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Elemental abundance enhancements of large Fe-rich gradual events

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Abstract. We report on a study of the largest of the gradual (CME driven) solar energetic particle events, as measured with the University of Chicago instrument on the IMP-8 satellite during solar cycles 21 and 22, in order to categorize these largest events. Our selection criterion for studying events is when the CNO flux exceeds 10^{-5} (cm^2 sec ster MeV/nucleon)$^{-1}$ for CNO above ~25 MeV/nucleon. The subset of gradual events whose Fe/O ratio is enhanced (≥1) is of great interest, both from a theoretical and practical point of view, and we have attempted to categorize these events. The enhanced-Fe gradual events can be divided into three broad subgroups. The first subgroup is a set of events for which the spectra of the heavy ions (e.g. Ca, S, Fe) is harder, and extends to higher energy, than that of the lighter ions (C and O),. The second subgroup of events spectra of identical shape for all heavy elements from C through Ni. When we compare the abundances of the heavy ions in this subset of gradual events to a general average abundance of heavy ions observed in all gradual events we see an increasing enhancement as an exponential function of charge. The final subset of Fe-enhanced gradual events looks very similar to the second subset, except that the C is relatively depleted and the Ne is additionally enhanced. This third subset shows abundance variations remarkably similar to those observed in some ^{3}He-rich impulsive events.

1 Introduction

Gradual solar particle events (SPEs) are events associated with coronal mass ejections (Kahler *et al.*, 1984) and type II and type IV radio bursts. The radio bursts are associated with the propagation through the corona and interplanetary medium of a shock generated by a CME. The seed populations for these accelerated particles are assumed to lie in the lower corona, and might have varying ionic charge states. These CME shocks continuously accelerate ions as they propagate through the interplanetary medium, and often energies of these particles extend to 100's of MeV/nucleon or even to several GeV/nucleon (Tylka, Dietrich & Boberg, 1997). It is the accelerated particles associated with these CME driven shocks that are the focus of this work.

The University of Chicago's Cosmic Ray Nuclear Composition (CRNC) experiment has been described previously (Garcia-Munoz et al., 1977). The CRNC measures energetic heavy ions in the range ~10-500 MeV/nucleon. Since the spectra of solar energetic particles (SEPs) are generally falling at E^{-3} or softer, the CRNC is often limited by statistics when studying SPEs. In order to obtain elemental composition information for the lower intensity ions (such as S or Ar), it was necessary to analyze the largest events, which of necessity are the largest gradual SPEs. While this may introduce a bias into our sample, there are other reasons to study large gradual SPEs. Energetic particles from these events will form the greatest possible hazard to the near-Earth space environment. Also these events are the only ones which can generate solar energetic ions in the range of 100's of MeV/nucleon, thus represent the high energy extreme for models of shock acceleration and solar energetic particle transport. We report on the analysis of the largest gradual SPEs observed with the CRNC experiment over the period 1973-1994.

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2 Discussion

The large gradual SPEs which we have studied have been separated into four classifications based on the elemental composition, labeled "nominal", "spectral", "progressive" and "Ne-rich". Of these, the last three classifications all are characterized by enhanced Fe/O at high energy. The Fe-rich SPEs are listed in Table 1, along with their elemental enhancements, and Figure 1 shows graphically the average enhancement for each of the three Fe-rich classifications. In order to minimize systemic error in the CRNC measurement, all the elemental abundances were calculated as ratios to the oxygen abundance. The enhancements listed in Table 1 are ratios of the CRNC individual SPE abundance ratios to the "nominal" gradual SPE ratios, i.e. (C/O) / (C/O)nom, so a value of 2.0 in the table means that the elemental abundance ratio for that event is twice our "nominal" abundance ratio for gradual SPEs.

2.1 "Nominal" SPEs

Twenty of the SPEs analyzed had elemental abundance ratios which were nearly identical to other canonical ratios associated with gradual SPEs (e.g. Reames, 1999). The average abundance ratios for our "nominal" gradual SPE are listed in the top lines of Table 2, where the ratios are listed are parts per 1000. As is usual, all the abundance ratios are taken with respect to oxygen, which would have an abundance ratio of O/O = 1000±50. The only abundance ratio statistically different from the values reported in Reames (1999) is that for Fe/O, where our "nominal" abundance ratio is about half the Reames (1999) value. This is because we are looking at the elemental ratio at a much higher mean energy than the previous studies and with the Fe spectrum for gradual SPEs generally breaking before than that of oxygen (in MeV/nucleon), the abundance ratio of a gradual SPE event drops as energy increases. The enhancement factor, as described above, is by definition 1.0 for all "nominal" abundance ratios.

2.2 "Spectral" SPEs

Twelve of the SPEs analyzed are Fe-rich, of the type we list as "spectral" class (solid dots in Figure 1). The abundance ratios for the "spectral" class are similar to the "nominal" gradual SPE class for the lower charger elements. It is only at about Ca that there begin to be significant changes in the abundance ratios. The increase in the abundances of high-Z elements is due to a difference in spectral shape at high energy. As can be seen in Figure 2, the Fe spectrum has not broken at high energy, though the C and O spectra begin turning over at ~100 MeV/nucleon. This causes the Fe/O ratio to increase at high energy. While there are not enough of PHAs from any SPE to form a definite spectrum for elements in the mid-charge range, it seems likely that a similar effect could be occurring for all high-Z elements. It is interesting to note that the change in the abundance ratios occurs at about the point where ions would be able to have significant numbers of charge states. As a possible explanation for the changes in abundance of these "spectral" class elements would be that the CME driven shock forms quickly, the seed population for these particles would be the lower corona, and there would be significantly more charge stripping of the high-Z ions. For example, in the "nominal" case, Fe has an ionic charge state of ~14 (e.g. Tylka et al., 1995) while in these cases, were the charge state closer to ~20 the Fe energy spectrum would be significantly harder, as we observe.

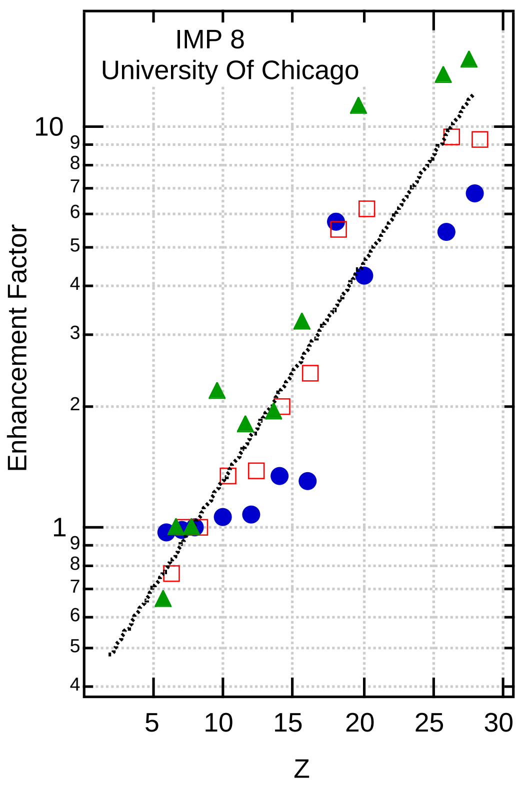

Figure 1. Abundance Ratio Enhancements for the three Fe-rich gradual SPE classes. Filled dots are "spectral" class, open squares are "progressive" class and filled triangles are "Ne-rich" class.

2.3 "Progressive" SPEs

Ten of the SPEs analyzed are Fe-rich, of the type we list as "progressive" class (open squares in Figure 1). The spectra for all elemental species in a "progressive" class flare are all hard power law at high energy, with the same exponent (see Figure 3). The abundance ratios for the "progressive" class are significantly different from the "nominal" gradual SEP abundance ratios for all species, with increasing enhancement as the Z increases. The abundance ratios for our "progressive" class SPEs lies almost midway between the "nominal" abundance ratios of gradual and impulsive SPEs (e.g. Reames, 1999). Thus as has been suggested (e.g. Boberg, Tylka and Adams, 1996) these "progressive" class events might consist of a mixture of two seed populations for acceleration, one located near the flare site where preferential acceleration of different ions can occur (e.g. Temerin and Roth, 1992) and the other from the coronal seed population normally associated with gradual SPEs; however in these cases we would require nearly equal contributions from each of these different seed populations. An alternate explanation has been offered by recent work of Tylka (2001), where there would be a fast formation of a well-connected CME driven shock in the lower corona (below ~0.2 R_S), which would mix varying charge states of all different elements, and which would allow fast access to Earth because of the good magnetic connection. This admixture of ionic charge states would cause all the elemental spectra to harden in a similar matter, and the abundances would be those found in the lower corona, nearer the flare-site material.

2.4 "Ne-rich" SPEs

Nine of the SPEs analyzed are Fe-rich, of the type we list as "Ne-rich" class (filled triangles in Figure 1). The abundance ratios in these SPEs are enhanced for all high-Z elements, but they are even more significantly enhanced in Ne and poor in C. The abundance ratios for these events are nearly identical to the nominal values used in the small ^{3}He-rich impulsive SPEs (e.g. Reames, 1999). The unusual enhancement of Ne alone argues against the fast shock formation and subsequent mixing of ionic charge states for all elements (as was possible with the "progressive" class SPEs). The extremely good agreement between all the abundance ratios of the "Ne-rich" class SPEs and impulsive flares suggests that the source of the seed population for the accelerated ions in the "Ne-rich" class is located near the flare sites where preferential acceleration can occur. If the CME driven shock were slow to form, perhaps forming in the upper corona or in interplanetary space, the seed population would be the pre-accelerated flare-site materiel. The shock would reaccelerate the flare-site material as it propagates through interplanetary space, thus giving the unusual abundance patterns we observe at Earth.

3 Conclusions

This study of 51 large gradual SPEs observed with the IMP-8 CRNC instrument is in large agreement with previous studies. At the high energies observed by the CRNC, the standard Fe/O ratio for gradual SPEs is slightly smaller than that of pervious studies. In 31 of the SPEs analyzed, there is a significant enhancement of Fe (and other heavy ions) over that generally assumed for gradual SPEs. These enhancements can be explained through models allowing for the mixing and acceleration of multiple charge state ions or by assuming mixtures of seed populations normally associated with flare-site acceleration and long-term acceleration of coronal material.

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References.

Boberg, P.R., Tylka, A.J., and Adams, J.H. Jr, "Solar energetic Fe charge state measurements: Implications for acceleration by coronal mass ejection-driven shocks", *Ap. J. (Lett.)*, **471**, L65, 1996.

Garcia-Munoz, M., Mason, G.M., and Simpson, J.A., "The age of the galactic cosmic rays derived from the abundance of 10Be", *Ap.J.*, **217**, 859, 1977.

Kahler, S.W., Sheeley, N.R. Jr., Howard, R.A., Kooman, M.J., Michels, D.J., McGuire, R.E., von Rosenvinge T.T., and Reames,D.V.,"Associations between coronal mass ejections and solar energetic proton events", *J. Geophys. Res.*, **89**, 9683, 1984.

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

Temerin, M. and Roth, I. "The production of He-3 and heavy ion enrichment in He-3-rich flares by electromagnetic hydrogen cyclotron waves", *Ap. J. (Lett.)*, **391**, L105, 1992.

Tylka, A.J., "New insights on solar energetic particles from Wind and ACE", (in press, 2001).

Tylka, A.J., Boberg, P.R., Adams, J.H. Jr., Beahm, L.P., Dietrich, W.F., and Kleis, T., "The mean ionic charge states in solar flares above 200 Mev/n", *Ap. J (Lett),* **444**, L109, 1995.

Tylka, A.J., Dietrich, W.F., and Boberg, P.R. "Observations of very high energy solar heavy ions from IMP-8", *Proc. 25th Int'l. Cosmic Ray Conf. (Durban, S.A.)*, **1**, 101, 1997.

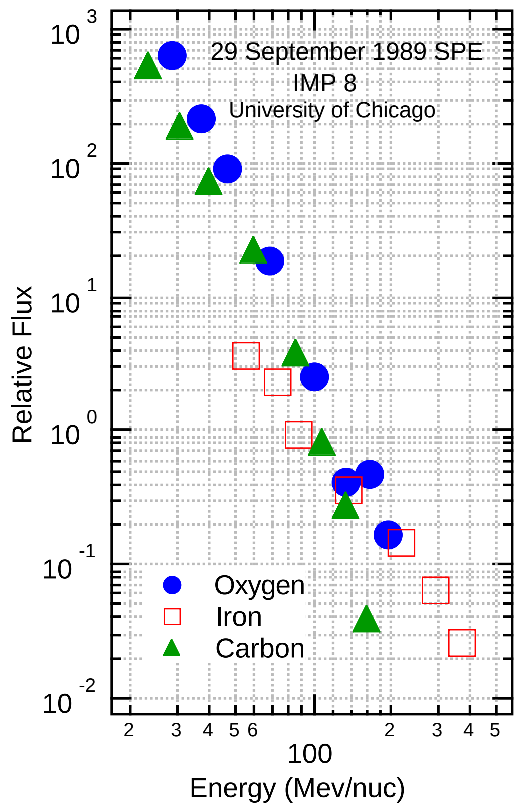

Figure 2. The C,O and Fe spectra for the "spectral" SPE event of 29 Sept 1989. The Fe spectrum is significantly harder than the C and O spectra, which begin to roll over at ~100 MeV/nucleon.

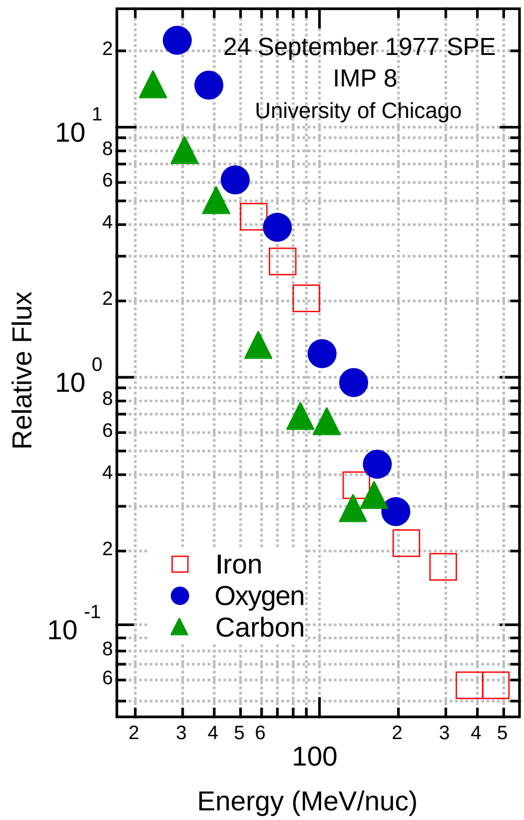

Figure 3 The C, O and Fe spectra for the "progressive" SPE event of 24 Sept 1977. Note that all three spectra are parallel, hard, and have no obvious roll-over at high energy.

Table 1 . Enhancement Factors for the Largest Gradual SPEs Observed with the CRNC Instrument on IMP-8
(to Determine the Abundance Ratios Multiply the Enhancement Factor by the "Nominal" Abundance
errors in parentheses () indicate the number of PHA events of that species, when the number is small)

Event	C/O	N/O	Ne/O	Mg/O	Si/O	S/O	Ar/O	Ca/O	Fe/O	Ni/O
"Nominal" Abundances	0.54	0.122	0.143	0.189	0.135	0.029	.0026	.0082	0.078	.0034
Fe-Rich Class Spectral										
30 Apr 1976	.93±.21	.66(2)	1.20(2)	.58(1)					6.3±4	
28 Apr 1978	1.12±.07	.75±.12	1.0±.22	1.21±.24	.98±.29	.5(1)			4.2±1.5	15(1)
23 Sep 1978	1.43±.2	1.32±.2	.81±.24	1.08±.26	1.58±.5	1.64(3)		3.4(1)	13±2.1	
8 Oct 1981	.76±.11	1.28±.32	1.04.32	1.04±.28	1.7±.5	1.4(2)		4.3	4.2±2.0	
12 Oct 1981	.94±.052	1.0±.1	1.52±.18	1.16±.15	1.25±.20	1.3±.5		2.9(2)	3.4±1.1	
30 Jan 1982	1.28±.11	.97±.17	1.31±.3	1.24±.27	1.48±.4	1.65±1.1	9.6(1)		4.2±1.7	
10 Mar 1989	.72±.14	.79±.28	.83±.43	2.01±.6	1.02±.6				6.4±3.2	
17 Mar 1989	.72±.13	1.14±.33	.65±.5	.98±.6	2.25±1.4				9.4(1)	
16 Aug 1989	1.15±.07	.89±.11	.86±.15	1.01±.16	1.49±.25	0.9±.5	2.8(1)	3.7(3)	5.3±1.1	4.5(1)
29 Sep 1989	.81±.025	.95±.05	.92±.061	1.11±.08	1.19±.08	1.0±.16	3.7±1.5	1.4±.65	2.7±.26	1.8(2)
24 Oct 1989	1.0±.06	1.06±.17	1.14±.11	1.35±.11	1.36±.15	1.65±.38	6.5±2.3	8.5±1.6	6.1±.7	2.3±2.3
25 Jun 1992	.73±.056	.79±.11	1.66±.21	.92±.14	1.46±.24	1.7±.7	6.2(2)	5.6±2.8	3.8±.7	10.5(2)
Fe-rich Class Progressive										
4 Jul 1974	.68±.07	1.08±.21	1.38±.4	1.53±.4	.80±.4	1.3(1)		7.9(1)	8.1±3.3	
19 Sep 1977	.85±.2	1.2±.26	1.02±.32	1.53±.33	2.37±.5	3.68±1.6		3.4(1)	18.7±3.	4(2)
24 Sep 1977	.70±.07	.80±.12	1.66±.22	1.32±.16	2.14±.25	3.17±.7	6.5±2.4	4.4±1.7	10.6±.9	11±4.5
22 Nov 1977	.79±.11	1.09±.26	1.59±.35	1.48±.23	2.0±.4	.96±.6	6.1(1)		6.7±1.3	
19 Aug 1979	.94±.08	1.05±.16	1.59±.28	.84±.18	1.4±.3	2.3±.9	4.2(1)	3.9(2)	8.0±3.4	7.3(1)
26 Nov 1982	.64±.12	.75±.26	1.07±.53	.49±.2	2.0±1.1			14.6(2)	8.7±5	2
8 Dec 1982	.72±.12	.96±.20	1.27±.38	1.11±.3	2.29±.57	2.4±1.5		3.8(1)	10±2.2	
19 Oct 1989	.83±.05	1.17±.11	1.31±.13	1.36±.1	1.9±.16	1.55±.32	6.1±2.1	1.3±.66	6.02±.45	4.2±1.9
29 Oct 1989	.87±.14	.89±.22	1.31±.28	1.28±.26	1.26±.32	3.0±1.1	4.6(1)	1.7(1)	9.1±1.4	
15 Nov 1989	.57±.14	.58±.33	1.31±.6	3.01±1.1	2.74±1.4	3.5(1)		15(1)	7.8±3.5	
Fe-rich Ne-rich										
23 Sep 1974	.70±.13	1.22±.31	2.50±.7	2.38±.63	1.15±.7			11.2(1)	4.9±2.0	
7 May 1978	.50±.15	1.06±.42	.97±.5	.84±.4	1.06(2)			5.6(1)	8.9±2.4	16.7(1)
3 Aug 1979	.57±.25	1.31±.65	1.59±1.2	2.5±1.2	1.4(2)	2.3(2)	34(1)		9.8±4.0	
24 Apr 1981	.81±.077	.86±.14	1.94±.3	1.64±.23	1.78±.32	2.3±.9		3.3(2)	7.7±1.3	
16 Feb 1984	.31±.09	.83±.37	1.59±.60	1.42±.50	1.48±.66	1.55(1)	17.6(1)	6.1(1)	9.5±2.8	
21 May 1990	.59±.11	1.0±.3	2.28±.6	1.48±.48	1.23±.17	2.8±1.6		20.3±9	14.7±2.7	12.2(1)
24 May 1990	.89±.17	.99±.29	2.01±.5	1.8±.4	2.4±.56	3.2±1.4		5.2(2)	12.1±2.0	7.6(1)
26 May 1990	1.0±.25		3.1±1.2	1.7±.7	.8(2)	6.0±3.5		15.8(2)	22±4.5	22(1)
28 May 1990	.61±.23	.75±.5	3.6±1.5	2.5±1.1	2.6±1.1	4.8(1)	58(1)	23.4(1)	31.6±10	

Table 2 . Average Enhancement Factors for the Lrgest Gradual SPEs Observed with the CRNC Instruement
(to Determine the Abundance Ratios Multiply the Enhancement Factor by the "Nominal" Abundance,
listed here as parts per 1000, with the "Nominal" Abundance Ratio O/O = 1000 ± 50)

Event-Class	C/O	N/O	Ne/O	Mg/O	Si/O	S/O	Ar/O	Ca/O	Fe/O	Ni/O
Nominal	540±42	122±20	143±31	189±40	135±36	29±13	2.6±1.8	8.2±4.8	78±33	3.4±2.1
	1.0±.078	1.0±.16	1.0±.22	1.0±.21	1.0±.27	1.0±.44	1.0±.71	1.0±.59	1.0±.42	1.0±.62
Spectral	.965±.03	.99±.06	1.07±.08	1.08±.09	1.35±.09	1.31±.23	5.8±2.2	4.3±1.0	5.41±.53	6.82±3.5
Progressive	.76±.04	1.0±.07	1.35±.11	1.39±.13	2.01±.17	2.42±.51	5.5±1.9	6.2±2.3	9.37±.88	9.3±4.4
Ne-rich	.66±.06	1.0±.14	2.18±.24	1.81±.23	1.95±.27	.3.25±.70		11.3±3.9	13.4±1.4	14.6±.7.8