM instrument, the magnitude and one directional angle of the magnetic field from ACE/MAG and the Fe charge state for individual ions from SEPICA. The integration period for the 3He/4He ratio was 00/114.3-115.75. The shock, as identified by Desai et al. (2000), passed the spacecraft at DOY 115.37. This may be seen by increases in |B| and proton speed, as well as a small increase in the solar wind density. A brief rotation in the magnetic field occurred between DOY 115.3 and 116.0, which is one indication of a magnetic cloud (Burlaga et al., 1981). EPAM electrons (not shown) show no sharp intensity increases, which would indicate the occurrence of an impulsive event, until perhaps 115.8. The integration period for the 3He/4He ratio ended at approximately this time to avoid direct inclusion of flare products. The Fe charge state was typically Q=16-18 throughout most of the event, with an additional lower charge component that was seen during the time from DOY 114.6 to 114.9. During the time period of interest, the charge state of Fe is considerably higher than what is normally observed in shock related events.

The Fe charge states in this event are compared to those in the interplanetary shock event of April 20, 1998 (98/111) in Figure 2. Although both were observed in association with an interplanetary shock, the Fe charge states from 00/115 are considerably higher than those of April 20, 1998, and thus more typical of an impulsive event.

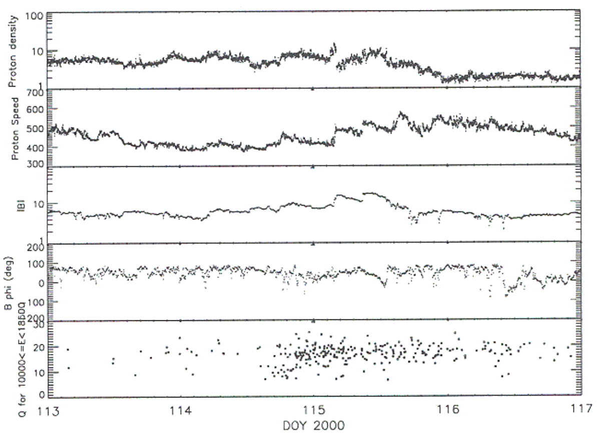

Figure 1. Plasma data and SEP ionic charge states are presented for a He3-rich shock event on April 24, 2000 (00/115) as a function of time. From top to bottom: proton density and speed, magnetic field magnitude and the azimuthal angle, and the Fe charge state for individual Fe ions at 0.18-0.33 MeV/nuc.

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Finally, the average Fe charge states for all five events from the sample of Desai et al. (2000) are plotted versus the 3He/4He ratio in Figure 3. In three of these events, the Fe charge state is high, while in the two others, it is typical of gradual, interplanetary shock events.

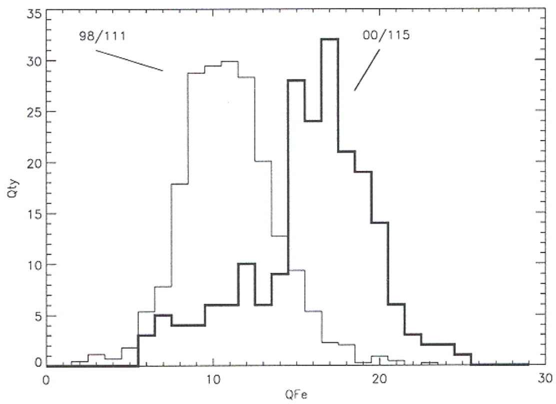

Figure 2. The Fe charge state histogram for the He3-rich event of April 24 2000 (00/115) is plotted over a typical gradual event Fe charge histogram from April 20, 1998.

4. Discussion

We have studied the Fe charge state distributions for five interplanetary shock events that were previously identified as 3He rich by Desai et al. (2000). We find substantially higher charge states than those typical for CME related events in three of the five cases, while the remaining two are more similar to CME events. Generally, ions of both high and low charge states are found at least for some time during these events. As a consequence, the Fe charge state distributions in these He3-rich shock events may be a mixture of what is normally found in shock events and what is found in flare-related events. In some cases, even if flare products are present during a shock period, they may represent a small fraction of the total accelerated population. In others, however, it is remarkable that a substantial fraction of high charge state Fe is found in interplanetary shock events with no evident connection to a flare event.

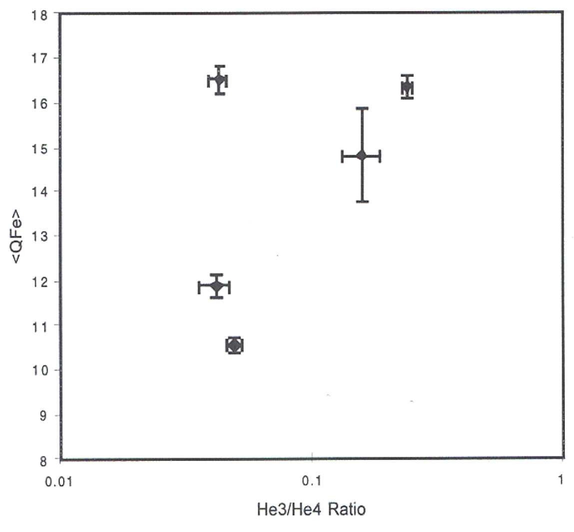

Figure 3. The average Fe charge states vs. 3He/4He ratio is shown for five 3He-rich shock events.

However, each of the events must be studied in detail for potentially hidden connections to events on the sun. A connection might take the form of direct injection from an impulsive event, which is not apparent in these five events. Alternatively, a connection to an impulsive event may occur if the spacecraft is inside a magnetic cloud. In this case, SEPs typical of an impulsive event may be detected from a flare occurring at the footpoints of a magnetically-connected cloud. In the example from DOY 115, 2000 shown in Figure 1, a magnetic field rotation occurred. This is one indication of a magnetic cloud passage. The rotation was brief, however, compared to the period during which high charge state Fe was observed. One other event appeared to contain a magnetic cloud, but only at the end of a period of high charge state Fe. It is unlikely, therefore, that magnetic cloud access to impulsive events can explain the high charge SEP Fe observed in these cases.

Finally, SEPs characteristic of impulsive events may be indirectly created if they are present in the solar wind and locally shock accelerated to SEP energies. This may explain the observation of high charge state Fe in three of the events selected by Desai et al. (2000). In this scenario, the solar wind source Fe very likely originated in an active region, but left the Sun days before the shock passed the spacecraft. The 3He observed during these three events may have been previously accelerated in a flare and reaccelerated by the shock, as suggested by Mason et al (1999). However, the simultaneous observation of high charge state Fe and 3He enhancement would then be coincidental. Alternatively, the 3He observed during these three events may have been present with high charge state Fe in the solar wind. Future work will address this possibility.

5. Conclusion

In three of five He3-rich interplanetary shock events, high charge state SEP Fe was found. No direct connection to impulsive events is apparent, yet Fe typically associated with impulsive events was observed. This is consistent with the suggestion that suprathermal 3He from impulsive solar energetic particle events may be reaccelerated by interplanetary shocks. Future work will extend the investigation to more shock events with variable levels of

He3 enhancement, and the simultaneous composition of the solar wind.

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