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Measurements of Iron Rich SEP Events Using the University of Chicago IMP-8 Instrument

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Abstract

Since the onset of solar activity in late 1997 there have been several large solar energetic particle (SEP) events. We report the spectra and absolute intensity of many of the larger SEP events as measured with the University of Chicago Cosmic Ray Nuclear Composition instrument on the IMP-8 satellite. Our instrument responds to ions over the energy range ~1-500 MeV/nucleon. We have found that, contrary to earlier analyses, for most of the new events, the largest of the SEPs are iron rich (Fe/O ratio ~1), with very hard heavy ion spectra - which were generally power law in energy/nucleon over our measurement range. We also report on a high correlation between ground level events, observed by neutron monitors, and iron rich SEP events.

1 Introduction:

In November 1997, the first large flare occurred signaling the onset of increased modulation during this solar cycle. Since then, there have been a number of solar energetic particle events observed at Earth and a general trend toward increased solar activity for the past year and a half. During this period there have been a number of moderate to large solar energetic particle (SEP) events observed at Earth. This report will focus mainly on the largest of the SEP events observed by the IMP-8 satellite in Earth orbit over the 2 year period from January 1997 through December 1998.

We have found that, contrary to earlier beliefs [e.g. Reames, 1990], large SEP events can be Fe rich, with hard Fe spectra extending to energies >~500MeV/nucleon. These Fe rich events can be not only "impulsive" events, as has been seen before, but also "gradual" events, as we show for the 1997-1998 SEP events. We have also found that there are significant ^{3}He enhancements, above the solar abundance, in a majority of SEP events, though often only on the order of a few percent.

We also report a strong correlation between ground level events (GLEs) observed with any of the neutron monitor stations (cutoff rigidities between ~1-15GV) and Fe rich SEP events. Two of the SEP events seen in the 1997-1998 period displayed this correlation, as do some 21 other GLEs observed in the past twenty-five years.

2 Instrumentation:

The data used here come from Chicago's Cosmic Ray Nuclear Composition (CRNC) experiment on the IMP-8 satellite [Garcia-Munoz, Mason and Simpson, 1977], launched into Earth orbit in 1973. Particle identification is accomplished with a standard energy loss (dE/dx) vs. residual energy (E) analysis. The CRNC instrument is able to distinguish the elemental composition of particles which stop in one of its detectors, and can differentiate the isotopes ^{1}H from ^{2}H and ^{3}He from ^{4}He. The energy response of the instrument is ~1-500MeV/nucleon, depending on the element.

3 Data:

The period of 1997-1998 showed a significant increase in the level of solar activity. The number of solar flares observed increased from ~5 per day to ~25 per day with a corresponding increase in the number of SEP events observed at Earth. In order to study this period we have decided to look at only the largest of the SEP events observed with the CRNC instrument on IMP-8. For consistency we looked at all SEP events and chose to study those which met the following criteria: 1) the 30-95 MeV

H rate increased by a factor >100 above background, 2) the 30-95 MeV/nucleon He rate increased by a factor >10 above background, and 3) the low energy heavy ion rate (responding primarily to Fe with mean energy ~5 MeV/nucleon) increased by a factor >10 above background. Of all the SEP events observed during 1997-1998 period, the 8 SEP events which met our criteria are listed in Table 1 along with the identification of the solar flare associated with each of the SEPs.

Table 1. Solar Flares associated with the SEP events of 1997-1998

Flare Date	Time(UT) Start	Max	End	GOES X-Ray	Active Region	Position
Nov. 6, 1997	1149	1155	1201	X9.4	8100	S18-W63
Apr. 20, 1998	0938	1021	1118	M1.4	8205	N20-W85*
May 2, 1998	1331	1342	1351	X1.1	8210	S15-W15
May 6, 1998	0758	0809	0820	X2.7	8210	S11-W65
May 9, 1998	0304	0340	0355	M7.7	8214	N30-W70*
Aug. 24, 1998	2150	2212	2235	X1.0	8307	N35-E09
Sep. 30, 1998	1322	1338	1350	M5.6	8346	S30-W28*
Nov. 14, 1998	0518	0519	0529	C1.7	8385	N24-W60*

*Flare is only a tentative identification with the SEP observed at Earth

Of the 8 SEP events listed in Table 1, 7 were positively associated with CMEs. There was a significant amount of solar activity at the time of the Sep. 30, 1998 event, and a CME was seen off the east limb of the Sun which might have been associated with the SEP seen at Earth, even though the flare site was tentatively identified as west 28. There was a CME ejected on November 4, 1997, just prior to the November 6 flare, which may have had a more significant impact on the SEP event seen at Earth than did the CME ejected on November 6 [e.g. Howard et al., 1998].

In Table 2, we list a number of pertinent characteristics for each of the SEP events under study. Except for 1 instance we were able to determine the elemental spectra for the species H, He, C, O and Fe for all the SEP events under study. During the April 20, 1998 SEP event, only 1 Fe was positively identified, so we were unable to generate an Fe spectrum. All the SEP spectra calculated from our IMP-8 CRNC experiment can be fit as power law in energy/nucleon over the energy ranges we measure. In Figure 1 we show two examples of the spectral measurements. Occasionally, as for the C and O spectra during the May 2, 1998 SEP event (Figure 1B), the spectra break at the highest energies suggesting a maximum energy of the associated acceleration. We have also calculated the relative abundance of Fe/O for each of the events.

Table 2. Characteristics of the SEP events of 1997-1998

Flare Date	CME	Fe/O	$^3He/^4He$	Spectral Indices O	Fe
Nov. 6, 1997	Yes*	0.55±0.10	0.02±0.005	2.60±0.35	2.80±0.50
Apr. 20, 1998	Yes	0.03±0.05	0.00±0.02	5.70±0.25	Unknown
May 2, 1998	Halo	0.70±0.40	0.04±0.02	2.50±0.25	2.50±0.35
May 6, 1998	Halo	0.70±0.50†	0.02±0.01	2.90±0.35	Unknown
May 9, 1998	Halo	0.80±0.30	0.02±0.01	3.20±0.50	3.05±0.85
Aug. 24, 1998	Yes	0.35±0.15	0.01±0.01	3.35±0.45	3.45±0.65
Sep. 30, 1998	No*	0.30±0.10	0.01±0.005	3.80±0.50	4.05±0.75
Nov. 14, 1998	Yes	0.45±0.15	0.02±0.01	3.50±0.40	3.80±0.60

†Fe/O ratio is calculated for high energies only

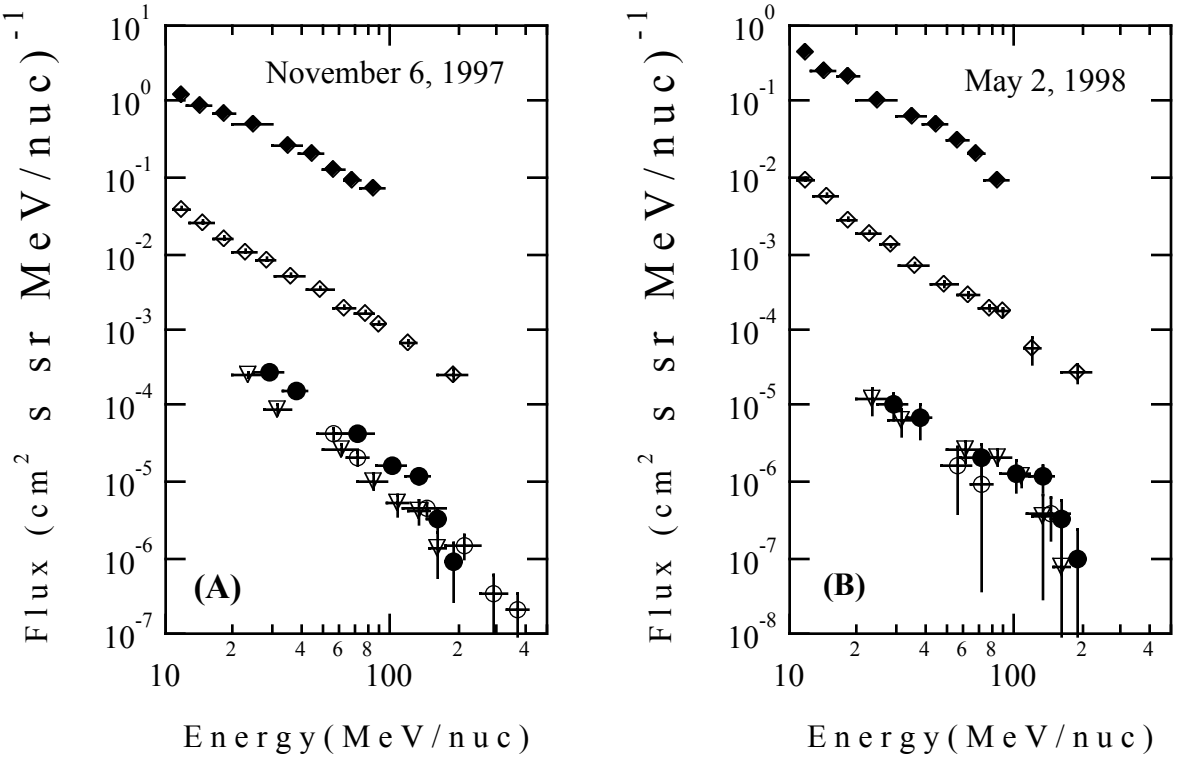

Figure 1. Spectra for the (A) Nov. 6, 1997 and (B) May 2, 1998 SEP events. Energy ranges (MeV/nucleon) are for each species are:
◆ H (11-95) ◇ He (11-220) ▽ C (20-175) ● O (25-200) ○ Fe (50-500)

The CRNC experiment has been able to measure the isotopes of He and H with reasonable accuracy during period of low solar activity [Beatty, 1986]. We have used the calibration established by Beatty to measure these isotopes during the recent SEP events. Because of the greater ^{1}H and ^{4}He backgrounds, these measurements have a much higher statistical error, but we have been able to calculate the ^{3}He/^{4}He ratio in 7 of the 8 SEP events. During the April 20, 1998 SEP event there was no ^{3}He signal observed, so the error quoted is an upper limit, above which we should have been able to detect ^{3}He. The ratio 3He/4He for these SEP events is generally on the order of a few percent, as has been seen in a number of other SEP events [Chen, Guzik & Wefel, 1995].

4 Discussion:

There has been a general feeling in the past that Fe rich flares occurred infrequently, and were usually small in their absolute fluence of particles. The 1997-1998 period appears to dispute this idea. Using the criterion that a ratio Fe/O >~ 1 is an indication of a Fe rich event (Fe normal events having a ratio Fe/O ~ 0.075-0.15), we see that of the 8 large SEP events seen during this period, 7 are Fe rich.

People have been using a standard set of identifiers for SEP events to categorize these events as "gradual" and "impulsive" [e.g. Reames, 1990 and Cane, Reames & von Rosenvinge, 1991]. The SEP events seen during 1997-1998 seem to fit many of the criteria for "gradual" events: they are associated with CMEs, type II radio bursts, and medium ionic charge state Fe [Dietrich & Lopate, 1999, Mobius, Popecki & Klecker, 1998, and Table 2]. However, we have seen that these SEP events are also Fe rich, a characteristic often associated with "impulsive" events. This may indicate that the Fe/O ratio is not a good quantity for separating the various types of SEP events.

People have also used enhancements in the $^3He/^4He$ ratio as another indicator of "impulsive" events. We see that 7 of the 8 "gradual" events studied here have $^3He/^4He$ ratios that are well above the solar ratio of $\sim 10^{-4}$. It seems likely that nearly all SEP events have enhancements in the $^3He/^4He$ ratio [Chen, Guzik & Wefel, 1995], perhaps due to resonance of ^3He with lower hybrid waves near the gyrofrequency of protons [Ramadurai & Thejappa, 1986]. Thus when discussing $^3He/^4He$ enhancements it is important to distinguish between an enhancement above the solar values, and enhancements $^3He/^4He > \sim 0.1$, as is normally considered when describing ^3He rich events.

The 1997-1998 period saw two ground level events (GLEs) observed with neutron monitors, one on November 6, 1997 and another on May 2, 1998. The SEP events associated with these two ground level events were Fe rich [see Figure 1 and Table 2]. We have a similar correlation between GLEs and their associated SEP events, which we have listed in Table 3. Of the 24 GLEs observed between 1973 and the present only 1 (June 15, 1991) does not show this correlation. One possible explanation for this correlation is that these Fe rich SEP events have hard enough Fe spectra that high energy Fe precipitating on the atmosphere creates an appreciable air shower signal which is observed with the neutron monitors. Preliminary work shows that the Fe contribution to the neutron monitor signal is at most 20%. The correlation between the September 29, 1989 GLE and its associated SEP event is discussed in detail in another paper at this conference [Tylka et al., 1999]. Another explanation for this correlation is that whatever mechanism accelerates large numbers of protons to extremely high energies simultaneously enhances the acceleration of Fe in preference to lower mass elements. We do not yet have a self-consistent explanation for this correlation between GLEs and Fe rich SEP events.

Table 3. Ground Level Events Observed at Earth and the Maximum of the Fe/O Ratio of the Associated SEP

Date of GLE	Fe/O	Date of GLE	Fe/O	Date of GLE	Fe/O
Apr. 29, 1973	~3.00	Nov. 26, 1982	0.68	Oct. 24, 1989	0.88
Apr. 20, 1976	0.49	Dec. 7, 1982	0.79	Nov. 15, 1989	0.72
Sep. 19, 1977	1.58	Feb. 16, 1984	0.85	May 21, 1990	1.52
Sep. 24, 1977	0.96	Jul. 25, 1989	~4.50	May 24, 1990	1.55
Nov. 22, 1977	0.77	Aug. 16, 1989	0.58	May 26, 1990	1.82
May 7, 1978	1.27	Sep. 29, 1989	0.61	Jun. 15, 1991	0.03
Sep. 23, 1978	0.58	Oct. 19, 1989	0.71	Nov. 6, 1997	1.01
Oct. 12, 1981	0.80	Oct. 22, 1989	0.27	May 2, 1998	0.75

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