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THE BASELINE COMPOSITION OF SOLAR ENERGETIC PARTICLES

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ABSTRACT

We analyze all existing spacecraft observations of the highly variable heavy element composition of solar energetic particles (SEP) during non-^{3}He-rich events. All data show the imprint of an ever-present basic composition pattern (dubbed "mass-unbiased baseline" SEP composition) that differs from the photospheric composition by a simple bias related to first ionization potential (FIP). In each particular observation, this mass-unbiased baseline composition is being distorted by an additional bias, which is always a monotonic function of mass (or Z). This latter bias varies in amplitude and even sign from observation to observation. To first order, it seems related to differences in the A/Z^* ratio between elements (Z^* = mean effective charge).

Subject headings: cosmic rays: abundances — Sun: abundances — Sun: corona — Sun: flares

I. INTRODUCTION

It is well known that the elemental composition of solar energetic particles (SEP; typically ~1–50 MeV per nucleon [MeV/n]) is highly variable from event to event, and even with time and energy during a particular event. Therefore the great wealth of available data on SEP composition at first gives an impression of confusion.[1]

Following the pioneering work of Mogro-Campero and Simpson (1972*a*, *b*), it has been progressively realized that some of the SEP events are globally enriched in heavier elements (in particular Fe) as compared to lighter ones, and that other events are not. It also became apparent that the Fe enrichments were often, but not always, largest at lower energies, and at the beginning of the event (O'Gallagher *et al.* 1976; Dietrich and Simpson 1978; Zwickl *et al.* 1978; McGuire, Von Rosenvinge, and McDonald 1979*a*, 1981; Von Rosenvinge and Reames 1979; Cook *et al.* 1979; Cook, Stone, and Vogt 1980; Mewaldt 1980; Mason *et al.* 1980). It was noted by some of these authors that the differences in enrichment from observation to observation appeared to be rather smooth, monotonic functions of the nuclear charge Z (or mass). It was also remarked that the abundance pattern in some of the events appeared to reflect a selection effect related to first ionization potential (FIP) and/or a similarity with the Galactic cosmic-ray source abundances (in which such a selection effect is present) (Mogro-Campero and Simpson 1972*a*, *b*; Webber 1975, 1982; Nevatia, Durgaprasad, and Biswas 1977; McGuire, Von Rosenvinge, and McDonald 1979*a*; Cook *et al.* 1979; Cook, Stone, and Vogt 1980; Mewaldt 1980). And a shaping of the composition of any particular event by a combination of the two effects related to Z and to FIP has been suggested in the seminal papers of McGuire, Von Rosenvinge, and McDonald (1979*a*), Cook *et al.*, (1979), and

[1] Snapshots of the SEP composition obtained with nuclear emulsions or plastics flown on rockets have suggested that above ~20 MeV/n the SEP composition becomes consistently identical to that of the photosphere. This is not confirmed by recent systematic spacecraft investigations of the entire event composition. Here we shall consider only the spacecraft data. See discussion in § II*a*.

Mewaldt (1980). But all these remarks were suggested by studies of small subsets of the available data on SEP composition.

Our purpose here is to find the order underlying the variable observed SEP compositions, by a synthetic study *bringing together virtually all existing data* obtained from spacecraft experiments by the various research teams. In § II we show that the whole of the observations point toward the existence of *an ever-present baseline composition* showing the imprint of a selection effect according to FIP (as compared to photospheric composition). The composition during each particular observation then results from the distortion of this baseline composition by additional highly variable, but always monotonic (in mass, or Z) biases. In § III, we show that these variable biases are probably related, at least in part, to rigidity effects acting on ions with the charge states common in the solar corona (and observed in SEP). In § IV we summarize the conclusions. Preliminary results of this study have been presented in Meyer (1981*a*).

The physical significance of these findings is discussed in a companion paper (Meyer 1985, hereafter Paper II), in which the very strong similarity between the SEP baseline composition and those of the solar corona, of the solar wind, and of Galactic cosmic-ray sources are pointed out and interpreted in terms of a selective filling of the solar corona (governed by the ionized fractions in the underlying chromosphere), and of a stellar injection of Galactic cosmic rays.

The present analysis of SEP composition does not cover hydrogen, whose flux is difficult to relate with that of heavier nuclei. Helium is considered, but will be found to behave at variance with all heavier nuclei. In addition, only "normal" events, not the so-called ^{3}He-rich events, will be considered.

II. EXTRACTING THE BASELINE SEP COMPOSITION

a) *Data Base*

Essentially four research teams have performed adequate, detailed spacecraft observations of the SEP composition (NASA/Goddard Space Flight Center; California Institute of Technology; University of Maryland–Max-Planck-Institut Munich; University of Chicago), and we have brought their data together. When comparisons were possible, the agreement between the data of the various teams proved to be generally remarkably good.

All these observations have been obtained with electronic counter telescopes on board spacecraft with good charge resolution (even elements always well resolved, and rarer odd elements often too). The measurements are performed continuously, and the composition is given integrated over the entire event, or large fractions of the event (at least one day).[2]

The data base we shall use is described in Table 1. It covers 53 spacecraft observations over 19 active periods. We have treated independently observations of the same active period performed at different times during the event, or in different energy ranges, or more or less duplicate observations performed by different research teams. The variations in composition with time and/or energy within individual events will be discussed in § III (Figs. 9 and 10).

[2] Counter studies which do not cover both O and Fe, and at least a few other elements, could not be considered (e.g., Webber *et al.* 1975; Zwickl *et al.* 1978; Scholer *et al.* 1978; Mason *et al.* 1981; Hamilton and Gloeckler 1981). We also did not use some data with very low statistical weight (e.g., earlier studies by Mogro-Campero and Simpson 1972*a*, *b* and the 1971 April 6 event in Teegarden, Von Rosenvinge, and McDonald 1973).

TABLE 1
DATA BASE OF SEP OBSERVATIONS[a]

Dates	E (MeV/n)	Group[b]	Authors	Remarks[c]
1971 Sep 1	13.5–47.	Fe-poorest	Teegarden *et al.* 1973	
1972 Oct 29–Nov 4	0.6– 7.	Fe-rich	Hovestadt *et al.* 1973	
1974 Jun 9–10	1. – 4.6	Fe-poor	Mason *et al.* 1980; Mason 1980	2
1974 Jul 3–5	1. – 4.6	Fe-rich	Mason *et al.* 1980; Mason 1980	2
1974 Jul 6–8	1. – 4.6	Fe-rich	Mason *et al.* 1980; Mason 1980	2
1974 Jul 4–7	3.5– 6.	Fe-richest	McGuire *et al.* 1981	3
1974 Jul 4–7	6.7–15.	Fe-rich	McGuire *et al.* 1979*a*	
1974 Jul 4–7	15. –45.	Fe-median	McGuire *et al.* 1981	3
1974 Sep 11–13	1. – 4.6	Fe-median	Mason *et al.* 1980; Mason 1980	2
1974 Sep 14–16	1. – 4.6	Fe-median	Mason *et al.* 1980; Mason 1980	2
1974 Sep 11–15	3.5– 6.	Fe-rich	McGuire *et al.* 1981	3
1974 Sep 11–15	6.7–15.	Fe-poor	McGuire *et al.* 1979*a*	
1974 Sep 20–22	1. – 4.6	Fe-median	Mason *et al.* 1980; Mason 1980	2
1974 Sep 23–24	1. – 4.6	Fe-poorest	Mason *et al.* 1980; Mason 1980	2
1974 Nov 8................	1. – 4.6	Fe-poorest	Mason *et al.* 1980; Mason 1980	2
1975 Nov 22	1. – 4.6	Fe-median	Mason *et al.* 1980; Mason 1980	2
1977 Jul 27–29...........	1. – 4.6	Fe-poorest	Mason *et al.* 1980; Mason 1980	2

TABLE 1—*Continued*

Dates	E (MeV/n)	Group[b]	Authors	Remarks[c]
1977 Sep 12–14	1. – 4.6	Fe-median	Mason *et al.* 1980; Mason 1980	2
1977 Sep 19	1. – 4.6	Fe-richest	Mason *et al.* 1980; Mason 1980	2
1977 Sep 20–21	1. – 4.6	Fe-rich	Mason *et al.* 1980; Mason 1980	2
1977 Sep 19–20	3.5– 6.	Fe-rich	McGuire *et al.* 1981	3
1977 Sep 19–20	6.7–15.	Fe-rich	McGuire *et al.* 1979*a*	
1977 Sep 20–21	8.7–15.	Fe-rich	Cook *et al.* 1979, 1980	1
1977 Sep 19–20	15. –45.	Fe-richest	McGuire *et al.* 1981	3
1977 Sep 24–26	1. – 4.6	Fe-rich	Mason *et al.* 1980; Mason 1980	2
1977 Sep 24–26	3.5– 6.	Fe-richest	McGuire *et al.* 1981	3
1977 Sep 24–26	6.7–15.	Fe-richest	McGuire *et al.* 1979*a*	
1977 Sep 25–27	8.7–15.	Fe-richest	Cook *et al.* 1979, 1980	1
1977 Sep 24–26	15. –45.	Fe-richest	McGuire *et al.* 1981	3
1977 Sep 24	25. –210.	Fe-richest	Dietrich and Simpson 1978	
1977 Nov 22–25	1. – 4.6	Fe-median	Mason *et al.* 1980; Mason 1980	2
1977 Nov 22–23	3.5– 6.	Fe-rich	McGuire *et al.* 1981	3
1977 Nov 22–23	6.7–15.	Fe-rich	McGuire *et al.* 1979*a*	
1977 Nov 23–26	8.7–15.	Fe-rich	Cook *et al.* 1979, 1980	1
1977 Nov 22–23	15. –45.	Fe-richest	McGuire *et al.* 1981	3
1978 Feb 13–15	3.5– 6.	Fe-rich	McGuire *et al.* 1981	3
1978 Feb 13–15	6.7–15.	Fe-median	McGuire *et al.* 1979*a*	
1978 Feb 15–18	8.7–15.	Fe-median	Cook *et al.* 1979, 1980	1
1978 Feb 13–15	15. –45.	Fe-median	McGuire *et al.* 1981	3
1978 Apr 24–28	8.7–15.	Fe-poor	Cook *et al.* 1979, 1980	1
1978 Apr 29–May 2	3.5– 6.	Fe-median	McGuire *et al.* 1981	3
1978 Apr 29–May 2	6.7–15.	Fe-poor	McGuire *et al.* 1979*a*	
1978 Apr 29–30	8.7–15.	Fe-median	Cook *et al.* 1979, 1980	1
1978 Apr 29–May 2	15. –45.	Fe-poorest	McGuire *et al.* 1981	3
1978 May 2–5	8.7–15.	Fe-poor	Cook *et al.* 1979, 1980	1
1978 Sep 24	2. – 3.1	Fe-rich	Von Rosenvinge and Reames 1979	
1978 Sep 26	2. – 3.1	Fe-median	Von Rosenvinge and Reames 1979	
1978 Sep 23–25	3.5– 6.	Fe-rich	McGuire *et al.* 1981	3
1978 Sep 24	3.9– 6.7	Fe-median	Von Rosenvinge and Reames 1979	
1978 Sep 24	6.7–12.4	Fe-poor	Von Rosenvinge and Reames 1979	
1978 Sep 23–25	6.7–15.	Fe-poor	McGuire *et al.* 1979*a*	
1978 Sep 23–25	15. –45.	Fe-poorest	McGuire *et al.* 1981	3
1978 Nov 11	2. –3.1	Fe-median	Von Rosenvinge and Reames 1979	

[a] Only observations performed with electronic counter techniques on board spacecraft are considered (§ II*a*). The various active periods are separated by blank lines. Only non–^{3}He-rich events are considered.

[b] Groups of observations: Fe-poorest: Fe/O = 0.015–0.043. Fe-poor: Fe/O = 0.043–0.08. Fe-median: Fe/O = 0.08–0.15. Fe-rich: Fe/O = 0.15–0.42. Fe-richest: Fe/O = 0.42–1.20.

[c] Remarks: (1) Data of Cook *et al.* 1979, 1980: Energy range for He/O: 4.6–7.8 MeV/n. (2) Data of Mason *et al.* 1980, Mason 1980: Energy range for He/O and C/O: 0.6–1.6 MeV/n. The study of Mason *et al.* 1980 is based on 37 days of enhanced flux, corresponding to larger flares. We have grouped the data for the 37 individual days (Mason 1980, private communication) as indicated in the table. See discussion in Appendix A. (3) The data of McGuire *et al.* 1981 in the 3.5–6 and 15–45 MeV/n ranges cover only C, O, (Mg + Si), Fe. Individual Mg and Si abundances have been derived from their sum by assuming Mg/Si ratios similar to those found in other observations in the same group.

The data obtained with nuclear emulsion or plastic detectors flown on sounding rockets have *not* been considered for the present study [they pertain largely to higher energy SEP, $E \gtrsim 15$ MeV/n; Bertsch *et al.* 1973; Bertsch and Reames 1977; Pellerin 1975; Crawford *et al.* 1975; Nevatia, Durgaprasad, and Biswas 1977; Durgaprasad, Biswas, and Vahia 1981*a*, *b*; and references therein]. First of all, they yield only a ~ 4 min snapshot of the event composition, which may not be typical of that of the entire event (or of large fractions of it). Second, the statistics is always low. Third, the charge resolution is not always entirely adequate.

An earlier conclusion from these emulsion data was that, in contrast to the low-energy findings (mainly from counter experiments), at higher energies ($E \gtrsim 20$ MeV/n) the SEP composition was generally identical to that of the photosphere (Bertsch *et al.* 1973, as quoted by Bertsch and Reames 1977; Durgaprasad, Biswas, and Vahia 1981*b*; see discussion in Pellerin 1975 and Nevatia, Durgaprasad, and Biswas 1977). This earlier conclusion was already in conflict with various higher energy counter and emulsion observations by Teegarden, Von Rosenvinge, and McDonald (1973), Webber *et al.* (1975), Bertsch and Reames (1977), and Dietrich and Simpson (1978) (see discussion in Mason *et al.* 1980 and Mewaldt 1980). It is now definitely contradicted by the recent high statistics and high resolution spacecraft study of eight individual flares up to 45 MeV/n by McGuire, Von Rosenvinge, and McDonald (1981). In all eight flares, these authors have found the key ratio (Mg + Si)/O between 20 and 40 MeV/n to be remarkably constant near a value $\sim 3.5\times$ photospheric, exactly like at lower energy (Fig. 10). As for the Fe/O ratio, it is found highly variable at high energy as well as at low energy (Fig. 10).

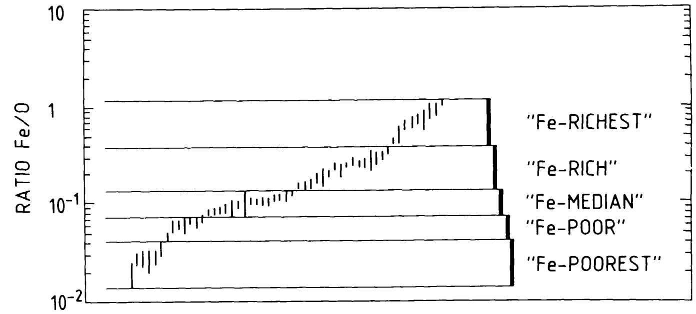

FIG. 1.—Fe/O ratios obtained in the 53 observations of SEP listed in Table 1 (non-^{3}He-rich events), ordered in terms of increasing values of Fe/O. These observations cover 19 active periods. The abscissae are arbitrary. The observations, whose measured Fe/O ratios form a wide continuum, have been *arbitrarily* split into five groups, with Fe/O ratios within the displayed ranges. The five groups have been labeled as shown on the figure, and the numerical values for the limiting Fe/O ratios are given in a note to Table 1.

b) Compaction of the Data

To get a clear general picture of the main, first order effects that shape the SEP composition, we shall have to put the data in a more compact form. We are conscious that, by doing so, we shall erase fine structure in the data. We believe these fine structures should be examined after the major, first order effects have been clearly assessed.

Our compaction procedure will go as follows. We shall sort the 53 SEP observations listed in Table 1 according to a very simple, directly observed parameter: the Fe/O ratio, which is known to vary much from observation to observation. The Fe/O ratios measured in the 53 individual observations are plotted in Figure 1 (independent of energy). They obviously form a continuum. As shown in Figure 1, this continuum has been *arbitrarily* split into five groups of observations: "Fe-richest," "Fe-rich," "Fe-median," "Fe-poor," and "Fe-poorest" observations (for the numerical values of the limiting Fe/O ratios, see note to Table 1). Table 1 indicates the group to which each individual observation belongs.

The abundances of all the other elements have then been extracted from the individual observations within each of the five groups, leading to five ranges of abundances for each element, which correspond to the five ranges first defined for Fe/O. These ranges of abundances have been plotted versus Z in Figure 2 (the five ranges for Fe being those of Fig. 1). We insist that each vertical bar in Figure 2 describes a number of independent observations of several flares.

c) SEP Abundances versus Charge Z

The sum-up of SEP abundances given in Figure 2 shows several remarkable features:

i) A steadily growing spread of the abundances between the five groups of observations from oxygen (the normalizing element) up to nickel.

ii) A remarkable regularity of the five groups of observations pattern, which for each individual element between O and Ni monotonically decreases, as for Fe, from "Fe-richest" down to "Fe-poorest" observations. This behavior suggests that the abundances of the various elements are correlated during each observation: the abundances of all elements seem affected by a more or less smooth, monotonic mass (or Z)-dependent bias, whose intensity varies strongly from observation to observation (as pointed out earlier by Dietrich and Simpson 1978; McGuire, Von Rosenvinge and McDonald 1979*a*; Cook *et al.* 1979; Cook, Stone, and Vogt 1980; Mewaldt 1980; Mason *et al.* 1980).

iii) If this monotonic mass-dependent bias observed between Ni and O is continued for elements lighter than O, one expects the abundances of lighter elements relative to O to anticorrelate with Fe/O. For the neighboring elements N and C the spread is, as expected, small, and nothing definite can be said. As for He, the well-defined pattern established by the bulk of the data above 2 MeV/n shows that, contrary to our expectations, He/O definitely correlates positively with Fe/O. Helium therefore does not fit within the general pattern observed for all the other elements between Ni and O (and plausibly C). At lower energy (0.6–1.6 MeV/n), the He abundances also show a surprising large spread, especially relative to C and O (Figs. 2 and 9; § III*a*; Mason *et al.* 1980). The following study will therefore apply to all heavy elements, except He.

In Figure 2, we have in addition plotted as "boxes" what we presently consider our best estimate of the composition of the Sun (photosphere), and its associated uncertainty (Table 2; and Table 2 of Paper II). These abundances are the so-called "local galactic" (LG) abundances we gave in Meyer (1979*a*, *e*), where we tried to have a synthetic view of the abundance determinations made in all available media in our galactic neighborhood (carbonaceous chondrites, solar photosphere, solar corona, solar wind, H I gas, H II regions, unevolved stars). For most elements, these abundances result essentially from a combination of carbonaceous chondrites and solar photospheric determinations, which agree remarkably well with each other (Meyer 1979*a*, *e*). The CNO abundances come mainly from the photosphere (in which the abundances of C and O are very reliably determined from a number of independent atomic and molecular line systems; Lambert 1978). The noble gas abundances (He, Ne, Ar) result mainly from a detailed discussion of the H II regions, H I gas

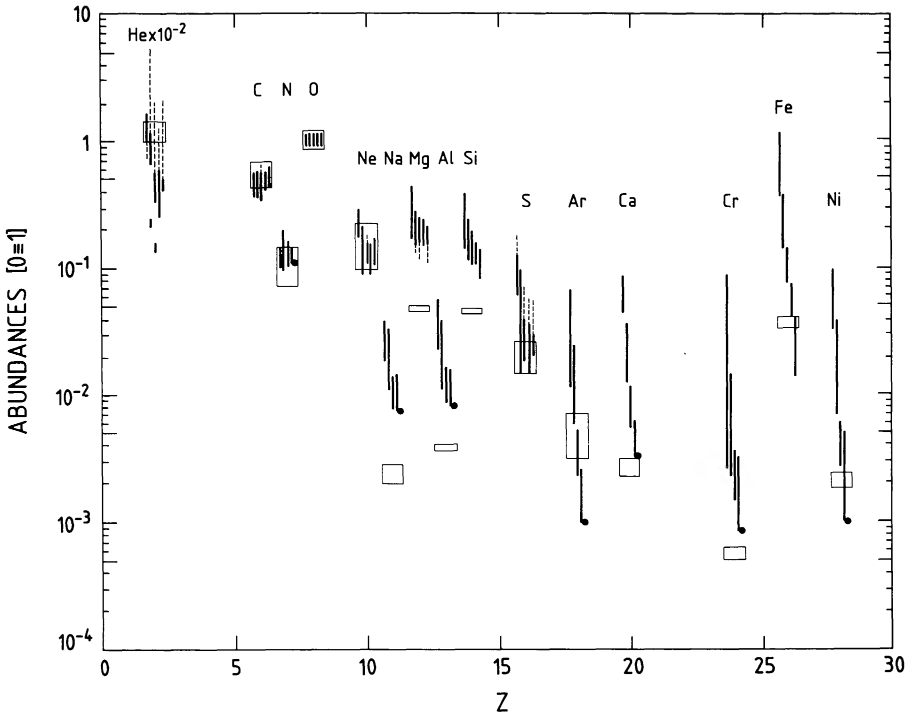

FIG. 2.—Abundances of elements between He and Ni in SEP, vs. Z. Only non–^{3}He-rich events are considered. Everything is normalized to oxygen. The five vertical bars for Fe show the ranges of Fe/O ratios that define the five groups of observations described in Fig. 1 and Table 1 (§ II*b*). The five vertical bars for each other element give the *corresponding* five ranges of abundances for that element, as extracted from the observations in each of the five groups. For rarer elements we have no data for the fifth ("Fe-poorest") group, and this lack is indicated by a heavy dot. The boxes give the "Local Galactic" (LG) abundances, taken as our best estimate of the composition of the solar photosphere (§ II*c*). The rich SEP data by Mason *et al.* (1980) and Mason (1980) at lower energy (1–4.6 MeV/n, and 0.6–1.6 MeV/n for He and C) sometimes give trends slightly different from a close consensus between all other data sets pertaining mainly to slightly higher energies (see discussion in Appendix A). Their ranges of values, when outside the range obtained by other investigations, are indicated by dashed prolongations of the full vertical bars. For He, we also have two isolated, low points by Von Rosenvinge and Reames (1979) and Cook *et al.* (1980) in the 2–3.1 and 4.6–7.8 MeV/n ranges.

TABLE 2

MASS-UNBIASED BASELINE SEP ABUNDANCES

ELEMENT	LOCAL GALACTIC (LG)	MASS-UNBIASED BASELINE SEP	SEP/LG[a] Si ≡ 1	SEP/LG[a] O ≡ 1
He[b]	260000. (1.25)[c]	[38300. (1.27)][b]	[0.14 (1.39)][b]	[0.51 (1.39)][b]
C	1260. (1.26)	290. (1.30)	0.23 (1.42)	0.80 (1.42)
N	225. (1.41)	81. (1.33)	0.36 (1.56)	1.24 (1.56)
O	2250. (1.25)	650. (1.13)	0.29 (1.29)	≡1.00 (1.29)
Ne	325. (1.50)	84. (1.32)	0.26 (1.64)	0.89 (1.64)
Na	5.5 (1.18)	8.5 (1.47)	1.54 (1.52)	5.34 (1.52)
Mg	105. (1.03)	123. (1.28)	1.17 (1.28)	4.05 (1.28)
Al	8.4 (1.05)	8.9 (1.55)	1.06 (1.55)	3.66 (1.55)
Si	≡100. (1.03)	≡100. (1.37)	≡1.00 (1.37)	3.46 (1.37)
S	43. (1.35)	20. (1.80)	0.46 (1.95)	1.61 (1.95)
Ar	10.7 (1.50)	3.8 (1.70)	0.35 (1.94)	1.23 (1.94)
Ca	6.2 (1.14)	7.6 (1.55)	1.23 (1.57)	4.24 (1.57)
Cr	1.29 (1.10)	2.25 (1.90)	1.73 (1.90)	6.03 (1.90)
Fe	88. (1.07)	99. (1.47)	1.13 (1.48)	3.89 (1.48)
Ni	4.8 (1.13)	4.5 (1.75)	0.94 (1.78)	3.24 (1.78)

[a] Error = quadratic sum of errors.
[b] The mass-unbiased baseline SEP abundance of He cannot be properly defined (§§ II*c* and II*e*).
[c] In parentheses: error factors ("within a factor of...").

and/or hot stars abundances (Meyer 1979*b*, *c*), which we slightly update in Appendix B. H II regions have also been useful for N and S, where they confirm the photospheric values (Meyer 1979*d*). Abundances in the solar corona and in the solar wind had also been considered in that work, but had never been essential in setting up the LG standard. We now believe that the abundances in these media are probably biased with respect to the general LG abundances (see Paper II). The LG standard of abundances is in good agreement with other recent compilations (Cameron 1982; Anders and Ebihara 1982), although we tend to assess more generous errors.

Now, to compare the SEP abundances to the photospheric (or LG) ones, it is convenient to take the SEP/LG abundance ratios, thus defining overabundance factors for our 5 groups of events. This has been done in Figure 3, in which we have, however, kept the "boxes" for the LG abundances, in order to clearly visualize the uncertainties attached to them. Striking features appear in Figure 3:

i) There is a sharp jump by a factor of ~ 4 between the overabundances of two well defined plateaus formed by C, N, O, Ne and by Na, Mg, Al, Si, well beyond all errors (including those on the LG abundance of Ne; Meyer 1979*b*, and Appendix B).

ii) For heavier nuclei the increasing spread of the abundances makes the interpretation of the data less straightforward. However, the overabundances of S and Ar seem centered below the Na–Si plateau.[3]

iii) On the other hand, Ca, Cr, Fe, and Ni clearly behave more like Na–Si, as judged from their median overabundances.

iv) Helium tends to be lower than all heavier elements (as judged by the bulk of the data above 2 MeV/n, which have a low dispersion).

[3] The low energy data of Mason *et al.* (1980) may indicate higher S overabundances, more similar to those of Si. But these data, discussed in Appendix A, are not particularly reliable for S since they do not resolve S from Ar and Ca. The S abundances of Figs. 2 and 3 have been roughly derived by ourselves from total (S + Ar + Ca) abundances; new investigations are required.

Such features (absolutely sharp jump between nonmetals and metals between Ne and Na, i.e., right at the closure of the outer electron shell of the neutral atoms; trend of S and Ar to be lower than all neighboring metals) is highly suggestive of some selection of elements according to FIP (as earlier suggested by Webber 1975; Nevatia, Durgaprasad, and Biswas 1977; McGuire, Von Rosenvinge, and McDonald 1979*a*; Cook *et al.* 1979; Mewaldt 1980). This implies that some selection betweens ions and neutrals *in a partly neutral* medium plays a major role in shaping the SEP composition.

Could these features find an alternative simple physical interpretation, in terms of effects not related to FIP? The question is considered in Appendix C, where (i) a selection among ions according to magnetic rigidity ($\propto A/Z^*$), with the charge states Z^* found in coronal plasmas of various temperatures, (ii) a generalization of the selective heating mechanisms that may explain the ^{3}He-rich events, (iii) a selective preacceleration in collapsing magnetic neutral sheets, and (iv) a possible input of interplanetary grain destruction products have been considered. None of these effects seems adequate to explain the above abundance patterns.

d) *SEP Abundances versus First Ionization Potential (FIP)*

The above discussion has shown that the FIP should help in organizing the SEP abundance data. In Figure 4, the overabundances SEP/LG have therefore been plotted versus FIP, separately for the five groups of observations. Here again, we have recalled the uncertainties on the reference LG abundances.

Let us first concentrate on the pattern for the "Fe-median" events in Figure 4, which happens to look the most ordered. There indeed, two well-defined plateaus are present, all elements with FIP < 8.5 eV being consistently more overabundant by a factor of ~ 3 than those with FIP > 10 eV. From now on, these two groups of elements will be denoted "low-FIP" and "high-FIP" elements. Again, helium does not fit into this simple pattern, although its FIP is quite close to that of Ne.

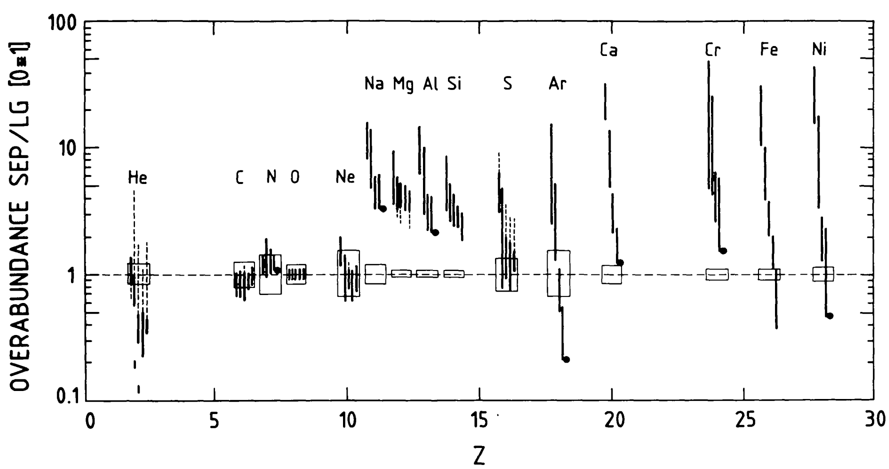

FIG. 3.—Overabundances of elements in SEP with respect to Local Galactic (LG) composition (representing the composition of the solar photosphere) vs. Z, for the five groups of observations. Only non-^{3}He-rich events are considered. Everything is normalized to oxygen. The boxes represent the error on the LG abundances. See legend to Fig. 2, from which this figure is derived by mere normalization to LG abundances.

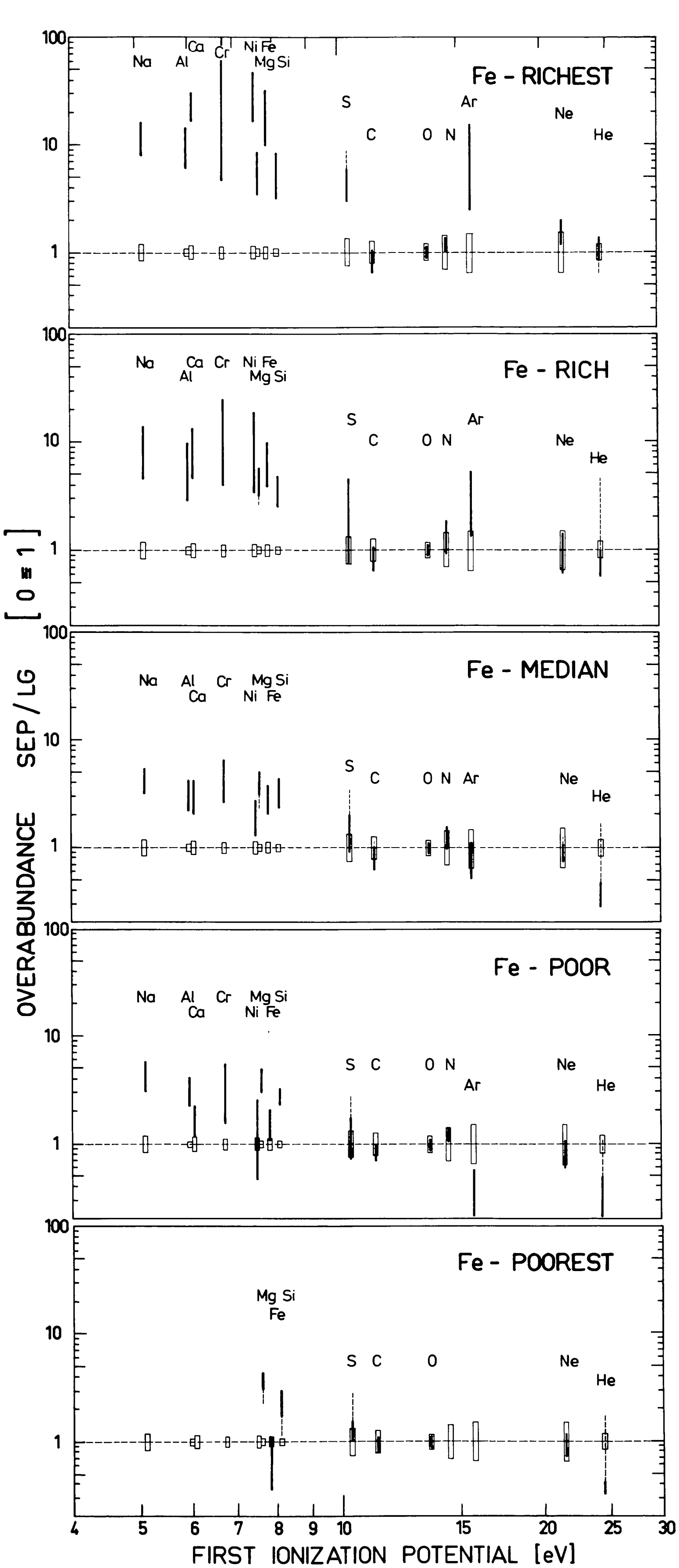

FIG. 4.—Overabundances of elements in SEP with respect to Local Galactic (LG) composition (as in Fig. 3), vs. first ionization potential (FIP). The five groups of observations have been plotted separately. Only non–^{3}He-rich events are considered. Everything is normalized to oxygen. The boxes represent the error on the LG abundances. See legend to Fig. 2.

Going over toward Fe-richer or Fe-poorer observations in Figure 4, the same general pattern is kept, but is being progressively distorted by the monotonic mass (or Z) dependence of the abundances. Consider first the "Fe-rich" and "Fe-richest" observations. Among the "low-FIP" elements,[4] heavier Ca, Fe, Ni lie above lighter Na, Mg, Al, Si, while among the "high-FIP" elements heavier S and Ar stand up with respect to lighter C, N, O, Ne. The converse behavior nicely appears in the "Fe-poor" observations, in which heavier Ca, Fe, Ni consistently lie below lighter Na, Al, Mg, Si, while Ar lies below the lighter "higher-FIP" elements (the behavior of S is less clear).[5] The data on "Fe-poorest" observations are still scanty.

e) *A "Mass-unbiased Baseline" Composition of SEP*

The five groups of Figure 4 obviously describe a continuum in which we steadily go from situations in which heavier elements are enhanced with respect to lighter ones, to situations in which they are depleted. Somewhere in this continuum, it must be possible to pick up a region with a zero effect: no systematic mass dependence of the abundances, which are ordered in terms of a single parameter, FIP.

To define this region, we choose as a convenient criterion that the relative abundances of Mg, Si, and Fe be ordered in terms of FIP only, undistorted by any residual mass effect. These three abundant elements are indeed well observed, they have very close FIPs, and they span a wide range of masses. So, we require that the Fe overabundance must lie right in between the Mg and Si overabundances. A close look at Figure 4 shows that according to this criterion the "Fe-median" observations are already slightly depleted in heavy elements, while the "Fe-rich" are somewhat enriched. We have therefore constructed a "*mass-unbiased* (*m.u.*) *baseline*" SEP composition by taking for each element a linear combination of its abundances in the "Fe-median" and in the "Fe-rich" observations, *adjusted* so as to yield the Fe overabundance right between the Mg and the Si ones:

$$\begin{aligned}\text{Abund (baseline)} &= 0.63 \cdot \text{Abund (Fe-medium)}\\ &\quad + 0.37 \cdot \text{Abund (Fe-rich)}.\end{aligned}$$

The resulting "m.u. baseline" overabundances are shown in Figures 5 and 6, and the derived SEP "m.u. baseline" abundances are given in Table 2.[6]

This baseline clearly shows the two plateaus for "low-FIP" and "high-FIP" element overabundances. The "low-FIP" plateau is possibly slightly inclined. The behavior of Si and S may suggest a smooth transition between the two plateaus (in most observations, Si is consistently found less overabundant than Mg). Unfortunately, we have no element at hand with intermediate FIP, around ~ 9 eV (like Zn in Galactic cosmic rays; see Paper II). On the other hand, He, which is not expected to fit into the pattern (§ II*c*), is as usual low.

This "m.u. baseline" has nothing to do with a mere "average" or "median" SEP composition. Provided that the apparent ordering of the SEP overabundances when plotted in terms of FIP (Figs. 3 and 4) corresponds to some physical reality, the above defined "m.u. baseline" has indeed a physical meaning: *all the SEP compositions of non*–^{3}He*-rich events observed from spacecrafts result, at least to first order, from variable, monotonic mass* (*or Z*) *dependent biases acting upon a common, well defined basic composition pattern, dubbed "mass-unbiased baseline." This baseline composition differs from that of the photosphere by a simple bias according to FIP.*

In other words, all spacecraft SEP composition observations of non–^{3}He-rich events can be understood in terms of the *separate* product of a unique, stable function of FIP and of a variable, but always monotonic, function of mass (or Z).[7]

f) *Comparison with Specific Interplanetary Energetic Particle Compositions*

Based on data for a limited number of elements (He, C, O, Ne, Mg, Si, Fe), *the fairly constant composition of very intense events* (Mason *et al.* 1980; Zwickl *et al.* 1978), characterized by an overabundance of Mg, Si, Fe with respect to C, N, O by a factor of ~ 3, appears *identical to* the m.u. baseline composition (Fig. 7*a*). These data probably correspond to the main phase of well connected flares.

The limited data on *quiet time energetic particles* (presumably of solar origin; Klecker *et al.* 1977; Webber and Cummings 1983) also show overabundances of Mg, Si, Fe with respect to C, N, O by factors of ~ 2 to 6 (Fig. 7*b*), again suggesting a basic pattern following the m.u. baseline.

The composition of *corotating energetic particle streams* (presumably particles accelerated directly out of the solar wind), while possibly suggesting a similar general trend, exhibits some distinctly different features (especially a high C/O ratio, Fig. 7*c*) (Gloeckler *et al.* 1979; Gloeckler 1979; McDonald 1981).

Note also that the "*average SEP composition*" obtained by Cook, Stone, and Vogt (1980) based on 4 flare observations is very similar to the m.u. baseline composition.

III. THE VARIABLE MONOTONIC MASS-DEPENDENT BIAS

a) *Description of the Observations*

Having isolated the ever-present baseline composition upon which we believe the variable mass-dependent biases are acting, we are now prepared to investigate these biases more specifically. To this purpose we have plotted in Figure 8 the SEP abundances for the five groups of observations *relative to* the m.u. baseline. It should represent the "pure" mass-dependent bias.

[4] The error on Cr is too large for its behavior to be interpreted in this context.

[5] First S (FIP = 10.4 eV) may have a behavior somewhat intermediate between "low-FIP" and "high-FIP" elements. Second, the spread of SEP abundances relative to O seems to increase abruptly right in the Si-S-Ar region (Figs. 3 and 8; interpretation in § III). As for the S data of Mason *et al.* (1980) and Mason (1980), see Appendix A.

[6] They are based on the bulk of the data, *not* on the broader ranges derived from the data of Mason *et al.* (1980) and Mason (1980) for a few elements (including Mg). The latter would, however, yield a very similar picture (see Appendix A).

[7] Within one particular event, this statement applies separately to the composition observations performed (i) at different times during the event and (ii) in different energy ranges.

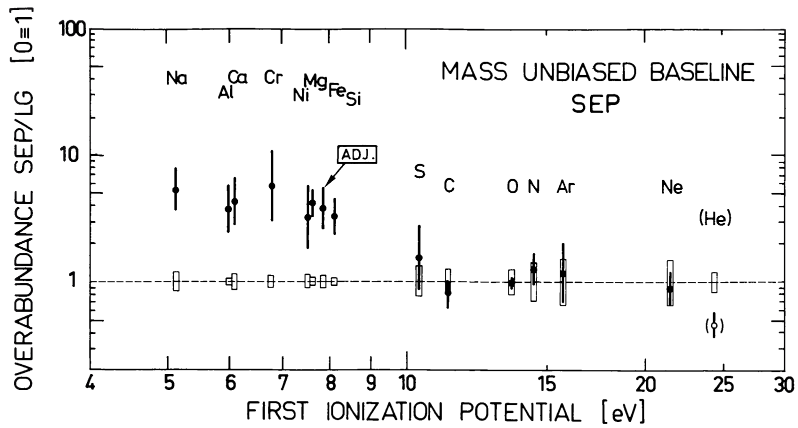

FIG. 5.—"Mass-unbiased baseline" SEP overabundances with respect to Local Galactic (LG) composition, vs. first ionization potential (FIP) (§ II*e*). Normalized to oxygen. The boxes represent the errors on the LG abundances. The indication "ADJ" recalls that this baseline SEP composition results from a one-parameter adjustment of the Fe abundance relative to the Mg and Si abundances (§ II*e*). Helium has been plotted, but its baseline SEP abundance cannot be properly defined since it does not behave like heavier elements (§§ II*c* and II*e*).

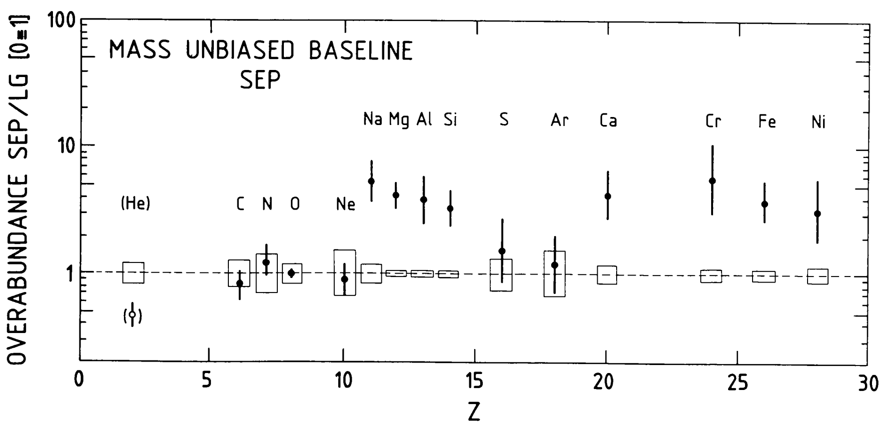

FIG. 6.—"Mass-unbiased baseline" SEP overabundances with respect to Local Galactic (LG) composition, vs. Z (§ II*e*). Normalized to oxygen. The boxes represent the errors on the LG abundances. See legend to Fig. 5.

From Figure 8, a few conclusions are apparent, which confirm our analysis of Figure 3:

i) The monotonic mass-dependent bias affects in the same way the "low-FIP" and the "high-FIP" elements.

ii) Provided one accepts the physical significance of m.u. baseline abundances, the additional processes leading to the monotonic mass-dependent bias work both ways: *they can deplete as well as enhance heavier species*. This feature has been earlier suggested in a slightly different context by Cook *et al.* (1979) and Cook, Stone, and Vogt (1980). But it has not been generally recognized because most studies have focused on the Fe/O ratio, which is almost always at least as large as LG (Fig. 3 or 4). But these consistently high values just reflect the high value of the baseline Fe/O ratio, associated with the difference in FIP between Fe and O. Had one investigated a ratio such as Fe/Mg, the frequent depletion of Fe relative to lighter species would have been stressed long ago (Fig. 3 or 4)!

iii) By and large, the amplitude of the spread does *not* seem to increase with mass in a steady fashion. It looks rather as if we had three groups of elements, with a roughly constant spread within each group. Relative to O, the spread of C and N is very small. Next, in the region Ne–Si (and probably S) the spread is distinctly larger, but with no significant indication of a systematic increase with mass. Finally a much larger spread is observed from Ar up to Ni, whose amplitude does not at all seem to change systematically with mass over this range (in particular Ca and Fe vary very closely in lockstep with one another).

iv) Beyond the first-order image of Figure 8, we can have finer information on the mass-dependent bias by looking into individual observations, and in particular into the changes in composition with time or with energy within given active periods, as illustrated in Figures 9 and 10 (see, e.g., O'Gallagher *et al.* 1976; Scholer *et al.* 1978; Von Rosenvinge and Reames 1979; McGuire, Von Rosenvinge, and McDonald 1981; Mason *et al.* 1981; Hamilton and Gloeckler 1981; Mason, Gloeckler, and Hoverstadt 1983). The general impression is that the large variations with time or energy on the Fe/O ratio are generally reproduced (with reduced amplitude) in other ratios to O over a certain range downward in mass. The

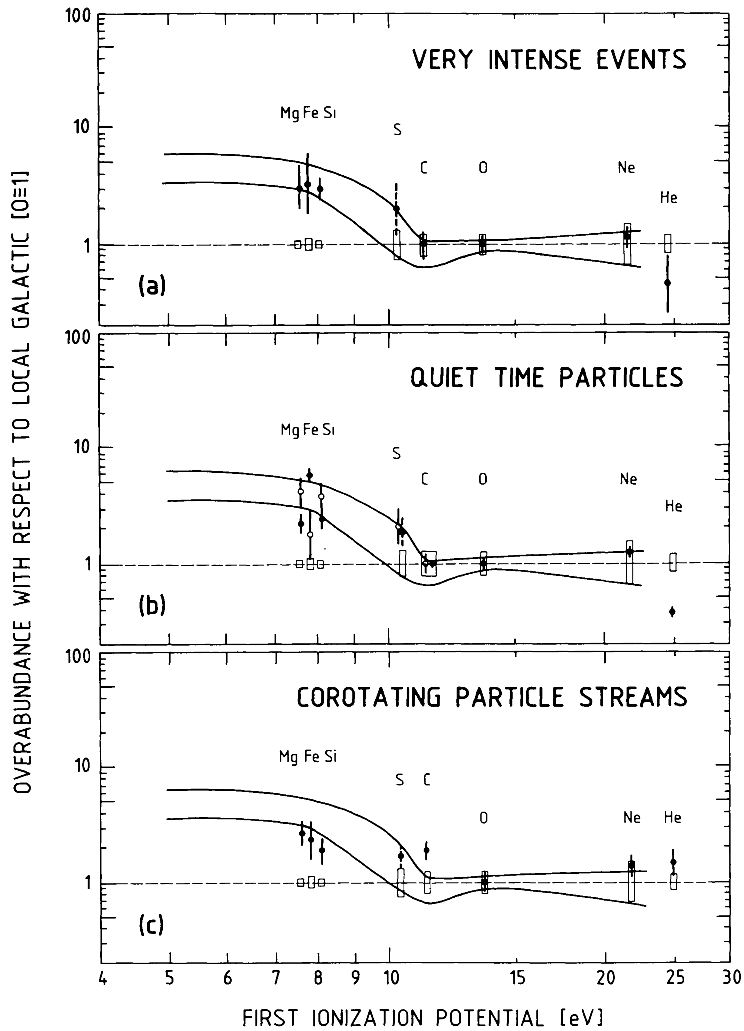

FIG. 7.—Overabundances in (*a*) very intense SEP events, (*b*) quiet-time energetic particles, and (*c*) corotating energetic particle streams with respect to Local Galactic (LG) composition, vs. first ionization potential (FIP) (§ II*f*). The boxes represent the errors on the LG abundances. For comparison, the envelope of the m.u. baseline points (Fig. 5) has also been sketched. (*a*) Data from Mason *et al.* (1980) between 0.6 and 4.6 MeV/*n*. (*b*) Data from Klecker *et al.* (1977) between 1 and 3.4 MeV/*n* (*filled points*), and from Webber and Cummings (1983) at 7 MeV/*n* (*open points*). (*c*) Data from Gloeckler *et al.* (1979) between 0.25 and 4.6 MeV/*n*. Normalized to O, except for the data of Webber and Cummings (1983), which are normalized to C since at 7 MeV/*n* the "anomalous" component masks the quiet-time SEP for all elements with FIP ≥ FIP (H). The S data of Mason *et al.* (1980), Klecker *et al.* (1977), and Gloeckler *et al.* (1979) have been plotted with dotted bars since (i) they have been derived by us from observations of the sum (S + Ar + Ca) assuming m.u. baseline SEP abundance ratios for these three elements, and (ii) the S abundances similarly derived for the SEP data of the same group tend to be higher than those observed by the other teams (Fig. 2 or 3; Appendix A).

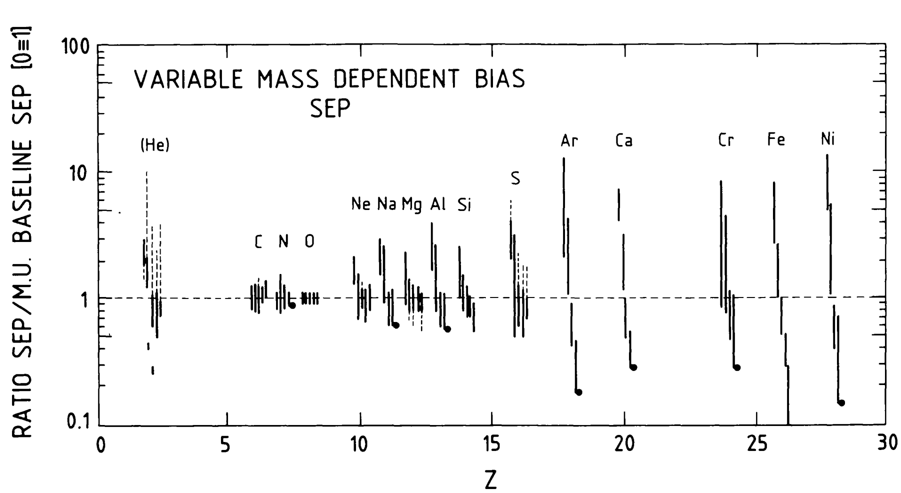

FIG. 8.—To describe the variable mass-dependent biases which are superposed on the m.u. baseline SEP composition, we plot the ratios of the abundances in the five groups of SEP observations *relative to* the m.u. baseline composition, vs. *Z*. Everything is normalized to oxygen. See legend to Fig. 2.

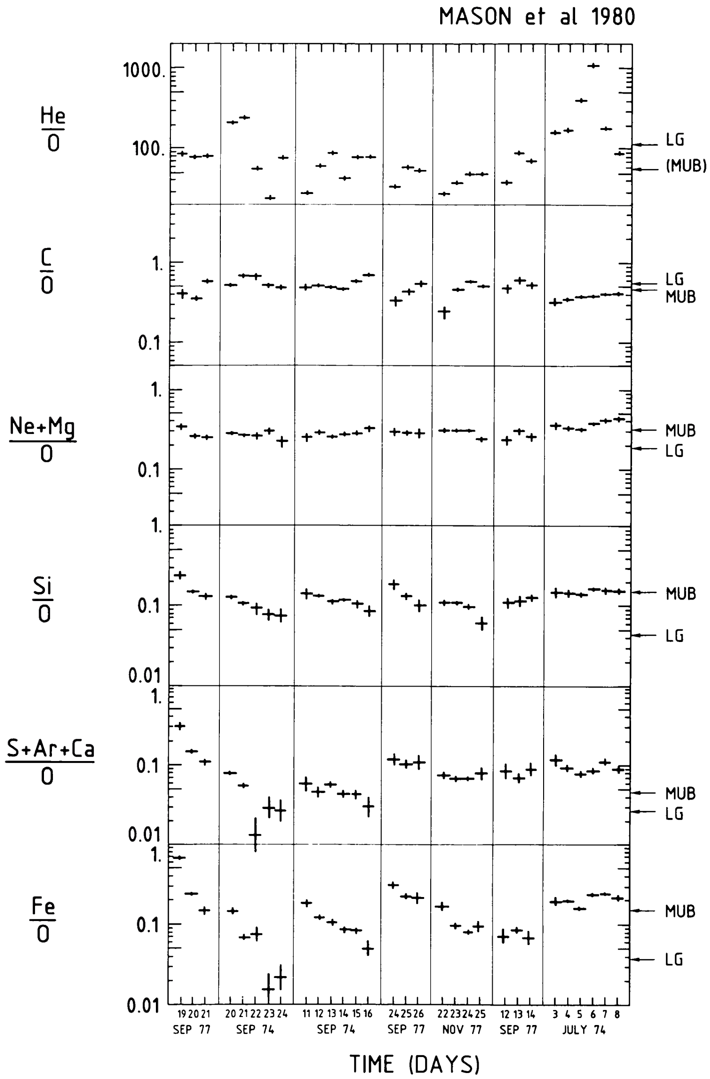

FIG. 9.—Variations of SEP abundances *with time* within given events in the 1–4.6 MeV/n range (0.6–1.6 MeV/n for He/O and C/O), after Mason *et al.* (1980) and Mason (1980). The seven events have been arranged in order of decreasing negative slope of the Fe/O ratio vs. time. The Local Galactic (LG) and mass-unbiased baseline SEP (MUB) abundance ratios are also indicated for reference. The abundance variations on Fe/O are generally reproduced down to Si, but not much is left in the Ne-Mg region. As a general rule, C/O does not anticorrelate with Fe/O (observed in a slightly different energy range), but it may do so in some events. The same is true for He/O (the anticorrelation with Fe/O may be more frequent during the onset phase). The difference in behavior between He/O and C/O, observed in the same energy range, is particularly conspicuous.

limit below which the correlation disappears varies from event to event, but generally lies somewhere in the Si, Mg, Ne region,[8] although in some events abundances variations seem correlated down to C. There may be a suggestion that abundances are correlated down to lower masses at lower energy (Figs. 9 and 10).

v) As concerns the He abundance relative to O, the bulk of the data above 2 MeV/n indicate that it tends to correlate positively with that of heavy elements instead of negatively as expected from a continuation of a simple, monotonic mass-dependent effect (Fig. 8, *full bars*). In addition, He stands out by showing an exceptionally wide (upward) dispersion of abundances at lower energy (0.6–1.6 MeV/n) (Fig. 8, *dashed bars*; Mason *et al.* 1980 and Mason 1980). Obviously, He/O does not at all behave like C/O, which is very stable. The time variations of both the low energy He/O and C/O ratios within particular active periods (Fig. 9) sometimes points to an anticorrelation with Fe/O during the onset phase (e.g., Mason, Gloeckler, and Hovestadt 1983). But when the entire events are being considered, large and erratic variations of He/O once again contrast conspicuously with the gentle behavior of C/O (Fig. 9).[9]

[8] Note in particular that "Fe-richest" and "Fe-poorest" observations are sometimes also very rich or very poor in Si (and, to a lesser degree, Mg), but not always.

[9] More precisely, Fig. 8 shows that the dispersion of He/O at low energy is large within each group of observations, i.e., for a given value of Fe/O. Now, in Mason *et al.*'s low-energy data the He/O and C/O ratios are the only ones to be observed in the 0.6–1.6 MeV/n range, while all heavier element ratios refer to the 1–4.6 MeV/n range. The significance of relating He/O and C/O to heavier element ratios pertaining to somewhat different energy ranges (Figs. 8 and 9) may be questioned. But C/O behaves nicely like heavier element ratios. And all statements

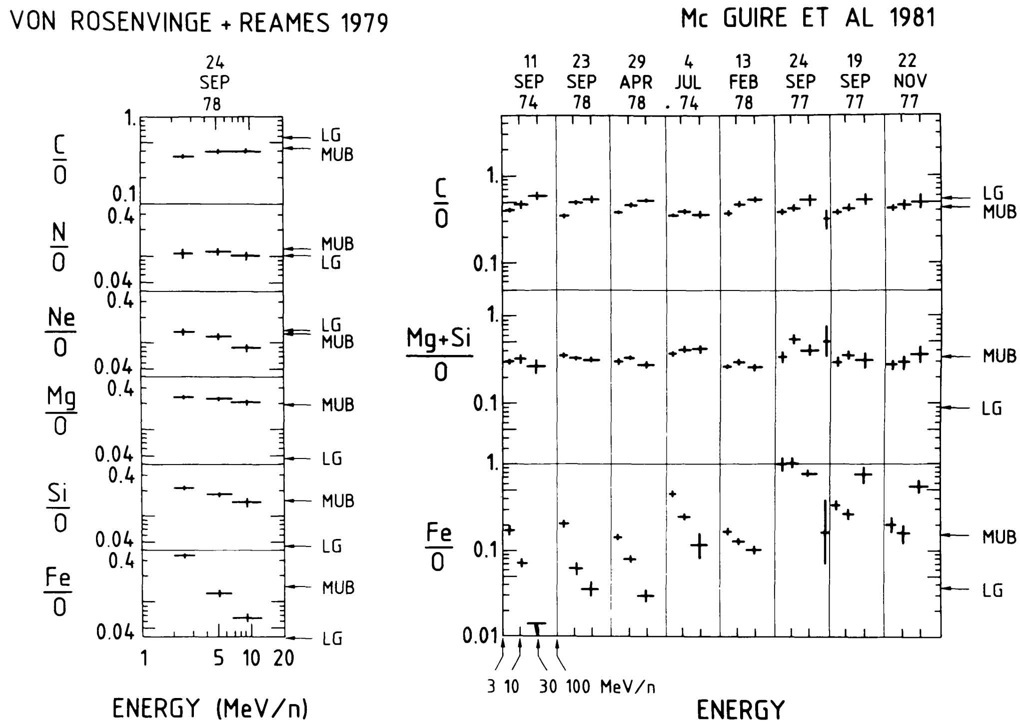

FIG. 10.—Variations of SEP abundances *with energy* within given events. The Local Galactic (LG) and mass-unbiased baseline SEP (MUB) abundance ratios are also indicated for reference. *Left*: one event observed at low energy (2–12.4 MeV/n) by Von Rosenvinge and Reames (1979); the energy dependences of the abundances seem nicely correlated down to Ne and even possibly C. *Right*: eight events observed at higher energy (3.5–45 MeV/n) by McGuire, Von Rosenvinge, and McDonald (1981); the events have been arranged in order of decreasing negative slope of the Fe/O abundance ratio vs. energy; here the energy dependence of (Mg + Si)/O is always very weak, while C/O seems to always increase with energy, irrespective of the energy dependence of Fe/O; the data might suggest that the (Mg + Si)/O ratio is higher at all energies in the events with higher Fe/O ratio *at low energy*.

b) *Interpretation*

It is generally believed that *the variations* in the SEP composition may originate in their acceleration process, in their coronal propagation and release into interplanetary space, in their interplanetary propagation, and/or in their occasional reacceleration by interplanetary shock waves (O'Gallagher *et al.* 1976; Scholer *et al.* 1978; Von Rosenvinge and Reames 1979; Mason *et al.* 1981; Hamilton and Gloeckler 1981; McGuire, Von Rosenvinge, and McDonald 1981; Mason, Gloeckler, and Hovestadt 1983). In particular, the frequent decreases of Fe/O and associated increase of He/O with time during the event onset phase is well interpreted in terms of interplanetary propagation (e.g., Mason, Gloeckler, and Hovestadt 1983). In all these processes the ratio A/Z^* (where Z^* = mean effective charge), which governs the magnetic rigidity at a given velocity, is a crucial parameter. But the above studies, based on the time variations of abundance ratios between a *few key elements* (H, He, C, O, Fe), suggest that simple A/Z^* effects are not sufficient to account for *all* the variations of the SEP abundances, even within a particular event (especially as concerns H).

Here we shall investigate the extent to which the parameter A/Z^* can order the data on the *variations* of the *detailed* SEP composition among *all observed heavy elements*: general spread around the m.u. baseline (Fig. 8), specific time and energy variations (Figs. 9 and 10). It seems now established that, due to a small amount of matter traversed, the states of ionization observed in SEP are frozen in, i.e., are those of the medium the particles have been extracted from, i.e., mainly the ordinary corona (Gloeckler *et al.* 1976, 1981; Sciambi *et al.* 1977; Hovestadt *et al.* 1981, 1983; Ma Sung, Gloeckler, and Hovestadt 1981*b*). In particular, Hovestadt, Klecker, and Gloeckler (1982) have pointed out that the dominant ionization states observed for He, O, and Fe are consistent with a thermal ionization equilibrium at a unique (coronal) temperature, and inconsistent with an equilibrium due to charge exchange during traversal of matter after acceleration.[10]

Figure 11 shows values of A/Z^* calculated at equilibrium for various coronal plasma temperatures between 0.5 and 3.2×10^6 K (after Jacobs *et al.* 1977*a*, *b*, 1979, 1980, Jordan 1969, and Arnaud and Rothenflug 1984).[11] The states of ioni-

concerning compared He/O and C/O ratios refer to the same energy range, and are thus strictly valid.

[10]There is an additional indirect argument in favor of the observed charge states representing those of the medium of acceleration: in a ^{3}He-rich event which is also Fe-rich and C-poor (i.e., O-rich), Ma Sung *et al.* (1981) have observed particularly large amounts of O^{+5} and $Fe^{+16,17,18}$, which is exactly what is required for the medium of acceleration by Fisk's resonant heating model to explain the ^{3}He, O, and Fe enhancements (Fisk 1978; Mason *et al.* 1980).

[11]We have not used (except for He) Shull and Van Steenberg's (1982) and Arnaud and Rothenflug's (1984) recent ionization calculations because they refer to the low-density limit and are therefore inaccurate for the solar corona. In addition, the lack of a broad Ne-like Fe XVII peak in Shull and Van Steenberg's (1982) calculation suggests possible errors.

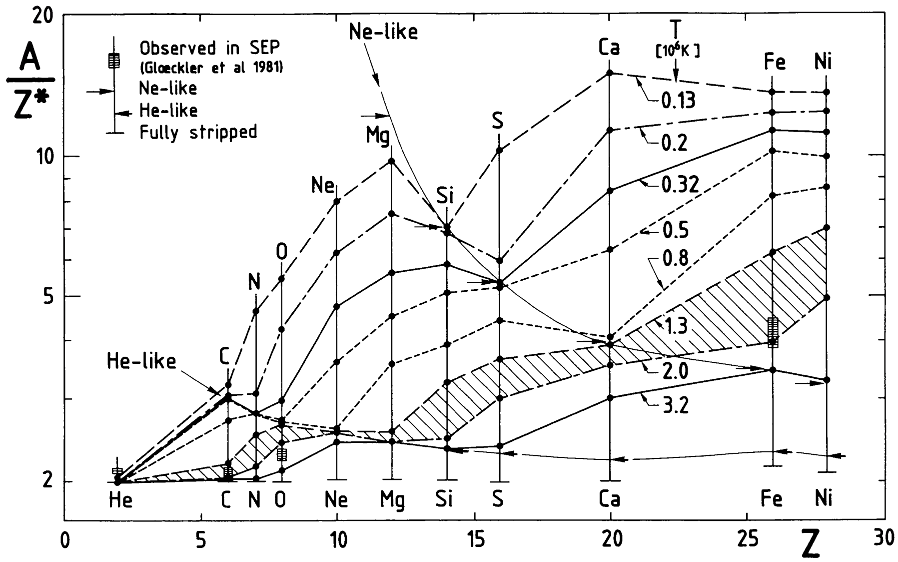

FIG. 11.—Calculated A/Z^* ratios (Z^* = mean effective charge) vs. nuclear charge Z for elements in coronal plasmas of different temperatures T (after Jacob *et al.* 1977*a*, *b*, 1979, 1980 for elements beyond Ne, Jordan 1969 for CNO, and Arnaud and Rothenflug 1984 for He in the low-density approximation; for the elements not plotted, we do not have as reliable calculations). We have pointed out the values of A/Z^* for fully stripped ions, as well as for the particularly stable He-like and Ne-like ions (with, respectively, 2 and 10 electrons left), which explain much of the structure of the figure. The hatched area between $T = 1.3$ and 2.0×10^6 K refers to the temperatures prevailing most commonly in the corona. Also plotted are A/Z^*'s corresponding to the mean charge states of He, C, O, and Fe *observed* in ordinary SEP events (Gloeckler *et al.* 1981; Hovestadt *et al.* 1983), which are most probably frozen-in coronal charge states (§ III*b*). The observed mean A/Z^* for He corresponds to the He^+ content of comparatively large flares (Hovestadt *et al.* 1983) for which detailed heavy-element composition data are available, at a given energy per nucleon (which may, however, not be the most adequate parameter, Gloeckler *et al.* 1981). Corresponding very low ionization states of C, O, and Fe may have remained unobserved by Gloeckler *et al.* (1981), due to their high rigidity (see n. 12).

zation observed in SEP indicate that, although some particles originating in very cool ($\lesssim 0.1 \times 10^6$ K) and very hot ($\gtrsim 5 \times 10^6$ K) media are always present,[12] *most* particles originate in *ordinary* coronal material in the comparatively large flares for which detailed composition data are available (Gloeckler *et al.* 1976, 1981; Sciambi *et al.* 1977; Hovestadt *et al.* 1981, 1983; Ma Sung, Gloeckler, and Hovestadt 1981). In Figure 11, we have also plotted the A/Z^*'s resulting from the *mean* charge states Z^* of He, C, O, and Fe, as observed in normal, comparatively large SEP events by Gloeckler *et al.* (1981) and Hovestadt *et al.* (1983) (He: $+1.94 \pm 0.01$; C: $+5.75 \pm 0.15$; O: $+7.1 \pm 0.2$; Fe: $+13.4 \pm 0.9$). As can be seen, these observations are roughly consistent with a coronal ionization equilibrium at a temperature close to $\sim 2 \times 10^6$ K, i.e., an ordinary (possibly slightly high) coronal temperature.

Figure 11 shows that at 2×10^6 K the calculated A/Z^*'s are about equal for C and N (~ 2.08, mostly fully ionized), a bit higher and very close to constant (~ 2.44) for O, Ne, Mg, Si (the observed value for O is slightly lower, ~ 2.27), and rise abruptly from Si through S up to fairly similar values for Ca and Fe (~ 3.6 and 4.0). This grouping of elements with similar A/Z^*'s is by and large reminiscent of the general picture of the amplitude of the spread of abundances in SEP (Fig. 8): a moderate spread (relative to O) up to Si, an abrupt increase of the spread in the S, Ar, Ca region, and very similar behaviors of Ca and Fe.[13] Figure 12 actually shows that the amplitude of the variations of the SEP abundances of the various elements relative to O is fairly well correlated with the deviation of their A/Z^* ratio from that of O in a 2×10^6 K coronal plasma. So, *the larger the difference in A/Z^* between two elements, the wider the amplitude of the variation of their abundance ratio*. We conclude that *the variations of the relative heavy-element abundances in SEP are, to first order, governed by simple A/Z^* effects*, i.e., by the fact that elements with different rigidities at a given velocity behave differently during acceleration and/or coronal and interplanetary propa-

[12] The unexpected presence of typically $\sim 6\%$ of He^+ (and sometimes much more in very small events; Hovestadt *et al.* 1983) along with the dominant He^{++} in SEP implies acceleration of some material at $T \lesssim 10^5$ K. From such low-temperature media, one would expect to get also some weakly ionized heavy species (e.g., $O^{+1,+2,+3}$) along with the dominant coronal type highly ionized states (O^{+7}). In fact, such low ionization states were not observed by Gloeckler *et al.* (1981), but this may be simply due to their high rigidity. However these data definitely show the lack of intermediate states of ionization ($O^{+4,+5,+6}$) in the source material. Altogether, the data suggest that, along with hot coronal material ($T \sim 2 \times 10^6$ K), some cool material ($\lesssim 10^5$ K) very commonly participates in SEP acceleration, with essentially no material from intermediate temperatures. It suggests that cool loops, or even lower transition-region material, in which very high temperature gradients can be found, are usually involved in SEP acceleration (Appendix C). Finally, it would be highly instructive to observe the heavy-element composition of those small events in which He^+/He^{++} reaches very high values ≥ 1, since most of their particles may have been accelerated out of chromospheric-type media whose composition may differ from coronal (Paper II) and in which high-FIP elements may still be neutral.

[13] The behavior of the composition during energetic storm particle events, which are probably ambient energetic particles locally reaccelerated by a shock wave, is also interesting in this respect (Klecker *et al.* 1981; Hovestadt *et al.* 1982).

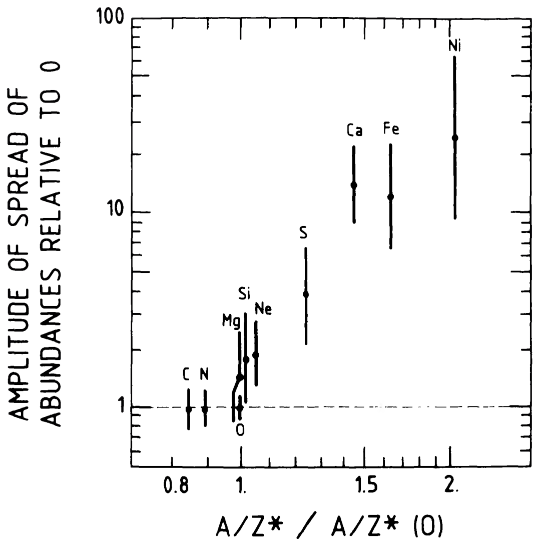

FIG. 12.—Amplitude of the spread of abundances (relative to O) observed in SEP events, vs. the calculated A/Z^* ratio of each individual elements in a 2×10^6 K coronal plasma, normalized to the A/Z^* value of oxygen (from Fig. 11). More precisely, the ordinates are the ratio of the abundances (relative to O) in "Fe-richest" observations to those in "Fe-poor" observations (the "Fe-poorest" observations are too scanty to be used here). Only those elements for which we have a calculated A/Z^* value have been plotted.

gation. (Note that a larger A/Z^* for an element will lead sometimes to a higher, and sometimes to a lower, abundance for this element, since the spread goes both ways, Fig. 8.)[14]

Going into finer details, the picture is however not entirely satisfactory. The values of A/Z^* observed in SEP for O and Fe cannot be fitted with exactly the same temperature (ionization model uncertainty?).[15] Relative to O, the spread on C and N is distinctly smaller than that on Ne, Mg, Si while the calculated A/Z^* for O is virtually equal to that of Ne, Mg, Si and the measured one is right in between. Also Si is commonly found to distinctly follow Fe more than Ne and Mg (Fig. 9), while the A/Z^*'s for Ne, Mg, and Si are virtually equal at 2×10^6 K. This behavior may indicate slightly lower coronal temperatures (say, between 2 and 1.3×10^6 K), for which the A/Z^* for Si increases rapidly while those of Ne and Mg do not (Ne and Mg being largely stuck in their He-like state). However, temperatures much below 2×10^6 K are probably not acceptable since they lead to very different A/Z^*'s for Ca (largely Ne-like at 1.3×10^6 K) and for Fe, while Ca and Fe behave alike in SEP. But these apparent discrepancies might partly arise from inaccuracies in the available ionization calculations.

One might also consider the selective heating models aimed at explaining the ^{3}He-rich events (Fisk 1978; Mason *et al.* 1980; Ibragimov and Kocharov 1977; Kocharov 1981; Hayakawa 1983) to account for the spread in the observed SEP compositions in normal, non-^{3}He-rich, events. Although such processes may sometimes play a role in enhancing the abundances of heavier elements, the discussion in Appendix C shows that they are probably *not* the dominant mechanisms that shape the spread of SEP heavy-element compositions in the vast majority of normal SEP events.

Let us now turn to He. At any coronal type temperature ($\sim10^6$ K) He is, like C, essentially fully ionized, with $A/Z^*(\mathrm{He}) \approx A/Z^*(\mathrm{C}) \approx 2 \lesssim A/Z^*(\mathrm{O}) \ll A/Z^*(\mathrm{Fe})$ (Fig. 11). In some of the event onset phases, He behaves nicely as expected from rigidity-dependent interplanetary propagation with such coronal values of A/Z^* (Mason, Gloeckler, and Hovestadt 1983). But more generally the strange behavior of He/O, its conspicuous divergence from that of C/O at very low energy, and its trend to correlate positively with Fe/O above 2 MeV/n (§ III*a* and Figs. 8 and 9) cannot at all be understood in terms of simple A/Z^* effects at roughly coronal temperatures. The presence of some cool source material, bringing significant amounts of He^+, might be of importance here (Mason, Gloeckler, and Hovestadt 1983). But such approaches will be severely constrained by the high degree of constancy of the C/O ratio (see n. 12) and by the absence of large He^+ fractions in all but the very small solar events.

In brief, the variations of the SEP heavy-element abundances seem to first order consistent with simple A/Z^* effects, where Z^* is the mean effective charge of the element in the ordinary coronal plasma. But the detailed observations suggest that more complicated phenomena may also be at work. As for He, it often does not at all fit into this pattern.

IV. SUMMARY

We have shown that:

1. All the various solar energetic particle (SEP) heavy-element compositions observed from spacecraft in particular time and energy intervals during non-^{3}He-rich events can be ordered in terms of highly variable, but always monotonic mass (or Z) dependent biases acting upon an ever-present, well-defined basic composition pattern. This basic pattern, dubbed "mass-unbiased baseline" SEP composition, differs from the photospheric composition by a simple bias according to first ionization potential (FIP): all heavy elements with FIP $\gtrsim 9$ eV are underabundant by a factor of ~ 4 with respect to those with FIP $\lesssim 9$ eV (Fig. 5).

2. Still based on limited data, the fairly constant heavy-element composition of very intense events appears identical to the mass-unbiased baseline composition (Fig. 7*a*). The observed compositions of quiet-time energetic particles also suggest a similar basic pattern (Fig. 7*b*). But those of corotating energetic particle streams show distinctive features (Fig. 7*c*).

3. The variable biases, which are monotonic in mass (or Z) during each particular observation, change from observation to observation, not only in amplitude, but even in sign: in some observations heavier elements are systematically en-

[14] One may also invoke the higher sensitivity of A/Z^* to plasma temperature for elements heavier than S (Fig. 11). But moderate changes of plasma temperature (consistent with the SEP charge states observations) affect merely *the magnitude* of the differences in A/Z^* between light and heavy elements. (In particular they cannot by themselves explain the spread of the SEP abundances *both ways* around the m.u. baseline, since they cannot change the sign of the differences in A/Z^*.)

[15] This may be due to the fact that we chose to use different ionization calculations for elements from Ne to Ni (most precise calculations by Jacobs *et al.* 1977*a*, *b*, 1979, 1980, which do not cover CNO) and for CNO (Jordan 1969). Hovestadt, Klecker, and Gloeckler (1982), who used consistently Jordan's (1969) older values, get a more exactly consistent picture, with a slightly higher temperature (2.5×10^6 K).

hanced with respect to lighter ones, while in others they are systematically depleted.

4. The amplitude of the variations of the abundance ratio between two elements is well correlated with their difference in A/Z^* (where Z^* is the mean effective charge of an element in the solar corona and most probably in SEP as well) (Fig. 12). This fact ought to reflect differences in acceleration and/or coronal and interplanetary propagation between elements with different A/Z^*'s. However, additional phenomena seem to be superposed on the first-order simple A/Z^* effect. The mechanisms that are responsible for the selective acceleration of ^{3}He and heavy elements in ^{3}He-rich events probably do not play a dominant role in shaping the various heavy-element compositions in non-^{3}He-rich events.

5. It is generally accepted that H often does not behave like heavier elements in SEP (e.g., Mason, Gloeckler, and Hovestadt 1983). We have found that, except in some particular situations, the He abundance variations cannot either be correlated with those of heavier elements in terms of simple Z or A/Z^* dependent effects (whenever ordinary coronal ionization states are prevailing in SEP, so that He is predominantly fully stripped). It remains to be investigated whether this deviation implies that the above ordering of the heavy-element abundances applies only to truly *trace* ions in SEP so that H and He naturally do not fit in, or can be explained in terms of the acceleration of significant fractions of "cool" material bringing substantial amounts of singly ionized He and associated low ionization states of heavies. Anyway, baseline abundance of H and He in SEP are at present difficult to define.

The implications of these findings are discussed in a companion paper (Meyer 1985).

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APPENDIX A

THE LOW ENERGY DATA OF MASON *ET AL.* (1980)

The major fraction of the data at the lower energy end of the range of available data come from Mason *et al.*'s (1980) study in the 1–4.6 MeV/n range (0.6–1.6 MeV/n for He/O and C/O). Mason *et al.* (1980) give a global analysis of 37 full days of enhanced flux. Mason (1980, private communication) has kindly provided us with the composition data for the 37 individual days. We have grouped these data into 15 one- to four-day periods (Table 1), chosen so as to group longer periods of roughly constant compositions, but not to dilute specific periods of marked different composition (e.g., first or last days of some active periods). The types of composition pattern in these long (24 or 48 h) onsets or tails of events do not differ from those commonly observed for entire events. Propagation effects certainly play a role in shaping these patterns (Mason *et al.* 1981; Mason, Gloeckler, and Hovestadt 1983), as they probably do in shaping the composition of entire events (§ III*b*).

In view of the charge resolution of the instrument, only the major even-Z nuclei are covered: He, C, O, Ne, Mg, Si, S, Fe. [We have derived approximate S abundances from the figures given for the sum (S + Ar + Ca), by assuming S/(S + Ar + Ca) ratios similar to those observed by other authors at slightly higher energies.]

By and large, the pattern found in Mason *et al.*'s data between 1 and 4.6 MeV/n is similar to the one obtained at higher energies. Some minor differences do however appear, which are partly illustrated in Figures 2–4. First, the spread on He/O, which is usually small above 2 MeV/n, is much larger at lower energies (0.6–1.6 MeV/n; see n. 9) with a trend toward much higher He/O ratios (see also Fig. 9). Other trends are more marginal. Compared to the bulk of the other sets of data with the same Fe/O ratio (which often converge with one another amazingly well), Mason *et al.*'s data show some differences on C/O, Ne/O, and mainly Mg/O (e.g., in Fe-median events, Mason *et al.*'s Mg/O differs by a factor of ~ 1.6 from a consensus of seven out of nine measurements by three groups, including two low-energy measurements between 2.0 and 3.1 MeV/n by Von Rosenvinge and Reames 1979). S/O also seems high for all types of events, but our derivation of S abundances from Mason *et al.*'s data on (S + Ar + Ca) may be questionable.

We do not know whether these differences represent real, systematic energy dependences of the composition, or whether they are instrumental. The observed trends are not found in the other, more limited low-energy studies by Hovestadt *et al.* (1973) and Von Rosenvinge and Reames (1979), which are more consistent with the higher energy data.

APPENDIX B

UPDATE OF THE LOCAL GALACTIC ABUNDANCE STANDARD FOR Ne, Ar, AND Zn

The "local Galactic" abundance standard is described in Meyer (1979*a*, *b*, *c*, *d*, *e*). Ne in H II regions is largely derived from the measured gas-phase Ne/O ratio. In Meyer (1979*b*), we considered that as much as $(30 \pm 15)\%$ of oxygen in H II regions could be locked in grains: $\sim 15\%$ certainly locked in silicate cores, and $(15 \pm 15)\%$ possibly locked *together with* C in polymer mantles. Now, the recent *IUE* observations of C in H II regions show that C is only slightly, if at all, depleted in the gas phase (Perinotto and Patriarchi 1980; Torres-Peimbert, Peimbert, and Daltabuit 1980). We therefore estimate that only $5\% \pm 5\%$ of O ought to be

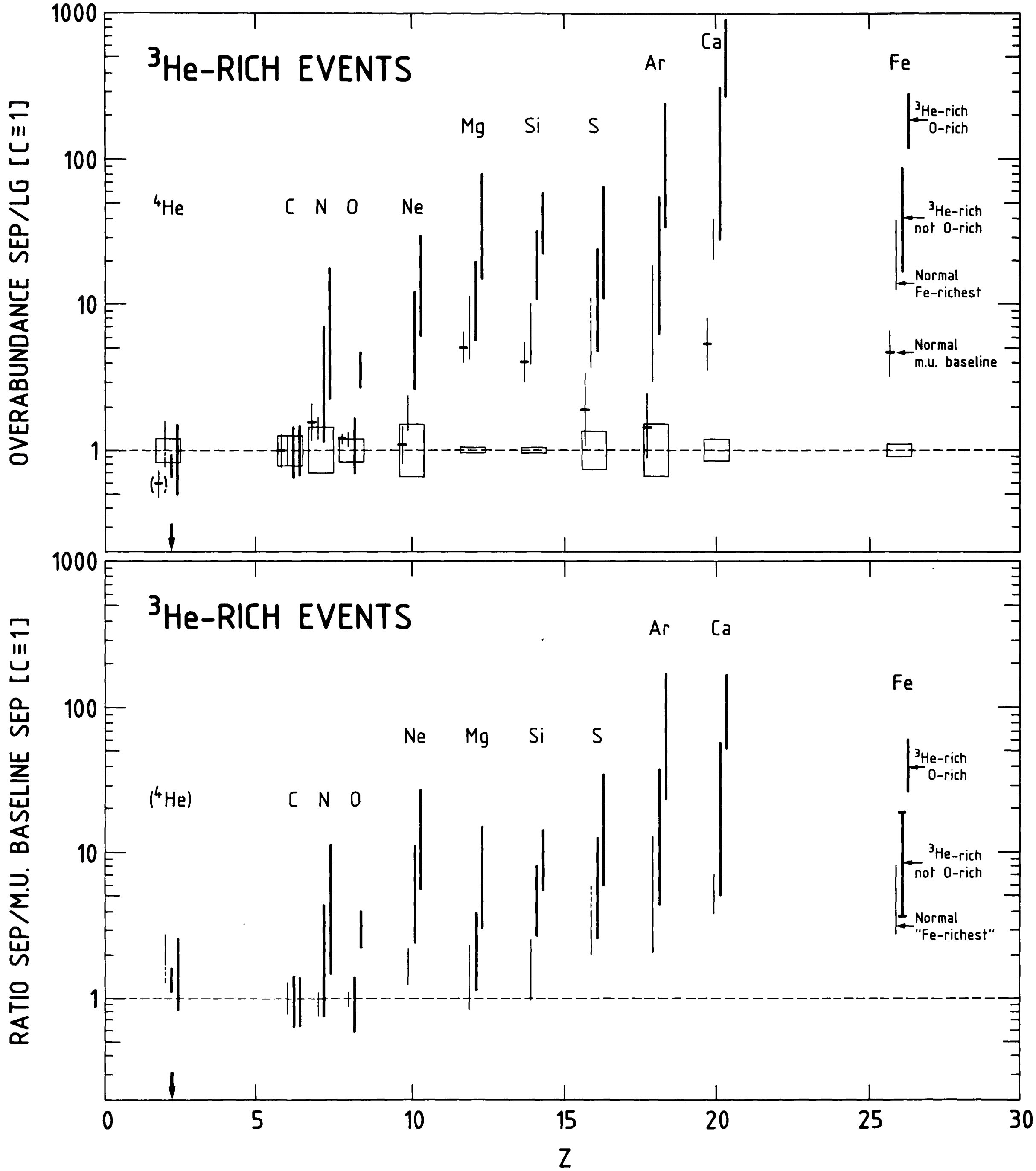

FIG. 13.—Abundances in ^{3}He-rich events vs. Z, after McGuire, Von Rosenvinge, and McDonald (1979*b*), Mason *et al.* (1980), and Reames and Von Rosenvinge (1981). *Top*: overabundances with respect to Local Galactic (LG) composition. *Bottom*: ratio to m.u. baseline composition of "normal", i.e. non–^{3}He-rich, events (Figs. 5 and 6). The abundances are *normalized to carbon* in this figure, because in the resonant heating model (Fisk 1978; Mason *et al.* 1980) C is expected never to be enhanced, and it is indeed observed to be sometimes underabundant relative to *all* neighboring elements, and especially O ("O-rich" events; see § II of Appendix C). The boxes represent the errors on the LG abundances. For each element, the vertical bars represent, from left to right: (i) the m.u. baseline abundance in normal events (top plot only; from Fig. 6); (ii) the range of abundances in "Fe-richest" normal events (from Fig. 3); (iii) the range of abundances in "non–O-rich" ^{3}He-rich events, in which O/C is standard; (iv) the range of abundances in "O-rich" (or "C-poor") ^{3}He-rich events, in which O is enhanced relative to C.

locked in polymers, leading to a total O depletion of only 20% ± 5%. The H II region Ne abundance is correspondly increased to 375(1.6)[16] on the scale Si ≡ 100. As for the hot star Ne/H measurement, we interpreted it in Meyer (1979*b*) by including a (20 ± 20)% difference in general metallicity between the solar system and the present-day local galactic medium. In the light of the more recent studies (Twarog 1980; Mayor 1976; Grenon 1977; Kane, McKeith, and Dufton 1980; Dufton, Kane, and McKeith 1981; Luck 1982*a*, *b*; Clegg, Lambert, and Tomkin 1981; Ferlet 1981; Peimbert and Torres-Peimbert 1977; Torres-Peimbert, Peimbert, and Daltabuit 1980; reviewed in Cassé 1983), this correction seems no longer necessary, and the adopted Ne abundance in hot stars is correspondingly increased to Ne = 270(1.7). The data from solar corona and SW are no longer taken into consideration because we believe that they are subjected to systematic biases (Paper II). Combination of the H II region and hot-star values yields the final estimate Ne = 325(1.5) on the scale Si ≡ 100, instead of 270(1.7) in Meyer (1979*b*).

The Ar value of Meyer (1979*c*) has to be updated along similar lines. In addition we shall consider some new measurements. In H II regions recent data (e.g., Shaver *et al.* 1983) confirm those used in Meyer (1979*c*). The lower limit derived from Ar^{++}/O is raised to Ar > 8 due to the smaller fraction of O believed to be locked in H II region grains. In H I gas, taking into account the latest analysis of the Ar/H ratio from the *Copernicus* data (e.g., Ferlet *et al.* 1980; Vidal-Madjar *et al.* 1982) and adopting a solar metallicity for the H I gas, we get Ar ≈ 6.5 (2.2). Combining these two determinations, we adopt Ar = 10.7(1.5), instead of 9 (1.7) in Meyer (1979*c*).

Finally, the value Zn = 0.135(1.6) in Meyer (1979*a*, *e*) has been updated to Zn = 0.098(1.22) in consideration of the precise photospheric determination by Biémont and Godefroid (1980), which we prefer to the slightly higher C1 meteoritic value in view of the volatility of Zn.

APPENDIX C

FAILURE OF TENTATIVE INTERPRETATIONS OF THE SEP COMPOSITION PATTERN IN TERMS OF PARAMETERS OTHER THAN FIP

The SEP overabundance pattern of Figure 3 has been interpreted in terms of a basic selection of elements according to FIP (with superposed variable monotonic mass-dependent biases). Here we shall explore a few alternate possibilities to explain this pattern, and find that none of them seems adequate.

I. A SELECTION ACCORDING TO MASS-TO-CHARGE RATIO BETWEEN IONS IN A CORONAL PLASMA

Let Z^* be the mean effective charge of each element in the corona. Figure 11 shows calculated values of the A/Z^* ratio for various plasma temperatures between 0.5 and 3.2×10^6 K. As can be seen, a jump between Ne and Mg can be obtained only *right near* $T \approx 0.8 \times 10^6$ K (at which temperature C, N, O, Ne are already He-like but Mg not yet). But then S should behave approximately like Si and Ca, and Fe very differently from Ca (while the overabundances of Ca and Fe are strikingly similar in all groups of observations; Fig. 3). And Na would probably behave in a fashion intermediate between Ne and Mg.

In addition, 0.8×10^6 K is a low temperature for the corona, which is reached only in a narrow layer within the transition region and around spicules (Beckers 1972) and in short-lived loops, i.e., in very limited regions of high temperature gradient (Foukal 1975, 1976, 1978; Raymond and Foukal 1982; Priest 1978), and possibly in coronal holes, which are clearly not regions of SEP acceleration (e.g., Zirker 1977). As shown in Figure 11, the *observed* mean ionization states in SEP (frozen in from the medium they were extracted from, as shown by Hovestadt, Klecker, and Gloeckler 1982; see § III*b*) indicate that, in the comparatively large flares for which detailed composition data are available, most of the particles should come from ordinary coronal material ($\sim 2 \times 10^6$ K), although particles originating in both *much* cooler ($< 0.1 \times 10^6$ K) and hotter (up to 5×10^6 K) media are always present (Gloeckler *et al.* 1976, 1981; Sciambi *et al.* 1977; Hovestadt *et al.* 1981; Ma Sung, Gloeckler, and Hovestadt 1981; Hovestadt *et al.* 1983). These observations, while probably confirming the major importance of cool magnetic loops in SEP acceleration, are totally inconsistent with the bulk of the accelerated material lying close to $T \approx 0.8 \times 10^6$ K.

II. THE MECHANISMS AT WORK IN ^{3}He-RICH EVENTS

Huge enhancements of the $^3He/^4He$ ratio are observed in some flares (reaching factors of $\sim 5 \times 10^4$), which are almost always accompanied by more limited enhancements of heavy-element abundances. To explain them, three models have been developed involving (i) a selective heating by *radiation pressure* (Hayakawa 1983), (ii) a selective *turbulent* heating (Ibragimov and Kocharov 1977; Kocharov 1981; Dubinsky *et al.* 1981; Kocharov, Charikov, and Kocharov 1981; and references therein), and (iii) a selective *resonant* heating (Fisk 1978; Mason *et al.* 1980). Could such mechanisms be the *basic*, *most usual* mechanisms that shape the SEP heavy element composition in "normal", i.e. non-^{3}He-rich events? The *radiation pressure* heating mechanism does not affect the heavy-element abundances (Hayakawa 1983). The *turbulent* heating mechanism heats ^{3}He in a cold medium (chromosphere, 10^4 K), in which heavier elements cannot be heated due to their low state of ionization. So this process too is inadequate to enhance simultaneously ^{3}He and heavy ions (Kocharov 1981; Klecker 1981). By contrast, the *resonant* heating mechanism does predict

[16] That is, within a factor of 1.6.

simultaneous enhancement of ^{3}He and heavy nuclei (Fisk 1978; Mason *et al.* 1980). In addition, the unusual charge states observed in ^{3}He-rich events, which imply a wide range of temperatures for the source material, are found entirely consistent with those required by this mechanism (Ma Sung *et al.* 1981).

^{3}He-enrichments are seldom found in large events, but are very frequent among the numerous events in which the particle flux is low (in 25% of these events ^{3}He/^{4}He is enhanced by a factor of greater than 250, and in 5% of them by a factor of greater than 1000; Möbius *et al.* 1982; Reames and Von Rosenvinge 1983). If interpreted in terms of a selective heating of ^{3}He, this fact suggests that the ^{3}He-rich events are those in which the threshold for particle acceleration *out of* the thermal population is high, so that the selectively heated ^{3}He population is accelerated while the bulk of the ^{4}He and H populations are not: thus few particles are accelerated altogether (Dubinsky *et al.* 1981; Möbius *et al.* 1982). In larger events, a significant fraction of the ordinary thermal population is believed to be accelerated, so that any selectively heated population becomes unimportant among the energetic particles.

We shall now show that, irrespective of these general considerations, an analysis of the heavy-element compositions in both ^{3}He-rich and normal events demonstrates by itself that the mechanisms that shape the heavy-element composition in the former cannot be important in shaping that of the latter.

Figure 13 compares the observed heavy-element compositions of ^{3}He-rich events with the m.u. baseline and the "Fe-richest" normal event compositions. The ^{3}He-rich data are due to McGuire, Von Rosenvinge, and McDonald (1979*b*), Mason *et al.* (1980), and Reames and Von Rosenvinge (1981). They have been split into "non–O-rich"events, in which O/C is standard like always in normal events, and "O-rich" (or "C-poor") events in which O is enhanced relative to C. The latter are richer than the former in all heavier nuclei as well. Figure 13 (*top*) shows that heavy-element enrichments in ^{3}He-rich events are not only much larger than even in the "Fe-richest" normal events (by factors of up to ~ 30), but show *distinctive qualitative characters*: (i) Ne, and in "O-rich" events also O and N are enhanced relative to C, while in normal events C/N/O/Ne is always close to standard (Fig. 3). (ii) Actually the behavior of Ne is fairly similar to that of Mg, while in normal events they behave drastically differently (Fig. 3). (iii) Ca is systematically more enhanced than Fe by factors of ~ 3, while in normal events Ca and Fe are always enriched by about the same factor (Fig. 3).[17]

Interpretation of the ^{3}He-rich event composition in terms of the resonant heating mechanism allows more specific statements to be made. Since the mechanism does not operate on C (Fisk 1978; Mason, Gloeckler, and Hovestadt 1979; Mason *et al.* 1980, 1981; Reames and Von Rosenvinge 1981; Fig. 14), and since the C/N/O/Ne ratios are *always* found close to standard in normal events (Fig. 3), it must not operate on all elements from C to Ne *in normal events*. These elements can therefore serve as a normalization basis, unaffected by the selective enhancements we are considering. Now, our mechanism *can only enhance*, *not deplete*, elements. It therefore cannot explain that at least Fe and Ar are sometimes underabundant with respect to C, N, O, Ne (Fig. 3). Neither can the usual depletions of S and Ar with respect to both their lower-Z and higher-Z neighbors Si and Ca (Fig. 3) be explained without a very ad hoc distribution of temperatures of the source medium (Fig. 14). In addition, to reproduce the ever-present jump between Ne and Na (Fig. 3), the enhancement mechanism in normal events should *always* set in brutally at Na, i.e., always at the same temperature $T \approx 0.7 \times 10^6$ K (Fig. 14), i.e., at half the ordinary coronal temperature. Such a behavior would seem very ad hoc, and it is totally different from what is observed to happen in ^{3}He-rich events.[18] So, the phenomena that shape the main features of the composition of normal events do not seem to be those that are at work in ^{3}He-rich events.

Could the latter still be an important factor shaping the *upward spread* of abundances in normal events? Probably not, for two reasons. First, it was noted above that the character of the heavy-element enrichments in ^{3}He-rich flares differs from that in normal flares (Fig. 13). Second, the spread may be organized in two ways: (i) either around the m.u. baseline composition, in which case the selective heating mechanism cannot be the sole dominant one because it cannot explain the depletions; (ii) or, if there are to be only enhancements, the "Fe-poorest" event composition must be taken as the baseline for the spread; but we see no obvious phenomenon that might explain such an odd baseline composition (Fig. 4, *bottom*).

III. A SELECTIVE PREACCELERATION IN COLLAPSING MAGNETIC NEUTRAL SHEETS

Mullan and Levine (1981) and Mullan (1983) have recently investigated possible selection effects between the various elements during a preacceleration phase by a first-order Fermi process within a collapsing neutral magnetic sheet in a coronal loop (which injects particles into a main acceleration phase by magnetic reconnection along the neutral line itself). Competition between energy gains and Coulomb energy losses ($\propto Z^{*2}/A$) then leads to preferential preacceleration of those elements whose dominant ionization states have low enough Z^{*2}/A ratios. A problem may lie in the fact that the authors have used ionization *equilibrium*

[17]When compared to the m.u. baseline SEP abundances (which probably reflect the coronal abundances, Paper II), Ar and Ca stand up with especially high enhancement factors in ^{3}He-rich events (Fig. 13, *bottom*). Note that in the resonant heating mechanism (Fisk 1978; Mason *et al.* 1980), Ar and Ca are selectively heated when the temperature of the material lies around ~ 1.7 to 2×10^6 K, a very ordinary temperature for the corona, while Fe heating dominates at slightly higher temperatures (Fig. 14). On the other hand, the fact that in ^{3}He-rich events O is sometimes enhanced relative to C, and sometimes not, is well accounted for by Figure 14: it shows that ^{16}O can be resonantly heated, or not, depending on the precise value of the electron-to-proton temperature ratio T_e/T_i (while ^{12}C is never heated).

[18]According to the electron-to-proton temperature ratio T_e/T_i and to the range of high temperatures experienced by the acceleration medium, one would also expect strong variations of the Ni/Fe ratio in Fe-enriched events (Fig. 14), which are not observed in normal events (Fig. 3). This difference in expected behavior between Fe and Ni in the resonant heating mechanism is due to different distributions of Z^*/A over the various Fe and Ni isotopes.

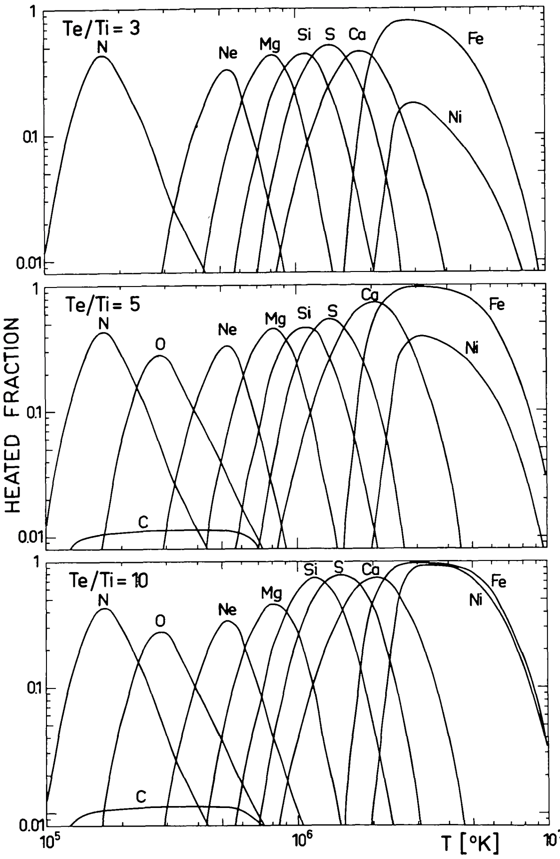

FIG. 14.—Calculated selectively heated (and hence accelerated) fraction of heavy elements in the resonant heating model for ^{3}He-rich events (Fisk 1978; Mason, Gloeckler, and Hovestadt 1979; Mason *et al.* 1980), vs. plasma temperature for three values of T_e/T_i (electron-to-proton temperature ratio). It is postulated that the medium starts from some cool temperature (possibly within a loop) and later on gets heated in the flare process, thus sweeping a wide range of plasma temperatures T and permitting selective heating (and acceleration) of a large number of elements. This figure has been constructed based on the analysis of Mason *et al.* (1980), as a generalization of their Fig. 11. The ionization equilibria are from Jacobs *et al.* (1977*a*, *b*, 1979, 1980) and Jordan (1969) for CNO, and the isotope fractions from Cameron (1982).

calculations, while loops are known to be out of equilibrium (rapidly cooling; see e.g., Vorpahl *et al.* 1975; Raymond and Foukal 1982).

Anyhow, the authors have been encouraged by the fact that the process does qualitatively reproduce some typical features of the SEP overabundance pattern versus Z: enhanced abundances of Mg, Si relative to C, N, O, Ne, a dip in the S–Ar region, and a rise again around Fe (Figs. 3 and 9 of Mullan and Levine 1981). We do, however, think the model has serious difficulties in fitting the essential characters of the observed SEP abundances (Fig. 3).

The predicted distortions of abundances are indeed much too large: e.g., for the very well observed elements C, N, O, Ne, Mg, Si the authors predict relative abundance distortions reaching factors of ~ 50 to 5000 according to the model used, while the observed distortions reach only a factor of ~ 4 in all but the "Fe-richest" observations (in which they reach factors of at most ~ 10) (Fig. 3). Even the C/N/O abundance ratios are predicted to be abnormal by orders of magnitude, while they are very close to normal in all non-^{3}He-rich SEP events.

The authors have noted this problem, and have suggested a dilution of these selectively accelerated particles with a component of normal composition. Whatever its physical significance, such a dilution with 30% to 60% as much normal matter (normalized to Si, which is most enhanced in all calculated models) would largely "fill the dips" in the predicted overabundances plot versus Z, and account for the underabundance factor of ~ 2.5–4 of C, N, O, Ne relative to Si commonly observed in SEP. It would thus erase the difficulties of the model with the *relative* abundances of those elements that are comparatively underabundant in both the calculations and the observed SEP (e.g., C/N/O/Ne; see Fig. 3). Only the abundances of the elements that are enhanced in SEP would then have to be accounted for by the model. But they are not. In all or most calculated conditions, indeed, ratios such as Na/Si, Mg/Si, Ca/Fe, and Ni/Fe (all elements that tend to be enhanced in SEP, Fig. 3) are predicted to be lower than normal (by a factor of ~ 2.5–4 after dilution), while they are definitely never observed to be so. In other words, after dilution Na and Mg would largely behave like C, N, O, Ne rather than like Si, contrary to observation (Fig. 3).

In addition, the observed remarkable constancy of the Si/(C+N+O+Ne) ratio (in all but "Fe-richest" events) at a level ~ 2.5–4 times higher than normal would imply the dilution ratio to be quite constant from flare to flare, which is not plausible. (This latter remark in particular is totally independent of the details of the ionization equilibrium calculation.)

IV. LOW-FIP REFRACTORY ELEMENTS AS INTERPLANETARY GRAIN DESTRUCTION PRODUCTS

Since most low-FIP elements tend to be refractory and high-FIP elements to be volatile, a correlation with FIP may more or less mimic a correlation with volatility. Therefore, the observed SEP composition pattern (apparent correlation with FIP) might be reproduced if energetic particles originated to a large extent from grain destruction products (which are predominantly refractory). This idea has been considered to explain the *galactic* cosmic ray source composition, which is also correlated with FIP (Cesarsky and Bibring 1980; Epstein 1980; Bibring and Cesarsky 1981; Meyer 1981*b*; Tarafdar and Apparao 1981). It cannot be formally excluded for SEP. However, the similarity between the compositions of SEP and of the solar corona strongly suggests that the baseline SEP composition is simply the coronal composition (Paper II). If this is true, the "grain hypothesis" would require that grain destruction products play a major role in shaping the composition of the entire solar coronal reservoir, a very bold hypothesis indeed!

We conclude that we are at present unable to find an adequate context in which the observed SEP composition pattern could be interpreted, apart from a selection of elements according to FIP.

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