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SOLAR PARTICLE ABUNDANCES AT ENERGIES OF GREATER THAN 1 MeV PER NUCLEON AND THE ROLE OF INTERPLANETARY SHOCKS

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ABSTRACT

We have examined the abundances of elements in large solar energetic particle events in the energy range 2–12 MeV per nucleon. There are large variations in abundances from event to event but the data show an organization. As found by previous workers, we find that the abundances relative to mean values vary approximately monotonically as a function of mass (A), except for ^{4}He. Some events show a gradual depletion of heavy ions, whereas a smaller number show a gradual increase. In this paper we show for the first time a further organization of abundance data which depends on the longitude of the source region. The abundances as a function of longitude can be understood in terms of two particle sources, namely (1) particles originating out of flare-heated material and (2) particles accelerated at coronal and interplanetary shocks. The greatest depletions of heavy elements occur when source regions are near central meridian which is also where the strongest shocks originate. The depletions are matched by a steepening of the spectrum and can be understood in terms of diffusive shock acceleration. The greatest enhancements of heavy elements occur when source regions are near west 60°. In this situation the observer can be magnetically connected to flaring regions and have access to flare-heated material which is enriched in heavy elements.

Subject headings: interplanetary medium — shock waves — Sun: particle emission

1. INTRODUCTION

The abundances of elements averaged over large solar energetic particle (SEP) events are well-established (McGuire, von Rosenvinge, & McDonald 1986; Meyer 1985; Stone 1989, and references therein). But, as has been known since the earliest studies, individual events depart quite markedly from one another, with both temporal and energy-dependent changes taking place within single events. Various authors have attempted to determine the baseline or "source composition" with respect to which individual events are either enhanced or depleted. The baseline abundances of Meyer (1985) and Breneman & Stone (1985) differ slightly, particularly for S; Breneman & Stone (1985) do not include the abundance of ^{4}He. It is found that the baseline abundances differ from photospheric values in a consistent manner with those elements with a first ionization potential above 10 eV being underabundant by a factor of about 4. Within individual events changes from element to element behave more or less systematically with variations relative to the baseline taking place monotonically as a function of mass (McGuire, von Rosenvinge, & McDonald 1979; Cook et al. 1979; McGuire et al. 1986; Meyer 1985). It is anticipated that the relevant physical parameter is charge to mass (Q/A) since this parameter determines the particle magnetic rigidity when particles of the same velocity are compared. The mean charge states have been measured for 12 particle increases by Luhn et al. (1985). Using the average values for each of the eight elements measured by Luhn et al. (1985) and values for other elements inferred from theory, Breneman & Stone (1985) showed that flare-to-flare variations are, to first order, organised by Q/A. However, there are some inconsistencies between the measured charge states, the inferred coronal temperatures and the behavior of the elements as discussed in detail by Meyer (1985). The element ^{4}He is a particular problem, as it does not behave like C as it should if both are fully stripped.

In a recent paper (Reames, Cane, & von Rosenvinge 1990) we have examined the abundances of elements in a class of solar events which were selected on the basis of prompt onsets in electrons of ~ 1 MeV. Most events were short-lived and associated with impulsive flares. Such events have heavy element abundances which are enhanced over those in the solar corona. In a series of preceding papers (e.g., Reames 1988, 1990) it has been shown that these enhancements can be attributed to the fact that flare material is being sampled in these events. This assertion is supported by the observation that in this class of solar event the charge state of Fe is about 20 (Luhn et al. 1987). By comparison, in large long-lasting SEP events the charge state of Fe is about 14. It has also been noted by Reames, Cane, & von Rosenvinge (1990) that some large, well-connected events show a period of high Fe/C in the initial stages. At these times it is also likely that one is seeing flare material. Thus enhancements in heavy ions can be attributed to sampling material that has a different composition than the corona which is the source region for "normal" SEP abundances.

McGuire et al. (1986) noted that the two events of their study which had the lowest values of Fe/O were events in which the particles were probably accelerated at interplanetary (IP) shocks. Similarly Stone (1989) suggested that depletions of heavy elements probably result from shock acceleration. The effects of shocks were also discussed by Klecker, Scholer, & Hovestadt (1981) who found a decrease in the Fe/O ratio at the time of the passage of an IP shock. All these authors noted that Fe, with its higher rigidity relative to O (at the same energy per nucleon) would be less efficiently accelerated by shocks. Further support for this picture was provided by Klecker et al. (1981) who found that for the event of their study the Fe spec-

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trum also steepened more near the shock than did the spectra of light elements.

In a previous paper (Cane, Reames, & von Rosenvinge 1988) we have proposed that most of the particles seen in large solar energetic particle (SEP) events are accelerated in the IP medium at travelling shocks. We showed that the intensity profiles as a function of the longitude of the associated solar flare could be understood in terms of the large-scale structure of IP shocks. In the present paper we show that our proposal can also explain some of the abundance variations seen in large SEP events. The greatest depletions of heavy elements occur in SEP events associated with strong IP shocks and the depletions are largest when the shocks accelerate particles locally. We have previously determined that the lowest daily Fe/O ratios in our data base are associated with the passages of IP shocks (Cane, Reames, & von Rosenvinge 1990).

It has been brought to our attention by Meyer (1989, private communication) that, since charge state is clearly of importance, it is better to organize abundance variations using C as a reference rather than O since C is more likely to be fully stripped. In this paper all abundances are relative to C.

2. OBSERVATIONS

The abundance measurements described in this study were obtained using the VLET telescope of the Medium Energy Cosmic Ray Experiment (von Rosenvinge et al. 1978) on *ISEE-3*. Abundance measurements from this experiment have been reported previously (see Reames et al. 1990, and references therein). We determined event-averaged abundances for 36 large proton increases. These events were selected on the basis of having high (more than 0.03 particles cm^{-2} sr^{-1} s^{-1} MeV^{-1}) proton intensities above 20 MeV, being well associated with solar flares, and by being sufficiently isolated from other events. The events and the solar source longitude are given in Table 1. The flare times are for the Hα maxima. Note that these associations have been made by a number of researchers and many are substantiated by the association of IP type II radio emission (Cane 1985).

Our instrument enabled us to obtain measurements of C, N, O, Ne, Mg, Si, S, and Fe in three energy ranges: 2–3, 4–7, and 7–12 MeV per nucleon. In addition, we obtained abundances for ^{4}He in the lowest range and Ca in the two higher ranges. Figure 1 illustrates mean abundances, averaged over all the events, for our highest energy range (which is the one most compatible with previous studies). The values in Figure 1 have been normalized relative to the baseline values of Breneman & Stone (1985), which were obtained at an energy of 5–15 MeV per nucleon, and it can be seen that there is agreement. Values for all three energy ranges are given in Table 2 along with the Breneman & Stone (1985) baseline values for all ions but ^{4}He. For ^{4}He we give the Meyer (1985) value. Note that these authors have attempted to construct a "baseline" based on certain criteria. Our values are just the mean of a number of event averages.

Our results suggest an energy dependence for the abundances. Figure 2 shows O, Si, and Fe abundances for individual events for the energy ranges 2–3 and 7–12 MeV per nucleon (*filled and open circles*, respectively). For none of the events are the O abundances at the two energies significantly different, whereas there are a number of events for which the Si abundances show an energy dependence. For most events the Fe abundances are significantly different at the two energies. Energy dependence of abundance ratios was reported by McGuire et al. (1986) who also found that the energy dependence is more pronounced for elements of greater *A*.

Figure 3 shows correlations between the mean particle intensites for ^{4}He, N, O, Ne, Mg, Si, S, and Fe as a function of mean intensites of C in the energy range 2–3 MeV per nucleon. The correlation coefficients are given. Note that in this figure the uncertainties on the points are smaller than the symbols used. It is clear that the element that behaves most like C is N and that O is very similar. The correlation decreases thereafter as a function of *A*. Note that if the relationship between the elements were strictly a function of *Q*/*A* then at a coronal

TABLE 1

DETAILS OF THE EVENTS

Event Number	Flare Time	Solar Longitude
1	1978 Sep 23 1000	W50
2	1979 Apr 3 0112	W14
3	1979 Jun 5 0514	E14
4	1979 Jul 4 1920	E36
5	1979 Aug 18 1430	E90
6	1979 Sep 14 0700	E90
7	1979 Nov 15 2140	W35
8	1980 Apr 4 1509	W35
9	1980 Jul 17 0604	E06
10	1980 Oct 15 0524	E55
11	1980 Nov 23 1755	W20
12	1981 Apr 1 0117	W52
13	1981 Apr 10 1651	W36
14	1981 Apr 24 1408	W50
15	1981 May 8 2214	E37
16	1981 May 16 0831	E14
17	1981 Jul 20 1322	W75
18	1981 Aug 7 1911	E25
19	1981 Oct 7 2311	E83
20	1981 Oct 12 0620	E31
21	1981 Dec 9 1825	W16
22	1982 Jan 31 2344	E13
23	1982 Mar 7 0250	W53
24	1982 Jun 6 1617	E25
25	1982 Jul 9 0737	E76
26	1982 Jul 12 0918	E36
27	1982 Jul 22 1707	W89
28	1982 Nov 22 1817	W36
29	1982 Nov 26 0236	W87
30	1982 Dec 7 2351	W86
31	1982 Dec 17 1857	W20
32	1982 Dec 25 0720	E45
33	1983 Feb 3 0608	W07
34	1984 Feb 17 2229	E81
35	1984 Mar 14 0324	W43
36	1984 Apr 25 0001	E45

TABLE 2

SOLAR ENERGETIC PARTICLE ABUNDANCES

Element	Abundance 2–3 MeV per nucleon	Abundance 4–7 MeV per nucleon	Abundance 7–12 MeV per nucleon	Breneman & Stone (1985)
^{4}He/C	116 ± 6.4	...	...	132[a]
N/C	0.27 ± 0.01	0.27 ± 0.01	0.27 ± 0.02	0.29
O/C	2.0 ± 0.05	2.2 ± 0.06	2.2 ± 0.12	2.3
Ne/C	0.31 ± 0.01	0.33 ± 0.02	0.35 ± 0.03	0.33
Mg/C	0.43 ± 0.02	0.44 ± 0.02	0.46 ± 0.04	0.45
Si/C	0.31 ± 0.02	0.31 ± 0.02	0.36 ± 0.04	0.37
S/C	0.086 ± 0.008	0.063 ± 0.007	0.075 ± 0.001	0.082
Ca/C	...	0.031 ± 0.006	0.028 ± 0.01	0.025
Fe/C	0.32 ± 0.05	0.33 ± 0.06	0.46 ± 0.11	0.35

[a] Meyer 1985.

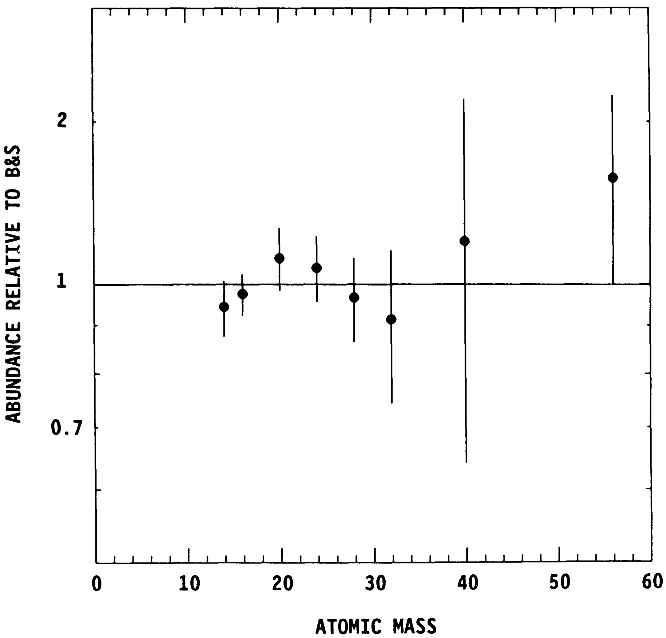

FIG. 1.—Mean event-averaged abundances in the energy range 7–12 MeV per nucleon normalized by the baseline abundances of Breneman & Stone (1985), as a function of atomic mass number.

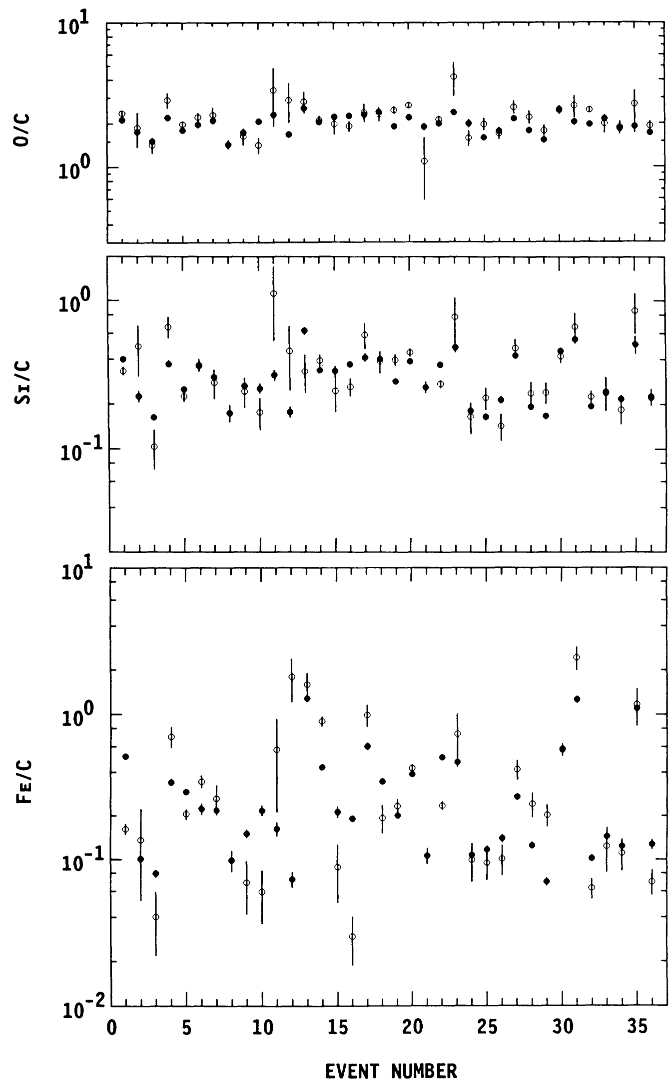

FIG. 2.—Event-averaged abundances of O, Si, and Fe relative to C, for the 36 events of this study for the energy ranges 2–3 MeV per nucleon (*filled circles*) and 7–12 MeV per nucleon (*open circles*).

temperature of about 10^6 K calculations imply that the element most like C should be N but followed in order by Ne, Mg, and O (see Fig. 11 of Meyer 1985). If we use the average charge states which were measured by Luhn et al. (1985) and a calculated value for Ca from Breneman & Stone (1985), then the Q/A ordering, which we have listed in Table 3, also puts O after Ne and Mg. This is not consistent with the correlation coefficients obtained from Figure 3.

At most coronal temperatures C and He should be fully stripped and have the same Q/A. However there is observational evidence for He^+ in SEPs (Hovestadt et al. 1981, 1984). For large SEP events the ratio of He^+/He^{++} is about 0.07 (Hovestadt et al. 1984). However this gives the same Q/A (0.48) as one obtains for C using the mean charge state of C measured in SEPs by Luhn et al (1985). Thus if Q/A effects were the only ones affecting abundances, He and C should behave in the same way. However the correlation coefficient between the ^{4}He and C intensities is slightly less than that between Mg and C. Note that in Figure 3 the scatter is considerably less than in a similar figure (using daily average intensities) presented by Mason et al. (1980) at a slightly lower energy (0.6–1 MeV per nucleon). Also we do not find the large variations in the He/O ratio within single events as discussed by Meyer (1985) who used the Mason et al. (1980) data. Thus the behavior of ^{4}He is not as erratic as presented by Meyer (1985). The ^{4}He/C ratio correlates positively with the behavior of the heavier ions. Events showing enhancements in heavy ions also show enhancements in ^{4}He. In Figure 4 (*lower panel*) we show ^{4}He/C as a function of O/C for each of the events. The correlation is weak but clearly positive. However the interesting feature is to compare Figure 4 (*upper panel*) with Figure 4 (*lower panel*) where a corresponding plot for N is shown. It would seem that in about two-thirds of the events the ^{4}He behaves in the same manner as the N. The remaining one-third of the events show large increases or decreases in ^{4}He.

In Figure 5 we show abundance enhancements relative to our mean values as a function of "Q"/A (see Table 3 for element identification) for some individual events for the energy range 2–3 MeV per nucleon. We do not know what the actual charge states are in these events, and like Breneman & Stone (1985) we assumed the charge states as measured by Luhn et al. (1985). The value for Ca is theoretical. Nevertheless, Figure 5 illustrates further that abundance variations are greatest for Fe with the other elements showing correlated but smaller variations. For ^{4}He we assumed a Q/A of 0.5 but note that the ^{4}He data in Figure 5 would be more consistent with the other elements if ^{4}He had a Q/A of about 0.4. This would imply an He^+/He^{++} value of about 0.3.

TABLE 3

Q/A VALUES INFERRED FROM LUHN et al. (1985) OBSERVATIONS

Element	C	N	Ne	Mg	O	Si	S	Ca[a]	Fe
Q/A	0.48	0.46	0.45	0.45	0.44	0.39	0.34	0.28	0.27

[a] Not measured.

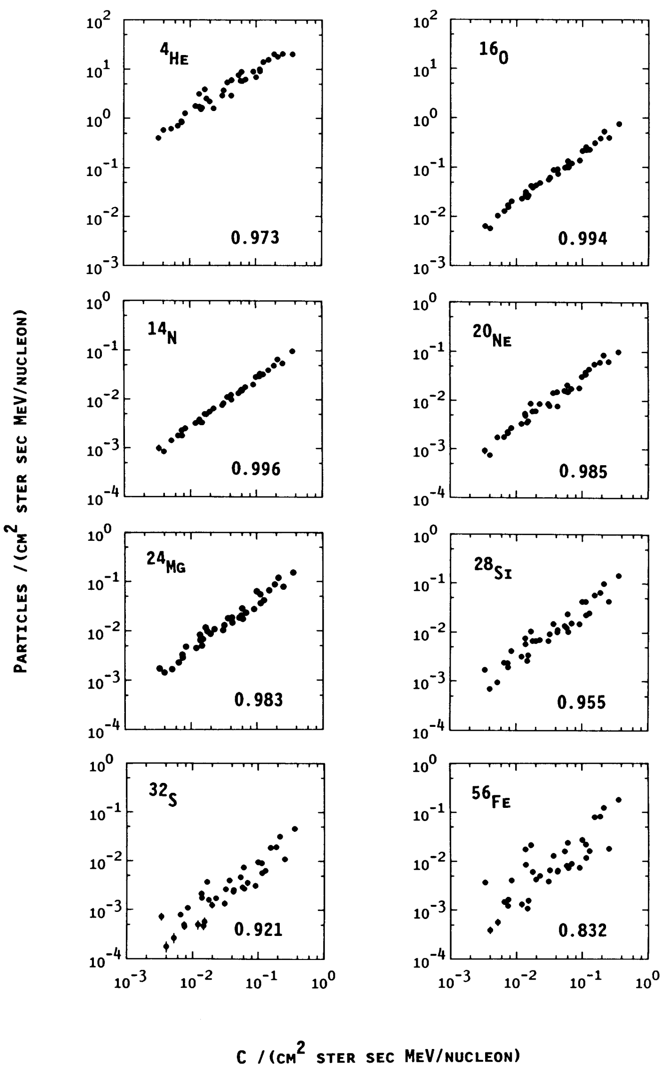

FIG. 3.—Event-averaged intensities (2–3 MeV per nucleon) of eight elements as a function of C intensities. Correlation coefficients are noted.

Finally we illustrate the abundance variations for all the events and all the species. Figure 6 shows the abundances relative to C as a function of the Fe/C ratio for each event (see Fig. 5 in Reames et al. 1990). Clearly the variations are correlated. However there is also scatter in the plot which is larger than the errors on the individual points.

We have illustrated that to first order, abundance variations relative to C increase monotonically as a function of A, except for ^{4}He. Thus to understand the dominant abundance variation, it is sufficient to look at variations in Fe relative to C (or in the Fe/C ratio). In Figure 7 we have plotted the Fe power-law slopes (derived from the ratio of the 2–3 MeV per nucleon to the 7–12 MeV per nucleon Fe intensities) as a function of the 7–12 MeV per nucleon Fe/C ratios. For two events the high energy intensities are too small to measure. For the 34 events the correlation coefficient is 0.48 which corresponds to a less than 1% probability that the quantities are not correlated.

As discussed above it has been proposed that enhancements in heavy ions occur because of a different source material. Reames et al. (1990) suggest that significant flare-heated material occurs in events with an Fe/C ratio of 0.5 or greater. The fact that there are few events of this kind in our study stems from our requirement of a high flux of more than 20 MeV protons. Iron-rich events are proton-poor. If we determine the correlation coefficient for the events in Figure 7 with Fe/C less than or equal to 0.5 we obtain a value of 0.71 which, for 24 events, is highly significant.

Finally we show (Fig. 8) the variation of the Fe/C ratio as a function of the source region of the event. Simultaneously we show the steepness of the spectrum. The circle size is a measure of the power-law slope as plotted in Figure 7. The important features of Figure 8 are the high Fe/C values for western regions and the low Fe/C values combined with steep spectra for central meridian regions. This figure shows a remarkable similarity to the panel showing the highest energy data of Figure 11 of Cane et al. (1988). In that figure we had plotted peak intensities at energies above 100 MeV for large proton events.

3. TIME HISTORIES

To gain a better understanding of the abundance variations it is necessary to look at time histories of individual events.

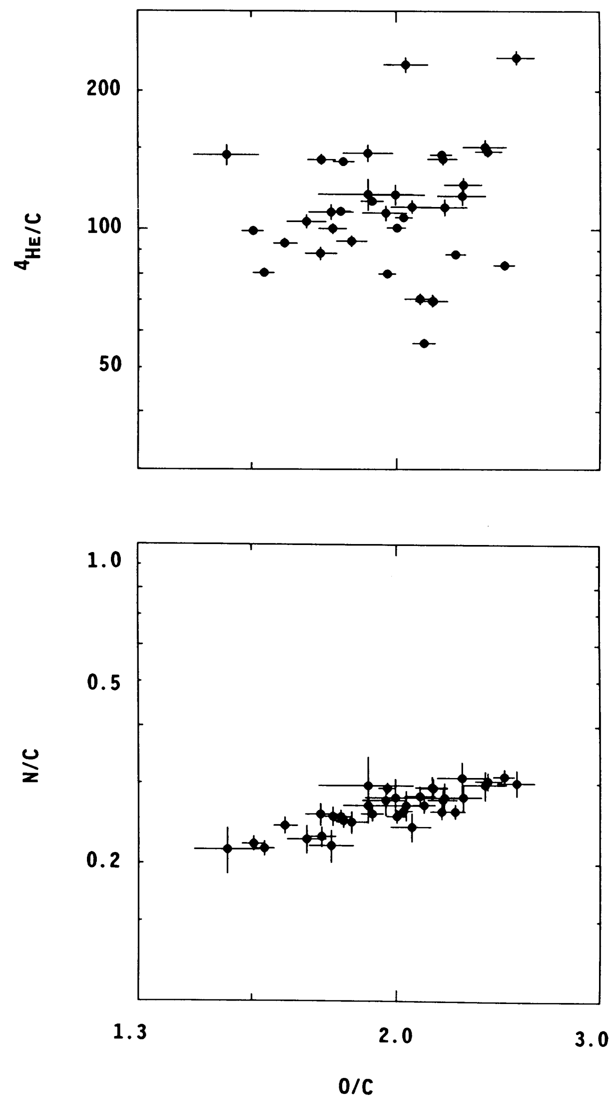

FIG. 4.—^{4}He/C (*upper panel*) and N/C (*lower panel*) ratios as a function of O/C ratios at 2–3 MeV per nucleon for the 36 events.

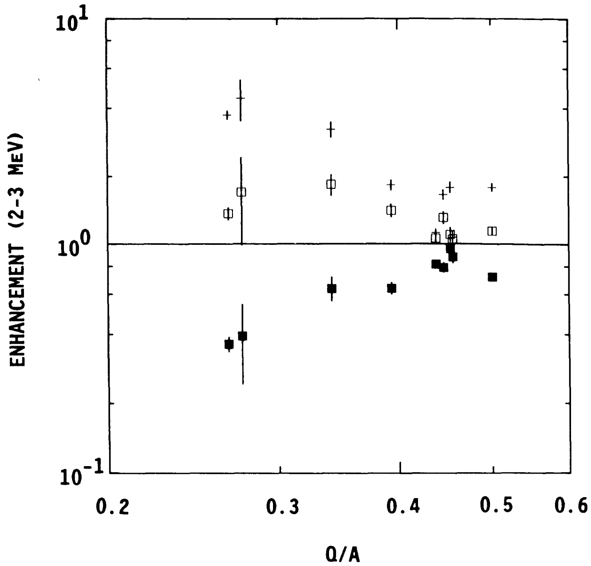

FIG. 5.—Enhancements/depletions relative to mean values (2–3 MeV per nucleon) as a function of Q/A, assuming Q/A values from Breneman & Stone (1985)—see Table 3. For the ^{4}He a Q/A of 0.5 is assumed. The three events shown are (*pluses*) 1981 April 10, (*open squares*) 1982 March 07, and (*filled squares*) 1984 February 17.

Figure 9 shows the Fe/O and ^{4}He/O variations (for the 2–3 MeV per nucleon range) as a function of time for six time periods. The measurements are 2 hr averages. In this figure we use O as the reference because the effect we want to illustrate is more prominent using O instead of C. The times of flare onsets are indicated by vertical lines and flare longitudes are noted. The ratios have been normalized to our event-averaged mean values. Looking first at ^{4}He/O it can be seen that for the 1982 July 22, 1982 December 7, and 1982 November 26 events this ratio shows a low value at onset which gradually increases throughout the event. All these events are ones with low event-averaged abundances of ^{4}He/C as seen in Figure 4*a*. In comparison the events of 1981 April 24, 1981 July 20, and 1982 November 22 have "normal" event-averaged abundances of ^{4}He/C and do not show the low ^{4}He/O value at event onset. For the 1981 August 7 event the event-averaged ^{4}He/O is normal. For this event, and the majority of those originating in eastern regions, the time period over which the event-average was performed is well after the solar flare event. The slow rise of eastern events means that there are only a few heavy ions until well after onset.

Look now at the Fe/O ratios for the six time periods of Figure 9. The 1981 April 24 and July 20 events show high Fe/O values at event onset. Reames (1990) has argued that this is due to the presence of material of a different composition (i.e., flare-heated material). Clearly this effect is large and might be expected to manifest itself in the ^{4}He/O ratio. The most likely possibility is that it causes an enhancement of ^{4}He relative to O since the two events with the highest Fe/C ratios also have the highest ^{4}He/C ratios (see Fig. 6). This enhancement of ^{4}He/C (or ^{4}He/O) would probably overpower a depletion caused by another process. In other words we think that these events would have had a steadily increasing ^{4}He/O ratio as a function of time, like the events discussed in the previous paragraph, except for the presence of flare-heated material.

We have used data from our experiment on IMP-8 (McGuire et al. 1986) to look at the ^{4}He/O ratio at a similar energy ($\sim$4 MeV per nucleon) and the proton/^{4}He ratio at a similar energy ($\sim$2 MeV per nucleon). We find that at higher energies the ^{4}He/O ratio is relatively constant throughout the majority of events. The proton/^{4}He ratio shows a similar behavior to the ^{4}He/O ratio at 2 MeV per nucleon.

4. DISCUSSION

4.1. ^{4}He

The behavior of ^{4}He is peculiar. If Q/A effects could explain all abundance variations the ratio ^{4}He/C should not vary from event to event since ^{4}He and C should have the same Q/A. Figure 6 shows that ^{4}He/C varies and correlates positively (albeit weakly) with the Fe/C ratio. From Figure 4 it can be seen that the majority of the events have ^{4}He/C values which behave in a similar manner to the N/C ratios. The high ^{4}He/C values we attribute to the presence of flare-heated material. We found that in seven events with low ^{4}He/C values the ratio is low near onset and increases throughout the event. These events are free of flare material. In the events which lie on the same "track" as the N/C in Figure 4 the event-averaged abundances do not encompass periods shortly after the associated solar events. In these smaller, more poorly connected events we do not detect sufficient particles to determine abundances until many hours after the solar flare. The low ^{4}He/C ratio at onset has been previously reported in terms of an enhancement of the O/^{4}He ratio (Mason et al. 1983). In that paper the decrease of the O/^{4}He ratio as a function of time was matched to a decrease in the Fe/O ratio, and both were attributed to rigidity-dependent propagation. Figure 9 shows that these two effects do not, generally, go together. Furthermore the flattening of the ^{4}He/O ratio does not coincide, except for a few events, with velocity dispersion as it should if this were a propagation effect. In addition this explanation must invoke charge states lower than are observed. If we ignore the question of the disparity between the measured charge states at 1 AU and effects which imply rigidity differences between elements, then we suggest that the depression of the lighter elements (^{4}He and protons) early in events arises because of their difficulty in escaping the shock region.

4.2. *Heavy Ions*

Enhancements of heavy ions occur in impulsive flare events and have been discussed in detail by Reames et al. (1990). Some gradual events show an Fe-rich phase at event onset which we believe is indicative of flare-heated material. It can be seen in Figure 8 that all but two of the events with an Fe/C ratio above average originate in well-connected regions. In the two exceptions there are additional ways in which these events are unusual. One event, 1981 October 12, is the only prompt ground-level enhancement ever recorded from such an easterly source. Richardson, Cane, & von Rosenvinge (1991) discuss the peculiar interplanetary magnetic field conditions which enabled the high-energy particles to propagate so freely to the earth. These same field conditions would also provide connection for flare-heated material. The other event, 1979 July 5, was peculiar in that few particles were seen from the solar event. The majority of the particles were seen after shock passage.

Let us then concentrate on the heavy ion depletions. As discussed in the introduction, heavy ion depletions have been attributed to shock acceleration. However, most of the previous work has only been in terms of a general recognition that shock acceleration should result in depletions. Acceleration at

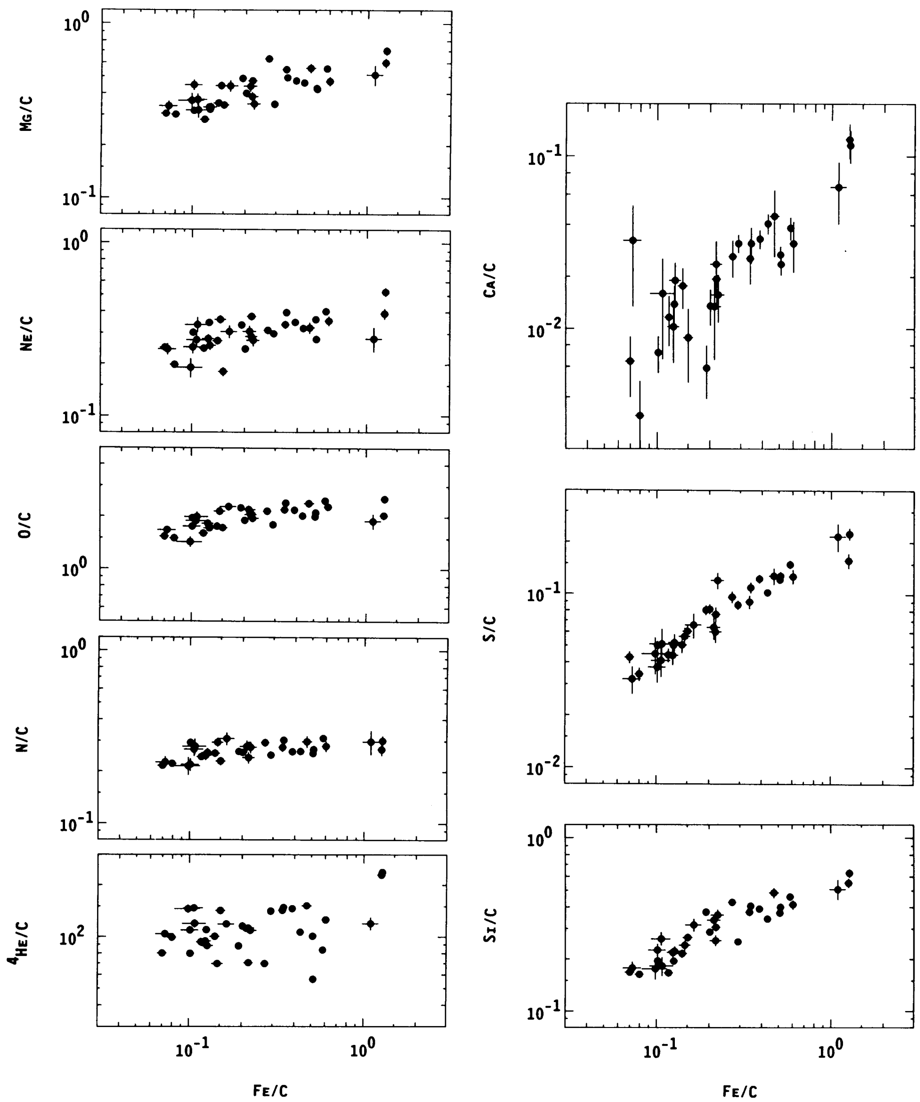

FIG. 6.—Abundances relative to C as a function of Fe/C at 2–3 MeV per nucleon. The Ca/C ratio is at 4–7 MeV per nucleon.

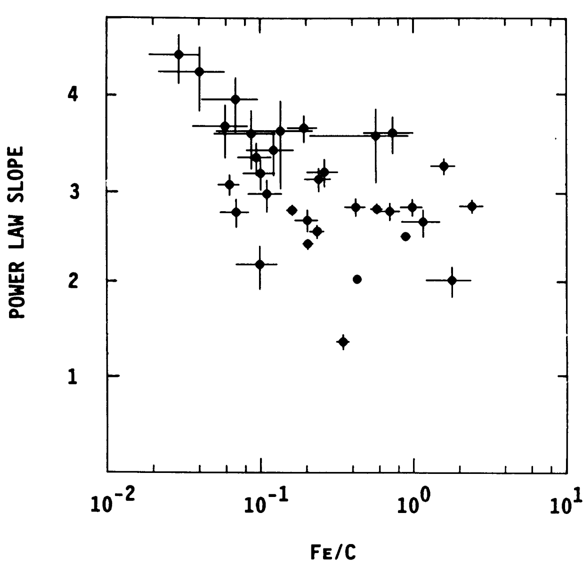

FIG. 7.—Event-averaged power law slopes as a function of Fe/C. The slopes are derived from the ratio of the 2–3 MeV per nucleon to the 7–12 MeV per nucleon Fe intensities. The Fe/C ratio is at 7–12 MeV per nucleon.

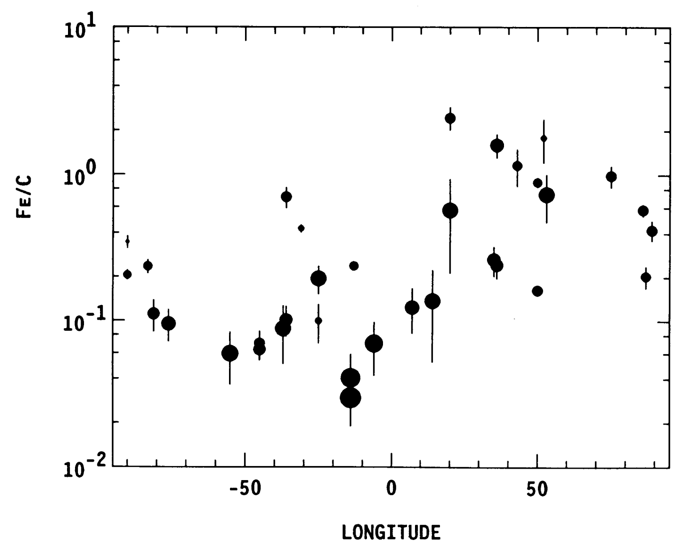

FIG. 8.—Fe/C ratios (at 7–12 MeV per nucleon) as a function of the longitude of the source region. The size of the circle indicates the power-law slope. Large circles indicate steep spectra.

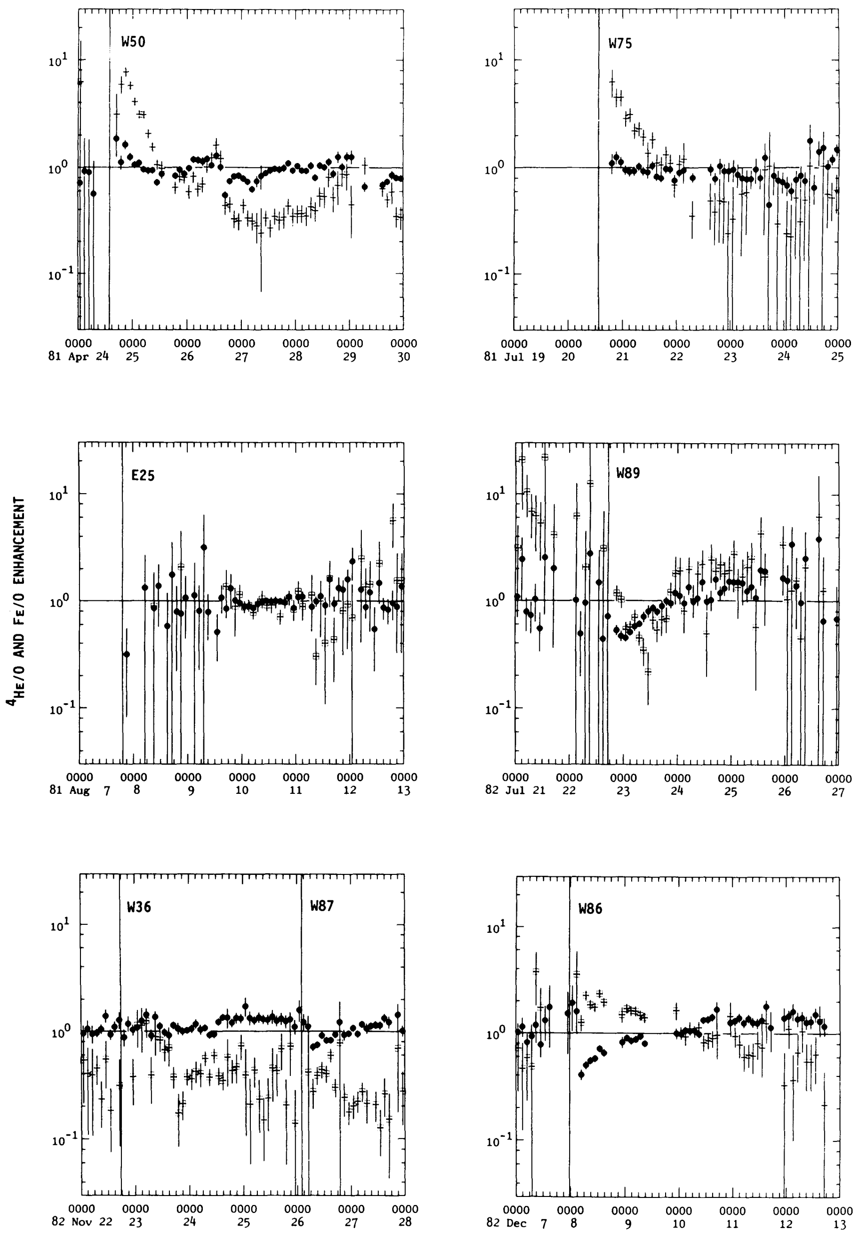

FIG. 9.—Normalized (relative to mean abundances of all events) abundance ratios at 2–3 MeV per nucleon as a function of time. Vertical lines indicate flare times and the flare longitudes are noted. ^{4}He/O and Fe/O ratios are indicated by filled circles and open squares, respectively.

a shock is rigidity-dependent so at the same energy per nucleon, partially ionized Fe ions (e.g.) will have a higher rigidity and hence be less efficiently accelerated than fully stripped C ions. The work of Klecker et al. (1981), who studied the time history of a single shock associated enhancement, is more detailed. In addition to the decrease of the Fe/O ratio in the shock vicinity they also find a spectral steepening which is greater for Fe than for O. They conclude that both these variations can be understood in terms of diffusive shock acceleration under conditions in which equilibrium conditions have not yet been attained. In steady state conditions diffusive shock acceleration should give the same power-law differential energy spectra for all species. We believe this same explanation can account for the variations seen in SEP events since we believe that most of the particles seen in large events are shock-accelerated. In Cane et al. (1988) we proposed that interplanetary shock acceleration was a prolonged phenomenon and was not restricted to the so-called energetic storm particle events in which one detects a distinct enhancement around shock passage. We suggest that the relative abundance changes as a function of longitude of the source region, shown in Figure 8, support this proposal.

The largest depletions of Fe and the steepest Fe spectra occur for solar events originating between about W20 and E50. This is where the strongest observed shocks originate (see Fig. 5 of Cane 1988). When these strong shocks pass the spacecraft, particles are being locally accelerated. Thus the spectra are steep and the depletions are marked. For western events the shocks are relatively weak by the time they reach the earth and there is little local acceleration. The majority of the particles will have been accelerated by relatively strong shocks in the low corona. Many events show enhancements in Fe/C due to an early contribution from the impulsive phase either directly or by reacceleration by coronal shocks. For eastern events most of the observed particles have been accelerated at some considerable height in the solar corona including some that have been accelerated beyond 1 AU.

As pointed out by Reames (1990) it is unlikely that the so-called "seed population" of IP shocks is Fe-rich flare material. The abundance data cannot differentiate between the corona and the solar wind as a seed population because they have the same composition. We believe that most of the time the seed population is the solar wind. In the Cane et al. (1990) study we found a number of particle events with low Fe/O ratios which were associated with IP shocks which were not preceded by solar flares.

We noted the similarity of the Fe/C distribution and the distribution of high-energy (>100 MeV) proton peak intensities. In fact a correlation plot of these two quantities for the 34 events of Figure 8 gives a correlation coefficient of 0.49. We do not think these quantities are correlated because of some direct physical connection. An observer must be well-connected to have access to flare-heated material and to the highest energy (500 MeV) particles so both phenomena have relatively narrow longitude distributions with peaks around west 50°. At lower energies (about 100 MeV) particles can be detected at other connection longitudes but at reduced intensities and only in association with interplanetary shocks. The connection to a shock and the shock properties then determine both the observed intensities and abundances.

5. SUMMARY

We have examined the abundances of elements in 36 large SEP events and find, as have previous workers, that event-averaged abundances of elements change monotonically as a function of A, except for ^{4}He. Nitrogen and oxygen behave very similarly to C with Ne, Mg, and Si showing slightly more scatter. Much larger changes are exhibited by ^{4}He, S, Ca, and Fe. Abundance variations cannot be entirely explained assuming only simple Q/A effects and typical charge states measured in other events.

We show for the first time a further organization of abundance data which depends on the longitude of the source region. Enhancements in Fe/C (and other heavy elements relative to C) occur when source regions are near west 60°. We attribute the enhancements to sampling of flare-heated material. This material may have a relatively high ^{4}He/C ratio.

Depletions in Fe/C (and other heavy elements relative to C) are greatest for source regions near central meridian. Depletions are matched by a steepening of the spectrum and can be understood in terms of diffusive shock acceleration.

We find that, as reported previously, ^{4}He does not behave like heavier elements. We show by examining time histories of individual events that the erratic behavior results primarily from changes at event onset.

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