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ENERGETIC PARTICLE ABUNDANCES IN SOLAR ELECTRON EVENTS

D. V. REAMES, H. V. CANE,[1] AND T. T. VON ROSENVINGE
NASA/Goddard Space Flight Center
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ABSTRACT

We report on the results of a comprehensive search of the *ISEE 3* energetic particle data for solar electron events with associated increases in elements with atomic number $Z \geq 6$. A sample of 90 such events was obtained. The events support earlier evidence of a bimodal distribution in Fe/O or, more clearly, in Fe/C. Most of the electron events belong to the group that is Fe-rich in comparison with the coronal abundance. The Fe-rich events are frequently also ^{3}He-rich and are associated with type III and type V radio bursts and impulsive solar flares. Fe-poor events are associated with type IV bursts and with interplanetary shocks. Some large well-connected events show Fe-rich intensity profiles early in the event, followed almost immediately by Fe-poor material associated with the rapidly approaching shock. These large two-component events usually show radio signatures of multiple phases of acceleration.

With some exceptions, event-to-event enhancements in the heavier elements vary smoothly with Z (or, probably, with the charge-to-mass ratio, Q/A) and with Fe/C. In fact these variations extend across the full range of events despite inferred differences in acceleration mechanism. The origin of source material in all events appears to be coronal and not photospheric. To the extent that the abundance variations are smooth with Z and with Fe/C, they argue against any first ionization potential–dependent fluctuations in the coronal abundances from one flare site to the next. The Ne/C ratio does show a discontinuity between the Fe-poor and the Fe-rich regimes that is consistent with an increase in the source abundance of Ne in impulsive flares or with a particularly large slope in Ne/C as a function of Fe/C.

Subject headings: Sun: abundances — Sun: flares — Sun: particle emission — Sun: radio radiation

I. INTRODUCTION

Measurements of the abundances of elements and isotopes provide a powerful tool that has allowed the identification of physical mechanisms that take place in a wide variety of astrophysical objects. The abundances in the Sun and in the protosolar nebula have become the standard against which other such measurements are judged (see Meyer 1985*a*, *b*).

The abundances of elements in the solar corona differ in a reasonably well-determined way from those in the Sun itself (Meyer 1985*a*, *b*). Elements with a first ionization potential (FIP) greater than 9 eV are suppressed in the corona by about a factor of 4 relative to their photospheric abundance, presumably because neutral atoms are transported up into the corona less efficiently than singly ionized ones. Confidence in our knowledge of the coronal abundances comes, in part, from agreement between recent measurements in the solar wind (see Bochsler, Geiss, and Kunz 1986; Schmid, Bochsler, and Geiss 1988 and references therein) and in large solar energetic particle (SEP) events (Breneman and Stone 1985; McGuire, von Rosenvinge, and McDonald 1986; Mason 1987; Stone 1989) and in the related interplanetary (IP) shock events (Cane, Reames, and von Rosenvinge 1990). Direct spectroscopic measurements of several key elements (especially O/Mg and Ne/Mg) also show evidence of the FIP–dependent fractionation of the corona (Meyer 1985*a*, *b*).

While SEP observations show some abundance variations in the large proton events, they show a dramatic difference in the abundances associated with impulsive solar flares (see reviews by Lin 1987; Mason 1987; Reames 1990). Historically, these events are called ^{3}He-rich events because they were first identified by ^{3}He/^{4}He ratios in the range 0.1–10.0, a huge enhancement over the coronal ^{3}He/^{4}He ratio, which is about 5×10^{-4}. The events are accompanied by enhancements of heavy nuclei of over an order of magnitude for Fe/O (Mason *et al.* 1986; Reames 1990) in comparison with the coronal Fe/O, and they are observed to be associated with low-energy electron events and the related type III radio bursts (Reames, von Rosenvinge, and Lin 1985, hereafter RvL; Reames and Stone 1986) and with impulsive X-ray events (Reames *et al.* 1988). The heavy elements in these events are also observed to be in higher ionization states than in large SEP events or in the solar wind (Luhn *et al.* 1987). Charge states of Fe, especially indicate that the temperature of the source region for impulsive flares is greater than 10^7 K. Reames (1988*a*) found that the element abundances in ^{3}He-rich events seemed to be correlated with the soft X-ray temperature of the flare.

We presently understand the abundance enhancements in the ^{3}He-rich events in terms of selective heating by resonance absorption of plasma waves by a mechanism such as that proposed by Fisk (1978) or by a related nonresonance mechanism (Varvoglis and Papadopoulos 1983). Recently, Winglee (1989) has proposed a model involving wave-particle interactions during coronal evaporations. The paradigm for understanding the differences between SEP events (Lee and Ryan 1986; Lin 1987; Luhn *et al.* 1987) is that the particles in impulsive events come directly from flare-heated material, while those in the large SEP events are accelerated by a coronal or IP shock from ambient coronal/solar wind material.

For many years the small solar ^{3}He-rich, Fe-rich events were believed to be a rare phenomenon. However, the number of these events has grown as instruments have become more sensitive. Also, searches for similar small events from impulsive flares without ^{3}He or Fe enhancements find almost no events.

[1] Also Department of Physics and Astronomy, University of Maryland, College Park.

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To determine the rate at which these small Fe-rich events occur, Reames (1988*b*; see also Reames, Ramaty, and von Rosenvinge 1988) examined daily averaged abundances over an 8 yr period and found a bimodal distribution of Fe/O that distinguished the ^{3}He-rich, Fe-rich, electron-rich events from their large-event counterparts. Reames (1990) presented more complete arguments that these enhanced-abundance events were typical of virtually all impulsive flares. Thus, it seems that the most common flares have the most unusual particle abundances.

Nearly all of the actual abundance measurements discussed above, however, pertain to impulsive flare events as a class rather than to discrete flare events. The studies of abundances in ^{3}He-rich events by Mason *et al.* (1986), for example, involves extensive time intervals that contain groups of flares, and the daily averages of Reames (1988*b*) include unknown numbers of events on a given day. The study of the relationship between abundances and flare temperature (Reames 1988*a*) does involve individual flares, but only about a dozen of them meet all of the necessary criteria. If we are to make further progress in understanding enhanced abundances in impulsive flares, we must obtain more information on individual events.

One of the clearest ways to locate impulsive events is by looking for electron increases. Electrons above 200 keV are nearly relativistic, and they flow freely outward along the IP magnetic field; hence they arrive within minutes of their acceleration. Energetic electron events were also the basis of the first paper to compare the particle properties of events associated with impulsive and gradual X-ray flares (Cane, McGuire, and von Rosenvinge 1986, hereafter CMvR). Element abundances have not been investigated previously in these events.

In the present paper we report the results of a comprehensive scan of the *ISEE 3* data base for solar electron events accompanied by measurable intensities of heavier elements. While the sample was not artificially restricted to impulsive flare events, the intent of this work is to obtain a sufficiently large sample to permit flare-to-flare studies of the abundances of elements in impulsive flare events.

II. OBSERVATIONS

a) Instrumentation and Event Selection

The particle measurements described in this paper were made with the Medium Energy Cosmic Ray Experiment (von Rosenvinge *et al.* 1978) aboard the *ISEE 3* spacecraft. Particle abundance measurements from this experiment have been reported in some detail (see von Rosenvinge and Reames 1979; Reames, von Rosenvinge and Lin 1985; Reames 1988*a*, *b*; Reames, Ramaty, and von Rosenvinge 1988). From launch in 1978 August through 1982 September, *ISEE 3* remained in halo orbit about the *L*1 Lagrangian point, 240 Earth radii sunward of the Earth. From 1982 September through 1983 December the spacecraft executed a series of maneuvers that took it into the deep geomagnetic tail region and thereafter began moving ahead of the Earth in solar orbit. Data coverage has not been uniform during the mission; coverage fell drastically after 1983 when the spacecraft began to be tracked by the Deep Space Network. In addition, electron data were not available for a period of 6 months at the end of 1979.

We used the 30 minute averaged data base from launch through 1987 February to conduct a computer search for statistically significant increases in the intensity of 0.2–2.0 MeV electrons. An increase was defined as two consecutive time periods with intensities that exceeded, by 2 standard deviations, the average intensity during the previous eight time periods. The computer-selected events were examined visually to eliminate spurious events that occurred during times of high background, etc. Many of the nonsolar electron increases occurred during 1983 from extremely rapid increases in terrestrial electrons when *ISEE 3* was in the Earth's magnetosphere. The magnetospheric electrons were identified by a lack of increases in any ion species. A sample of 250 candidate electron events resulted from this procedure.

Since we wished to study abundances of elements, we then selected events with distinct increases in 2–3 MeV amu^{-1} particles with $Z \geq 6$ above preexisting background, if any. To ensure that the events were solar, we required that the elements, including He, exhibit velocity dispersion, i.e., a delay of at least 1 hr after the electron onset as evidence of propagation through a distance of at least 1 AU. A sample of 90 solar electron events with a measurable number (≥ 6) of heavy ions resulted from this process.

Event-averaged abundances of elements were determined by integrating the intensities over the duration of each event. The integration was terminated when the intensities approached background, when a new onset was observed, or after a duration of 30 hr. The particles are observed to stream outward along magnetic field lines throughout impulsive flare events (see RvL; Reames and Stone 1986); hence integration over the event is an appropriate measure of the number of particles injected at the Sun (see, for example, Van Hollebeke, McDonald, and Meyer 1990).

To establish a framework for discussing the events and to relate them to earlier work, we first show the distribution of Fe abundances observed. Figure 1 shows both the Fe/O and the Fe/C distributions for the electron events. The events with well-measured ^{3}He enrichments (^{3}He/^{4}He > 0.1) are shown by the circle size in the intensity distributions and by the blackened region in the histograms. The diagonal lines in Figure 1 are drawn at coronal abundances as determined from the "mass-unbiased" abundances reported by Meyer (1985*a*); these same coronal abundances are indicated in the histograms. Different numbers of events appear in the Fe-C (82) and Fe-O (88) plots because a few events do not have measurable intensities of both C and O.

Meyer (1985*a*; 1989, private communication) has suggested that C may provide a better reference than O in these events, since it is more likely to be fully stripped of electrons. Using C as a reference does seem to improve the resolution of the Fe-rich and Fe-poor events, and we use this reference in the remainder of this paper where abundances for all events are compared. In individual events, however, where resolution is less important, we show the more familiar O intensities to permit comparison with earlier published data.

The Fe/O distribution in Figure 1 may be compared directly with similar daily averaged measurements of Reames (1988*b*). The presence of both particle populations, Fe-rich and Fe-poor, discussed in that earlier work, can be seen in the figure. Observationally, it is much easier to classify events on the basis of Fe/C than on the basis of ^{3}He/^{4}He. We can observe that an event is ^{3}He-rich, but we cannot easily say that an event is ^{3}He-poor from our measurements at low energy. An event with ^{3}He/^{4}He ≤ 0.1, i.e., below our low-energy instrumental limit, could be ^{3}He-rich by a factor of 200 in comparison with the coronal or solar wind value of ^{3}He/^{4}He $\sim 5 \times 10^{-4}$. For this reason, Fe/O or Fe/C may provide a more measurable indica-

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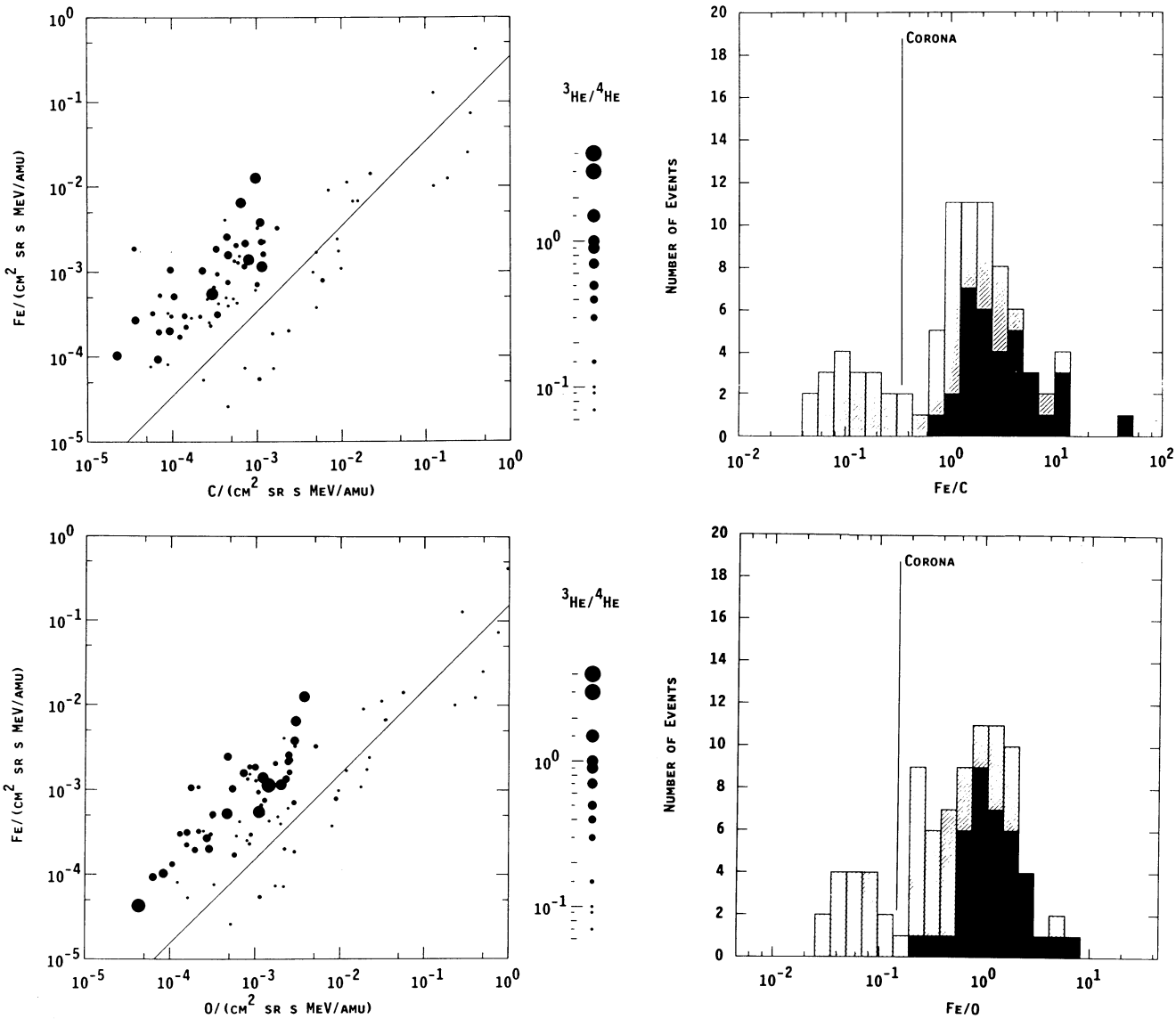

FIG. 1.—Left-hand panels show the intensity of 1.9–2.8 MeV amu^{-1} Fe vs. the intensities of C and O at the same energy for the 90 electron events in which heavy elements are observed. ^{3}He-rich events are indicated by the circle size, which increases logarithmically with ^{3}He/^{4}He as shown. The right-hand panels show histograms of the distribution of Fe/C and Fe/O in the electron events with the ^{3}He-rich subset blackened. The plots may be compared with similar plots of daily averaged abundances shown by Reames (1988*b*). The diagonal lines are drawn at the "mass-unbiased" coronal abundances of Meyer (1985*a*), and these same values are indicated in the two histograms.

tor of the presence or absence of impulsive flare–related material.

b) *Time-Intensity Profiles*

The next three figures show time-intensity profiles of some of the individual events that contribute to Figure 1. Figure 2 shows some of the variety in electron, He, O and Fe abundances in the moderate-sized events in the sample. The events are flagged with the longitude of the associated Hα flare, if any. The flare and radio associations are discussed in greater detail below. The 1980 June 7 event shown in Figure 2 is a well-known γ-ray line event (Forrest *et al.* 1981). The event shows one of the largest electron increases in the sample, but it has extremely low intensities of the heavy nuclei. The 1980 July 8 event in the next panel of Figure 2 shows a small increase in electrons but a substantial increase in Fe. Note the low relative abundance of ^{4}He and the fact that the Fe/O ratio is near 1.0 in this event. The 1980 November 10 event shows somewhat lower Fe/O and higher ^{4}He/O. The event on 1980 November 11 is one of the rare small events with Fe/O $\approx$ 0.1. Finally, the 1981 February 7 event shows somewhat smoother profiles and greater propagation delays than seen in the other events. Both the 1981 February 7 and the 1980 June 7 events show electron increases prior to the large increase. We are unable to associated heavy-ion increases with these earlier events, and we believe that the observed ion increases are associated with the large electron increase; however, some ambiguity does exist in such associations.

At this point we should also note that Fe-rich flare events often occur in sequences of many events from the same active region. These sequences have been discussed in detail elsewhere and are only mentioned here, although most of them are

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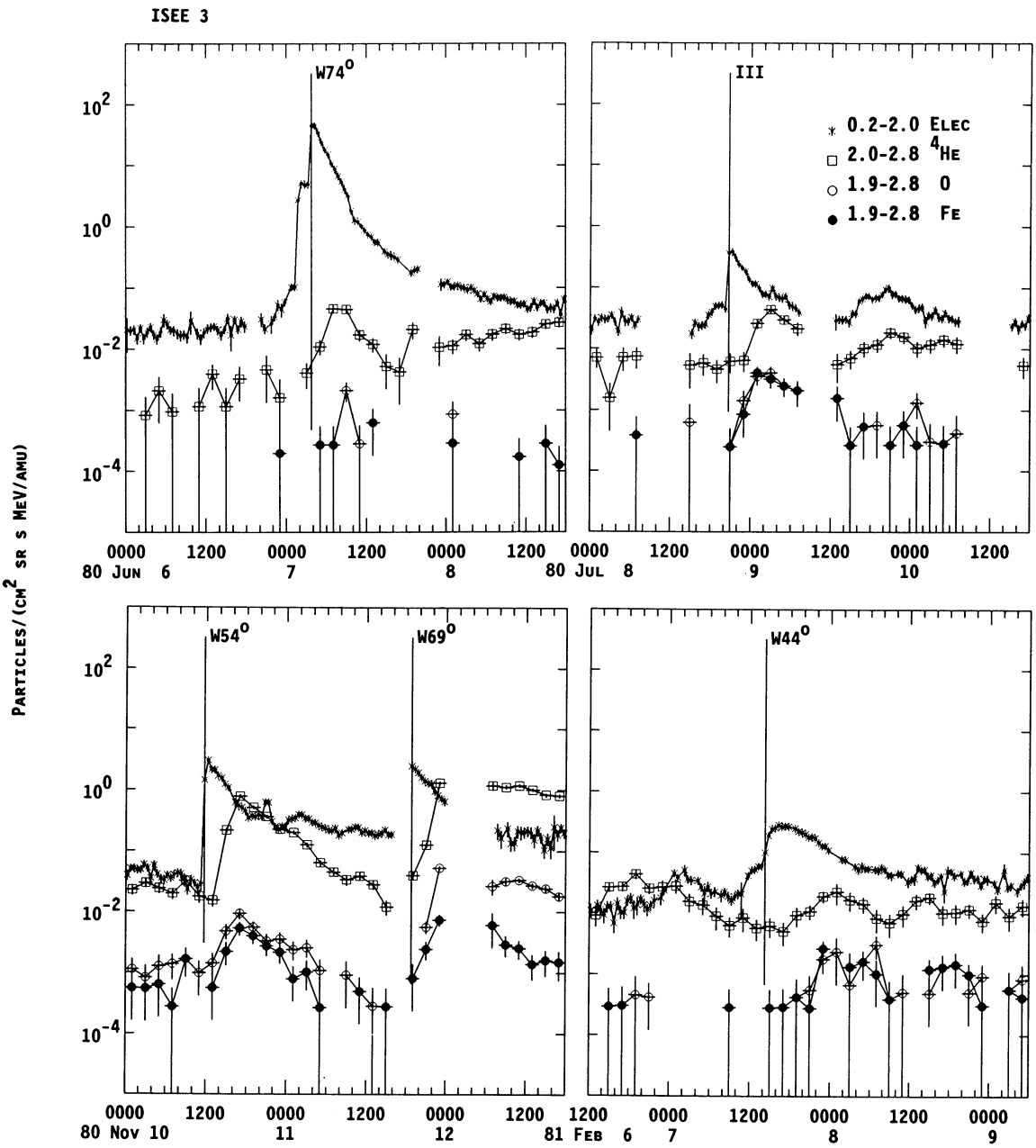

FIG. 2.—Time-intensity plots for the indicated particle species for several of the electron events. The event times are flagged with the longitude of the Hα flare, if any, or the time of the type III burst is indicated. The plots show the variety of abundance variations among the events (see text).

included in the sample. Electron and Fe intensities for the 1980 April 11–14 sequence are shown in Reames (1990). The 1982 August 13–14 sequence is shown in Reames and Stone (1986). The 1979 September 6 sequence discussed by RvL also includes Fe-rich events but is not included here because the electron instrument was not operating during the last 6 months of 1979.

Figure 3 shows an interesting period during 1981 November that demonstrates the contrast between Fe-rich and Fe-poor phenomena that is often seen. The flare-associated increases on 1981 November 20 and 22 show typical impulsive electron increases and accompanying ions enriched in Fe (Fe/C = 2.0 ± 0.6 and 2.5 ± 0.8, respectively). About 12 hr after the second event, after the particle intensities have diminished, a gradual rise in the ions is seen up until the passage of a shock on November 25. The shock is associated with a gradual flare event on November 22 at 0658; this event is not flagged in the figure, since it has no electron increase that passes the selection criteria of this study. Notice that the shock-associated material is extremely Fe-poor ($0.1 \leq \mathrm{Fe/C} \leq 0.2$, during the 2 days of the event). The intensities of Fe in this extended event remain below those seen in the preceding flares, even though the ^{4}He intensity is one or two orders of magnitude larger (electron intensities are omitted during the large event because the sensitive telescope measuring electrons is saturated by the high intensities of low-energy protons). With few exceptions, the Fe-poor periods involve large extended events associated with interplanetary shocks. These events are slightly under-

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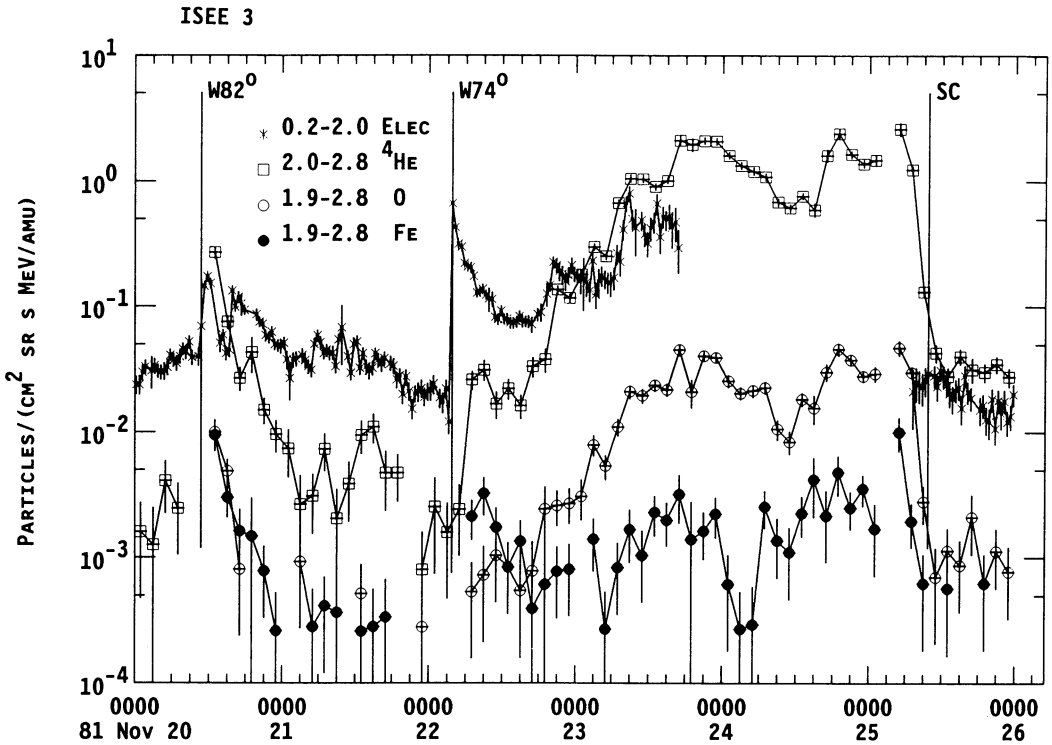

FIG. 3.—Two impulsive electron events with high Fe/O ratios followed by a slow intensity increase with an extremely low Fe/O ratio that we believe to be an IP shock–associated event. This type of contrast in abundances related to these types of sources is often observed.

represented in the present study because the time scale used in the electron scan tends to bias against extremely slow increases. Fe-poor and shock-associated events have been made the subject of a separate study (Cane, Reames, and von Rosenvinge 1990).

In large well-connected events, Fe-rich and Fe-poor components are often juxtaposed in time. A good example of an event like this is shown in Figure 4. Especially at higher energies, the Fe-rich component from the early phases of the event may be seen to form a well-defined peak. Subsequently, Fe-poor material from the rapidly approaching shock begins to encroach and Fe/O falls to a new equilibrium value like that found in isolated shock events (Cane, Reames, and von Rosenvinge 1990). Several of the large events in the sample show evidence of two components like the 1981 April 24 event in Figure 4.

c) *Relative Abundances of the Elements*

For each of the electron events, we examined the abundances of the dominant elements, H, He, C, N, O, Ne, Mg, Si, S, Ca, and Fe, principally in the 1.9–2.8 MeV amu^{-1} energy interval. Figure 5 shows several of the abundance ratios plotted as a function of Fe/C. Points with large errors (>70%) have been omitted from the plots. To the extent that Fe/O (and hence also Fe/C) correlates with flare temperature (Reames 1988*a*), it may be appropriate to think of the abundances in Figure 5 as being plotted as a function of temperature. The open circles in Figure 5 are plotted at the SEP "mass-unbiased baseline" abundances of Meyer (1985*a*). These abundances purport to represent the coronal material from which the energetic particles are accelerated. Since the Meyer abundances do not include H/^{4}He, the spectroscopic coronal abundance $\sim$10 is plotted in Figure 5; the solar wind value $\sim$25 may be equally appropriate. More recent large-event SEP abundance measurements (Breneman and Stone 1985; McGuire, von Rosenvinge, and McDonald 1986; Cane, Reames, and von Rosenvinge 1990) are in good agreement with most of the abundances in the Meyer (1985*a*) survey.

The values of the abundances in individual events are given in Tables 1 and 2. In order to limit the events tabulated to those with significant abundances of all species, only events with an error in Fe/C less than $\pm$50% have been included. Errors shown in the table are Gaussian statistical errors only, based upon the number of particles observed. Thus only 51 of the 90 events are tabulated. The division of events between the two tables has been made at Fe/C = 0.5, roughly the value that separates the two populations in Figure 1. In the tables and in Figure 5, most of the abundance ratios are measured in the 1.9–2.8 MeV amu^{-1} energy interval. However, primarily because of instrument limitations, H/^{4}He, Ca/C, and ^{3}He/^{4}He are measured in the 4.4–6.4, 3.0–7.0, and 1.3–1.6 MeV amu^{-1} intervals, respectively. The reader should note some low-energy (1.9–2.8 MeV amu^{-1}) Ca abundances reported previously (Reames 1988*a*) have been found to be contaminated with Fe. Therefore, the 3.0–7.0 MeV amu^{-1} interval that is free from this contamination is used here.

It has been noted (Reames 1990) that the proton intensity itself shows a strong inverse correlation with Fe enhancement. In Figure 6 we show Fe/C as a function of the proton intensity. Figure 6 also shows the poor correlation of Fe/C with the peak electron intensity. The correlation of Fe/O with *p*/*e* noted in earlier work (Reames 1988*b*) is clearly being influenced by protons rather than electrons. Note that Fe/C is actually more strongly correlated with proton intensity (Fig. 6) than with the H/^{4}He ratio (Fig. 5).

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TABLE 1

ABUNDANCES OF ELEMENTS IN Fe-RICH EVENTS

Onset	$H/^4He$	$^4He/C$	N/C(%)	O/C(%)	Ne/C(%)	Mg/C(%)	Si/C(%)	S/C(%)	Ca/C(%)	Fe/C(%)	$^3He/^4He$(%)
1978 Sep 23 1015	8.9± 3.0	23.6± 1.2	31± 2	245± 9	33± 2	57± 3	63± 3	23± 2	2.7± 0.4	107 ± 5	<10
Oct 9 2045	466. ± 176.	245. ± 93.	65± 38	356±151	184± 85	105± 55	133± 65	41± 28	24. ± 20.	171 ± 80	<10
1980 Apr 19 1530	28.4± 3.1	93. ± 38.	30± 25	92± 53	62± 40	31± 25	124± 67	32± 26	<98	215 ± 105	15± 5
Jul 8 2030	9.6± 1.1	58. ± 23.	65± 38	553±226	237±106	145± 70	186± 86	68± 40	49. ± 43.	580 ± 236	27± 5
Aug 6 1615	119. ± 19.	73. ± 18.	59± 23	434±116	76± 27	76± 27	55± 22	28± 14	<10	87 ± 30	<10
Oct 15 0630	167. ± 53.	63. ± 10.	24± 9	252± 48	32± 10	56± 15	37± 11	8± 5	5.5± 4.0	63 ± 16	<10
Oct 23 1100	35.1± 3.5	125. ± 40.	27± 18	249± 92	65± 32	83± 38	84± 38	10± 10	<25	74 ± 35	<10
Oct 25 1000	7.8± 0.4	98. ± 14.	23± 7	210± 35	116± 22	85± 17	55± 13	26± 8	14. ± 11.	188 ± 32	<10
Nov 10 1145	7.8± 0.5	239. ± 46.	57± 18	297± 66	92± 15	109± 29	65± 20	21± 10	<9	188 ± 44	<10
1981 Feb 7 1400	6.8± 0.8	34. ± 13.	<13	316±136	66± 39	119± 60	53± 33	54± 34	<14	277 ± 121	<10
Mar 23 0700	8.0± 0.8	56. ± 19.	40± 24	236± 92	143± 61	123± 54	93± 44	32± 21	33. ± 38.	451 ± 165	28± 5
Apr 10 <1930	61.4± 12.	162. ± 11.	29± 4	270± 19	50± 5	69± 7	72± 7	23± 3	9.2± 3.4	129 ± 10.5	<10
Apr 24 1400	19. ± 2.2	70.2± 2.6	29± 2	228± 7	39± 2	58± 2	48± 2	20± 1	7.5± 1.1	103 ± 3.7	<10
Jul 20 1330	106. ± 22.	89.3± 4.3	30± 3	268± 13	42± 3	60± 4	58± 4	19± 2	6.2± 1.8	96 ± 6.0	<10
Jul 28 2045	100. ± 10.	159. ± 40.	23± 12	271± 78	81± 30	52± 22	76± 28	36± 17	20. ± 22.	115 ± 39	<10
Jul 31 0100	<20	80. ± 31.	13± 14	158± 75	171± 80	132± 65	159± 76	14± 14	<14	343 ± 146	33± 5
Aug 21 <1115	110. ± 13.	102. ± 29.	7± 7	184± 63	36± 19	106± 40	64± 28	22± 14	<14	121 ± 44	<10
Nov 7 0500	42.8± 4.6	75. ± 21.	21± 14	149± 53	57± 26	142± 51	93± 36	29± 17	16. ± 18.	248 ± 81	<10
Nov 14 <2230	151. ± 21.	213. ± 59.	35± 18	376±116	50± 23	135± 49	50± 24	29± 17	<20	213 ± 71	17± 5
Nov 20 1045	9.5± 1.4	50. ± 13.	46± 20	231± 68	121± 40	133± 43	105± 36	48± 21	<33	202 ± 61	<10
Nov 22 0345	27.5± 3.3	40. ± 12.	15± 12	138± 52	123± 47	115± 45	70± 31	16± 12	98. ±139.	246 ± 83	<10
1982 Jan 2 0615	23.6± 2.1	202. ± 49.	64± 24	288± 80	152± 46	130± 41	126± 40	56± 22	16. ± 13.	320 ± 88	<10
Jan 3 0030	29. ± 2.8	102. ± 30.	8± 8	169± 61	46± 23	92± 38	70± 31	24± 15	<98	215 ± 74	<10
Feb 10 2030	-	116. ± 29.	63± 24	283± 81	138± 44	81± 30	70± 27	66± 25	<12	167 ± 52	<20
Feb 14 0845	12.5± 0.8	76. ± 16.	42± 16	302± 73	130± 36	143± 39	118± 34	26± 12	8. ± 8.	361 ± 86	<20
Feb 20 0915	4.8± 0.3	173. ± 58.	71± 37	512±186	543±196	287±110	155± 65	95± 45	148. ± 95.	974 ± 340	<10
Mar 10 1900	25.7± 2.1	54. ± 10.	26± 10	176± 39	39± 13	60± 17	81± 21	25± 10	33. ± 38.	101 ± 25	74± 5
Jun 25 1945	17. ± 2.4	64. ± 16.	57± 23	265± 77	144± 46	150± 48	99± 34	36± 17	14. ± 15.	352 ± 99	36± 5
Aug 13 2300	9.1± 1.7	77. ± 35.	109± 66	387±193	129± 76	332±168	334±169	152± 87	<15	1310 ± 606	80±10
Aug 14 0500	8.9± 1.5	146. ± 60.	76± 46	461±206	415±187	369±168	310±144	127± 69	44. ± 24.	999 ± 426	25± 5
1983 Jan 5 0615	-	36. ± 12.	61± 32	154± 64	72± 36	31± 20	21± 16	<11	24. ± 28.	174 ± 72	71± 9
Jan 5 1345	10.9± 1.0	88. ± 19.	42± 16	210± 54	84± 26	101± 30	55± 19	39± 15	24. ± 20.	164 ± 44	<20
1984 Apr 6 2200	3.7± 0.4	73. ± 26.	57± 33	277±113	104± 50	81± 42	46± 28	12± 13	<33	161 ± 71	24± 5
Apr 7 0300	4.5± 0.3	75. ± 19.	22± 12	212± 62	98± 33	87± 30	82± 29	22± 13	28. ± 22.	136 ± 43	<20
May 20 2230	<600	63.9± 4.8	24± 3	254± 18	31± 4	37± 4	39± 4	12± 2	7.3± 2.5	64.3± 6.1	<10
May 31 1145	150. ± 50.	170. ± 42.	38± 17	282± 79	92± 32	92± 32	66± 25	17± 11	66. ± 60.	70 ± 26	11± 5

III. RADIO AND Hα FLARE ASSOCIATIONS

For each of the 90 electron events we searched the *Solar Geophysical Data* for associated radio bursts and Hα flares. Radio bursts were found for 80 of the events and Hα flares for 59 of them.

In Figure 7 we show each of the metric radio-burst types and intensities on Fe versus C plots. Type III bursts and type V emission are strongly associated with the Fe-rich population. Type IV bursts tend to be associated with the Fe-poor events. The type II bursts occur with comparable probability in both classes of event, as was noted initially by CMvR. Several of the events emit many types of radio burst. The 1981 April 24 shown in Figure 4 has type III, type II, and type IV bursts, all with intensity 3, so it is not surprising that we find evidence of both Fe/O populations in the event. In large two-phase events,

TABLE 2

ABUNDANCES OF ELEMENTS IN Fe-POOR EVENTS

Onset	$H/^4He$	$^4He/C$	N/C(%)	O/C(%)	Ne/C(%)	Mg/C(%)	Si/C(%)	S/C(%)	Ca/C(%)	Fe/C(%)	$^3He/^4He$(%)
1978 Dec 11 2030	166. ± 35.	94.5± 5.1	27± 3	226± 13	30± 3	52± 4	38± 4	7± 1	4.3± 3.1	19. ± 2.3	<10
1979 Apr 3 <0400	43.1± 8.5	80.1± 3.2	25± 2	186± 7	25± 2	48± 2	24± 2	4± 1	<0.8	8.1± 0.8	<10
1980 Apr 4 1615	206. ± 46.	99.5± 6.4	24± 3	150± 12	19± 3	41± 5	20± 3	5± 1	<10	13.3± 2.3	<20
Nov 11 1830	41.6± 2.9	84.8± 5.4	31± 4	252± 18	43± 5	58± 6	33± 4	11± 2	3.5± 3.5	27.2± 3.4	<10
1981 Mar 28 0430	81.9± 8.2	74.0± 9.4	17± 5	94± 16	23± 6	25± 7	16± 5	1± 2	<33	8.5± 3.6	<10
Dec 5 1430	166. ± 33.	55.9± 4.6	46± 6	210± 20	24± 4	37± 5	32± 5	7± 2	18.9± 9.2	21.6± 3.9	<10
Dec 27 0730	77.7± 11.	50.4± 4.1	28± 5	237± 21	31± 5	34± 5	33± 5	9± 2	1.6± 1.6	33.6± 5.0	<10
1982 Feb 7 0045	31.1± 4.0	62.7± 4.2	31± 4	224± 16	43± 5	71± 7	54± 5	13± 2	1.2± 1.2	43.5± 4.7	<10
Mar 7 0330	83.4± 11.	105.0± 4.8	30± 3	251± 12	33± 3	60± 4	53± 4	14± 2	5.7± 2.4	49.5± 3.5	<10
Jul 22 1715	17.7± 2.2	35.4± 1.3	29± 2	220± 6	31± 2	64± 3	42± 2	10± 1	0.9± 0.4	21.3± 1.2	<10
Sep 4 0630	112. ± 18.	61.1± 5.1	21± 4	159± 16	24± 4	39± 6	17± 3	0± 1	<3	7.5± 2.2	<10
Nov 21 1445	46.4± 3.3	71.1± 4.6	26± 3	178± 13	32± 4	32± 4	19± 3	3± 1	<2.2	11.1± 2.1	<10
Nov 26 0245	12.9± 1.9	50.0± 1.5	22± 1	157± 3	25± 1	31± 1	17± 1	5± 1	0.4± 0.2	7.9± 0.5	<10
Dec 25 0745	90.1± 19.	54. ± 11.	24± 10	243± 55	34± 13	27± 11	10± 6	11± 6	<12	10.2± 6.2	<10
1983 Feb 3 0600	59.9± 9.8	44.9± 1.7	31± 2	218± 7	34± 2	44± 2	21± 1	5± 1	0.5± 0.3	6.7± 0.7	<10

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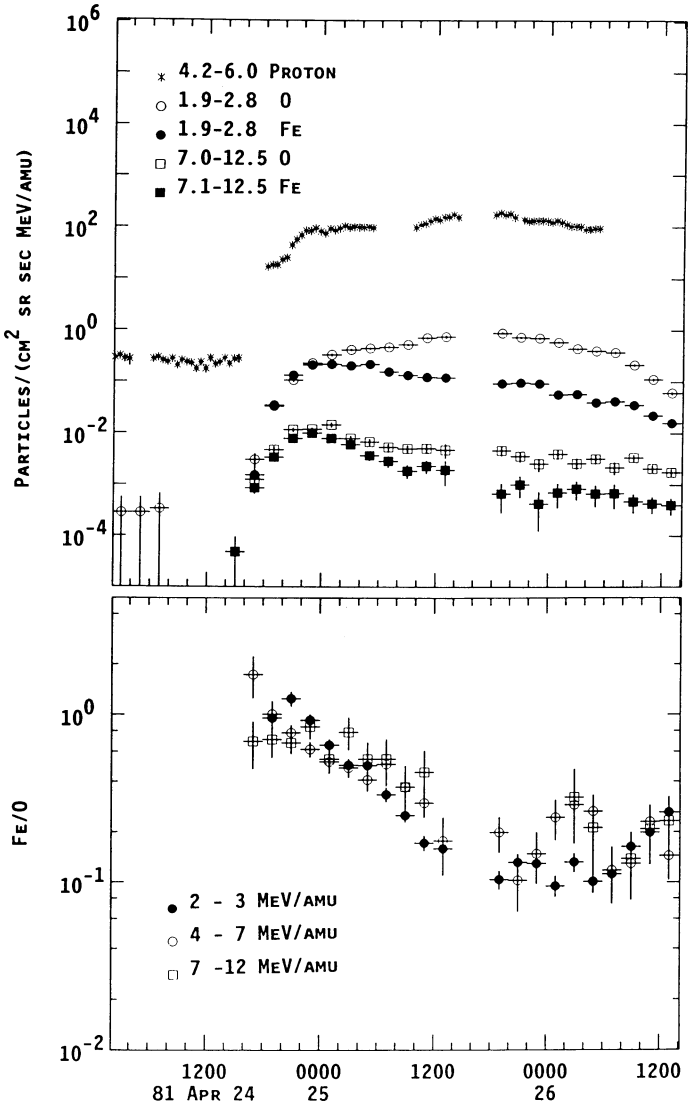

FIG. 4.—Several of the large well-connected flare events show Fe-rich material early in the event, followed immediately by Fe-poor material like that of the 1981 April 24 event shown. In these large energetic events the impulsive-phase and IP shock components are both present.

the observability undoubtedly depends upon the relative strength of the two phases and on the flare longitude.

In Figure 8 we show Fe/C as a function of the flare longitude for events with Hα flares. Nearly 90% of the flares with Fe/C > 0.5 come from the western hemisphere on the Sun, and 75% of them come from longitudes between 30° and 70° west. Events with Fe/C < 0.5 show a more uniform distribution from 50° east to 90° west. As stated previously, slow-rising events from far-eastern flares are not well represented in this study.

The distribution of Fe/C versus Hα flare durations is shown in Figure 9. Fe/C shows a general decline with flare duration. Most, but not all, of the Fe-rich flares have durations that are less than an hour. Most of the Fe-poor flares have durations greater than an hour. Nevertheless, Fe-rich and Fe-poor events are not distinguished solely on the basis of flare duration. The single event in the lower left-hand corner of Figure 9 is the 1981 March 28 event. This same event stands out with O/C ≈ 1.0. We believe that it is likely that the heavy ions in this event are only coincidentally associated with the flare and the electron increase; however, we have no *a priori* reason to reject the event.

IV. DISCUSSION

Perhaps it is not surprising that our understanding of particle abundances in impulsive solar events, which began with the observations in ^{3}He-rich events and was enlarged by studies of daily averaged composition, remains valid for the large sample of individual solar electron events that we have studied here. The electron events show evidence of a bimodal distribution in the Fe/C ratio.

Most of the events in this study are in the population in which Fe/C is enhanced by an order of magnitude over the value in the solar corona. These Fe-rich events are strongly associated with type III and type V radio bursts, and any associated Hα flares are usually relatively impulsive. Very few of the events are accompanied by type IV bursts. The events are observed only when the flare is magnetically well connected with the Earth. In these events, the lower velocity ions arrive with a 2–6 hr delay after the near-relativistic electrons. The abundances remain constant throughout the events. The events usually have low proton intensities.

Over half of the Fe-poor electron events are associated with type IV radio bursts. Frequently they are slow-rising events that are associated with IP shocks. Nearly always they have high proton intensities. In a related study, Cane, Reames, and von Rosenvinge (1990) find that the mean value of Fe/O in events associated with strong IP shocks is 0.11 ± 0.017, and also find that 72% of the periods with low Fe/O have associated shocks. The associations between type IV radio bursts, coronal mass ejections (CMEs), IP shocks, and large proton events are now well established (Svestka and Fritzova-Svestkova 1974; Svestka 1976; Kahler 1982*a*, *b*; Kahler *et al.* 1984; Cane, Reames, and von Rosenvinge 1988; Kahler, Reames, and Sheeley 1990). The CMEs drive IP shocks which accelerate particles, often to much higher energies than those considered here. The lack of Fe-rich material in these events and their association with IP shocks suggests that particles are accelerated directly from the solar wind rather than reaccelerating the Fe-rich particles from the preceding impulsive flare, if any, i.e., the Fe-rich particles from the flare do not become the "seed population" for the IP shock.

This view helps to understand large complex events like the one shown in Figure 4 which begin as normal Fe-rich impulsive flare events but subsequently become Fe-poor shock-associated events. Depending upon the relative strength of its impulsive and its CME/IP shock phases, the event-averaged abundances will appear more or less Fe-rich. Events of this type obviously blur the bimodal distribution.

In a sense, the present paper is an extension of the studies of electron events by CMvR (see also Cane and Reames 1990). In order to increase the size of the event sample, we have used 200 keV electrons rather than 3 MeV electrons. With the larger sample, we are able to find a large number of events with significant abundances of heavy elements. However, despite small differences in the time covered by the CMvR study, 12 of the CMvR impulsive events and 18 of the long-duration events had sufficient numbers of heavy nuclei to be among the 90 events studied here. All but one of these impulsive events have Fe/C > 0.5. Of the 18 long-duration events, 10 have Fe/C < 0.5 and eight have Fe/C > 0.5. The 1981 April 24 event shown in Figure 4 is one of these eight Fe-rich, long-duration

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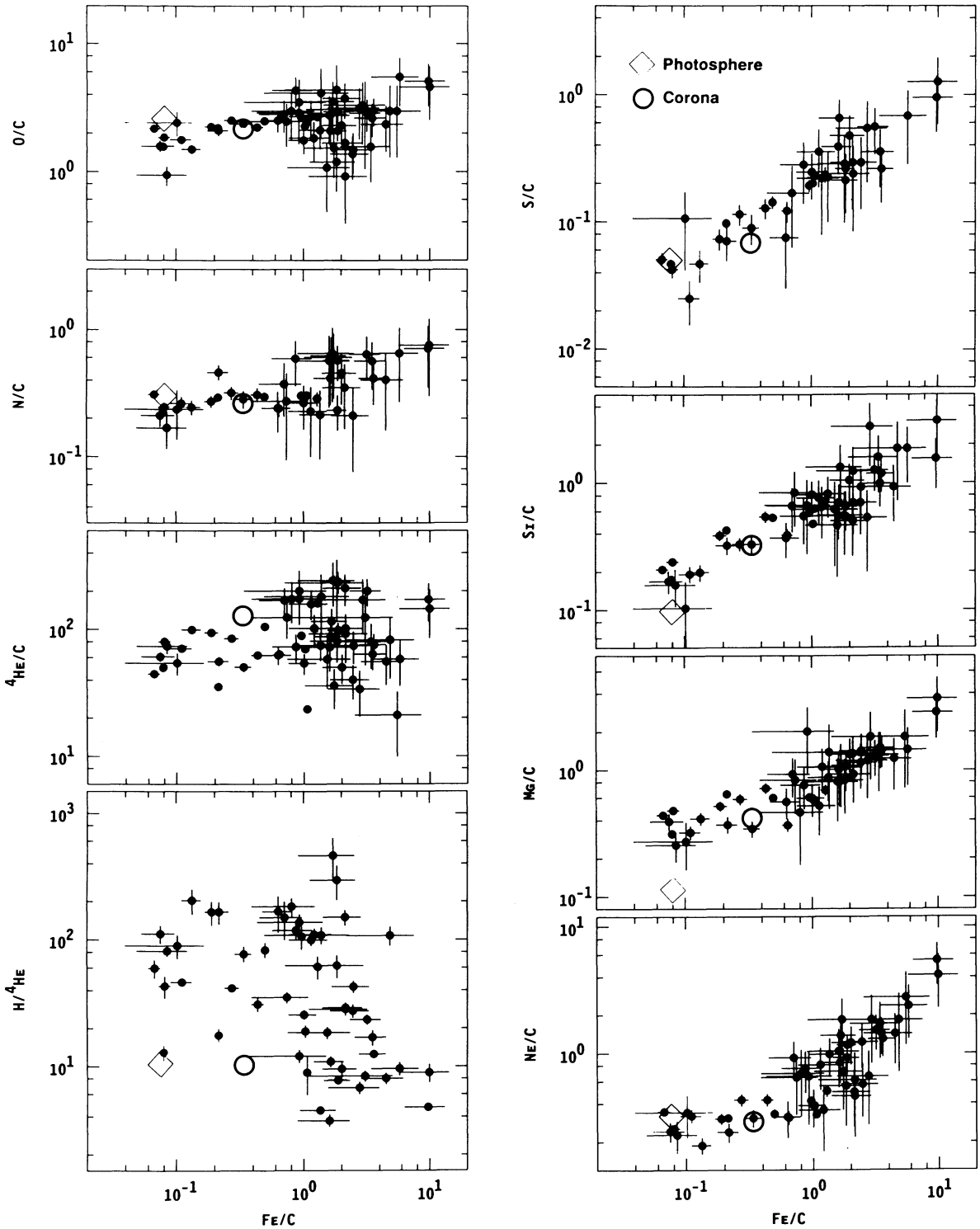

FIG. 5.—Abundance ratios for a variety of elements as a function of Fe/C. Individual electron events are represented as filled circles. The open circles show the SEP "mass unbiased" abundances of Meyer (1985*a*) that represent source coronal abundances, and diamonds mark the photospheric abundances. The coronal abundances represent a reasonable point of departure for most of the acceleration-induced variations, while the photospheric abundances do not.

events, and several of them are similar complex multiphase events. In some of these events we cannot rule out the possibility that Fe-rich material from a weak first phase is being accelerated by the coronal or interplanetary shock and hence is being incorporated into the strong second phase so that the event remains Fe-rich throughout.

The inverse correlation of Fe/C with proton intensity, seen in Figure 6, parallels a similar correlation between ^{3}He/^{4}He and proton intensity that was described many years ago (Ramaty *et al.* 1980). It is not strictly correct to generalize this correlation as being dependent upon "event size." Protons seem to play a special role; the correlation of Fe/C with ^{4}He

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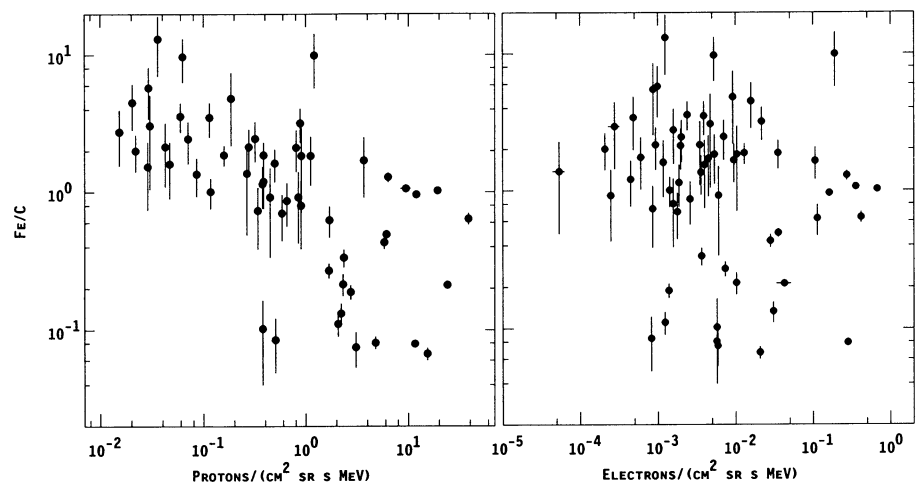

FIG. 6.—Fe/C ratio in the electron events shown as a function of the proton and the electron intensities. Low proton intensity is a good indicator of Fe-rich events, but the electron intensity is essentially uncorrelated with Fe/C.

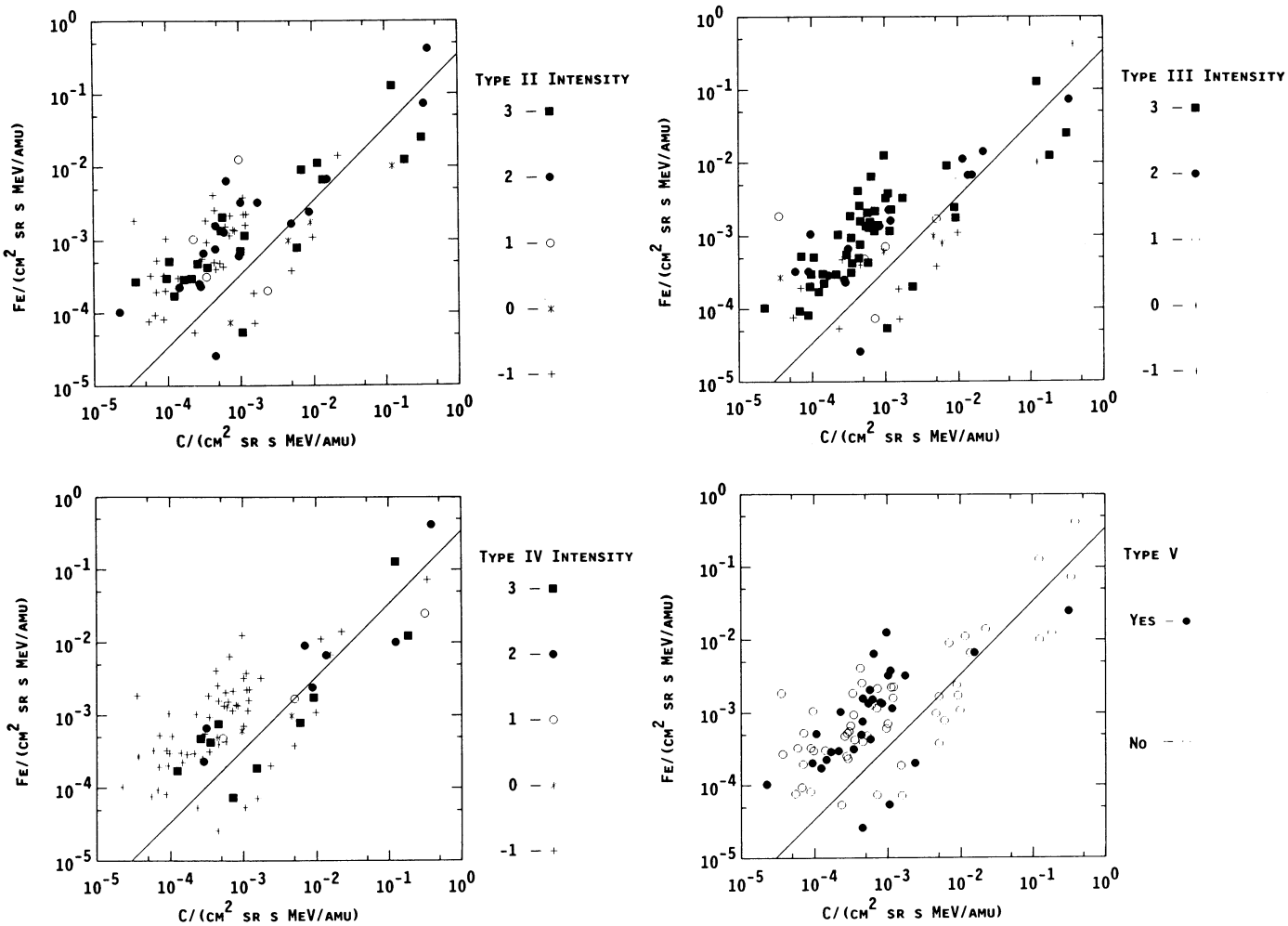

FIG. 7.—The four panels show the distribution of types II, III, IV, and V radio bursts on the Fe-C intensity plot shown previously in Fig. 1. Burst intensities 0–3 are indicated by different symbols for types that have such intensities reported in *Solar Geophysical Data*, as shown. The Fe-rich events are strongly correlated with type III and type V bursts. Fe-poor events are correlated with type IV bursts.

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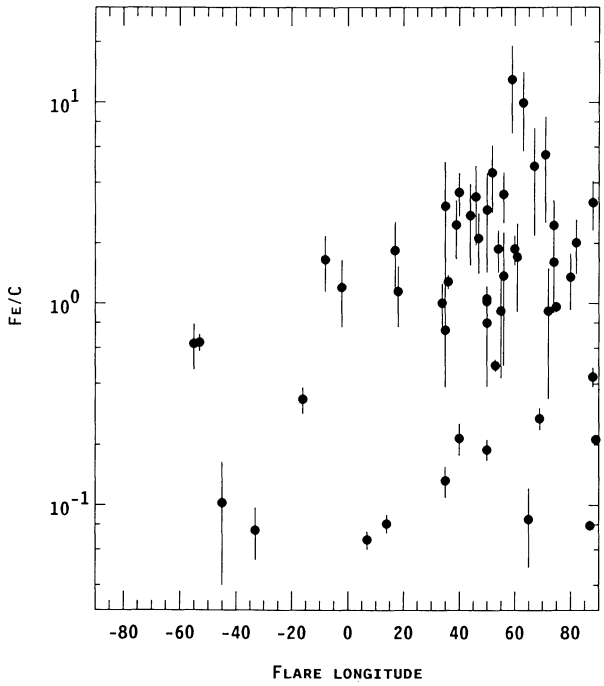

FIG. 8.—Fe/C ratio as a function of the solar longitude of the Hα flare. Fe-rich events tend to come from well-connected flares.

intensity is much weaker, and Fe/C and electrons are uncorrelated. It is changes in proton intensity, therefore, that drive the differences in p/e and H/He ratios that distinguish the impulsive events. The importance of the proton *intensity* is rather surprising, since one would expect this intensity to depend upon the connection of the flare. Perhaps differences in acceleration overpower other variations of this type. The low

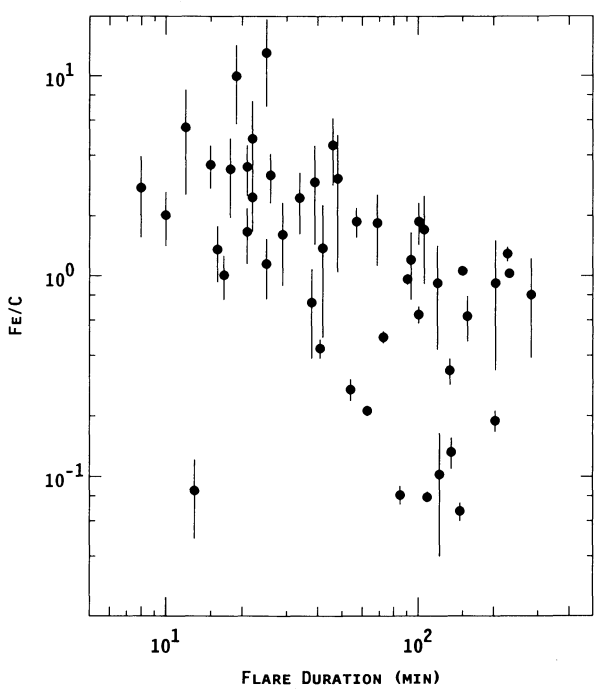

FIG. 9.—Fe/C vs. the duration of the Hα flare. A general decline of Fe/C is seen with increasing duration. The isolated event in the lower left-hand corner of the plot may involve an incorrect association (see text).

proton intensities are one of the main reasons that impulsive Fe-rich flare events were rarely seen in early studies, since these studies usually began by searching for proton increases.

Coronal shocks, which generate metric type II bursts, seem to play little role in determining particle abundances (see Fig. 7). In fact, there is evidence to support the idea that coronal shocks, unlike IP shocks, often reaccelerate Fe-rich impulsive phase material. This may be the case in large γ-ray line events (Van Hollebeke, McDonald, and Trainor 1985; Van Hollebeke, McDonald, and Meyer 1990) and in the early stages of events like the 1981 April 24 event (see Fig. 4), where ^{3}He-rich, Fe-rich material is seen at very high energies. Based upon the frequency and timing of the radio bursts and the duration of the related X-ray emission, Cane and Reames (1988*a*, *b*) argued that a coronal shock is a blast wave generated by heating in the impulsive phase of a flare, while an IP shock is a driven shock formed as the bow shock of a CME. Since the two types of shock form at different locations and different times, perhaps it is not surprising that one frequently has access to a "seed population" of Fe-rich energetic particles from the impulsive phase while the other does not.

The pattern of change of the abundances of individual elements provides a new type of information on abundance enhancements in impulsive flare–associated events. All of the elements heavier than C show some correlated enhancement as a function of increasing Fe/C. With the possible exception of Ne/C, the slope of this enhancement in logarithmic space in Figure 5 increases with Z, approaching one as Z approaches 26. With the exception of Ne, the slope of the enhancements seems to be the same in the Fe-poor and the Fe-rich region. This continuous behavior is somewhat surprising, since the underlying mechanisms for the abundance variations might be expected to be quite different for the Fe-rich and the Fe-poor events.

The fact that the enhancements of the different elements obey a power-law relationship in an event was first noted by Breneman and Stone (1985). Those authors expressed the variations seen in large (Fe-poor) events as a power law in the variable Q/A, where the charge state Q of each element was taken to be the same in all events, and equal to the average value measured by Luhn *et al.* (1987). For the Fe-rich events we know that the elements are much more highly ionized, so that the element-to-element variation in Q/A is much smaller yet the enhancements are much larger. We are unable to study the abundances as a function of Q/A, since the values of Q undoubtedly vary from event to event in a manner that is not easy to determine. It is, of course, true that most of the physical phenomena of interest, from resonant heating by wave absorption to diffusive scattering across an IP shock, will depend upon the particle gyrofrequency and, hence, upon Q/A. It has been suggested (Reames 1990) that the smooth, temperature-dependent enhancements in Fe-rich events may only be a consequence of increasing wave energy with increasing kT as in blackbody radiation. If the wave spectrum causes selective heating, then increased wave energy might further exaggerate the enhancements.

To the extent that the abundances of elements depend smoothly upon Fe/C and upon Z, the flare-to-flare differences must arise during the process of heating and acceleration. If there were abundance variations from one flare site to another that depended upon FIP, for example, Q/A dependence would be destroyed. Mg, Si, and Fe are low–FIP elements (Meyer 1985*a*), while He, C, O, Ne, and S are high–FIP elements. Thus

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Fe/C would be affected by differences between high- and low–FIP elements as well as Q/A dependence, while S/C, for example, would reflect only Q/A variations. A good correlation between S/C and Fe/C, and other similar combinations, suggests that these abundances in the underlying coronal material do not have FIP–dependent variations from site to site.

The Ne/C ratio, shown in Figure 5, does seem to vary discontinuously as a function of Fe/C. Most of the Fe-rich events show a larger enhancement in Ne/C than in Mg/C. It has been proposed (Reames, Ramaty, and von Rosenvinge 1988) that the material in these impulsive flare events comes from a region, perhaps lower in the chromosphere, where the abundance of Ne is higher. The Ne abundance deduced from γ-ray line intensities is also about a factor of 3 higher than that in the ambient corona. Reducing Ne/C in the Fe-rich events by this factor of 3 in Figure 5 would make the trend line in Ne/C more consistent with those of the other elements.

The large scatter in the ^{4}He/C ratio plotted in Figure 5 is puzzling. If ^{4}He and C are both fully ionized, as we would certainty expect for the Fe-rich events, it would be extremely difficult to alter this ratio, since both species have the same value of Q/A. As expected, the ratio shows no consistent dependence on Fe/C. There is always a possibility that the ^{4}He/C variations and similar but smaller variations in O/C come from abundance variations in the source material from unknown causes. It is premature, however, to rule out changes in the charge state of C.

The variations in H/He are qualitatively consistent with Q/A–dependent effects. Suppression of Fe in the Fe-poor events might be expected to accompany an enhancement in protons with their much larger value of Q/A. It is also interesting that several of the Fe-rich events shown in Figure 5 have H/^{4}He ratios that cluster near the coronal value. However, we have not been able to find an explanation for the wide variation in H/^{4}He at a fixed value of Fe/C. Variables such as type II burst intensity, for example, do not help to organize these H/^{4}He variations. Related differences in the energy spectra of H and ^{4}He complicate this comparison.

Recently, Winglee (1989) has proposed a mechanism to explain heavy-ion enrichment during bulk chromospheric evaporations into the corona. In his mechanism, energetic electrons precipitate into the corona and heat secondary electrons that expand outward. The expanding electrons create an ambipolar electric field that accelerates the ions outward. Differential motion between the ion species leads to ion-ion steaming instability. The instability causes acceleration of the heavy ions at the expense of lighter ions. The model has the advantage of decoupling ^{3}He and heavy-ion enhancements as is observed (Mason 1986). Observationally, however, the events with chromospheric evaporations and those with ^{3}He and heavy-ion enhancements do not seem to coincide.

V. CONCLUSIONS

We have studied the abundances of elements using measurements in a large sample of individual solar electron events. We find that the events show a bimodal distribution in Fe/C, in support of the conclusions of earlier work using daily averaged abundances. Most of the events fall in the Fe-rich group that also includes ^{3}He-rich events and that is associated with impulsive flares and type III and type V radio bursts. The Fe-poor events are associated with type IV events and with IP shocks. Some large well-connected events display Fe-rich flare material early in the event, followed by Fe-poor material as the IP shock approaches; these events often have both type III and type IV radio bursts.

Proton intensities are very low in the Fe-rich events, and the H/^{4}He ratio is often at or below its coronal value. Fe-poor events are often large proton events, and the H/^{4}He ratio is often an order of magnitude larger than the coronal value.

With the exception of Ne, the abundances of heavier elements vary rather smoothly with Fe/C and with Z or probably Q/A, although Q is poorly known in the higher temperature environment of the Fe-rich events. It is probable that C is fully ionized in all of the events, but there is a large scatter of unknown origin in ^{4}He/C. The Ne/C ratio shows a discontinuity that may be consistent with a higher Ne abundance in the source region as has been proposed previously.

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H. V. Cane: Physics Department, University of Tasmania, G.P.O. Box 252C, Hobart, Tasmania 7001, Australia

D. V. Reames and T. T. von Rosenvinge: Code 661, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

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