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ELEMENTAL COMPOSITION OF SOLAR ENERGETIC NUCLEI

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ABSTRACT

We find for four major solar-flare events that the average solar energetic particle (SEP) abundances are similar to abundances in the solar wind and to recent coronal measurements. The average SEP and galactic cosmic-ray source abundances are also similar for elements with nuclear charge $8 \leq Z \leq 28$, but are different for helium, carbon, and nitrogen.

Subject headings: cosmic rays: abundances — Sun: abundances — Sun: atmosphere — Sun: flares — Sun: solar wind

I. INTRODUCTION

The elemental composition of energetic nuclei accelerated in solar flares and ejected into interplanetary space varies from flare to flare (e.g., Armstrong and Krimigis 1971; Mogro-Campero and Simpson 1972; Teegarden, von Rosenvinge, and McDonald 1973; Crawford *et al.* 1975) and differs from the composition of the photosphere (e.g., Webber 1975; Bertsch and Reames 1977; Dietrich and Simpson 1978). In this *Letter* we present new data on the abundances of energetic nuclei with nuclear charge $2 \leq Z \leq 28$ from the seven largest solar energetic particle events observed in the 1977 September to 1978 May period.

II. OBSERVATIONS

The observations were performed at heliocentric distances between 1 and 3 AU with the Low Energy Telescopes (LETs) of the cosmic-ray detector systems (CRS, see Stone *et al.* 1977) aboard the *Voyager 1* and *Voyager 2* spacecraft. The rms charge resolution ranges from 0.08 charge units at carbon to 0.27 units at iron.

For each flare event we list in Table 1 the observed relative abundances for helium through nickel and the spectral indices of the major elements from carbon through iron. Both composition and energy spectra were averaged over time intervals chosen to exclude event onset periods when propagation effects may be important.

We have compared our abundance results to other reported observations (McGuire, von Rosenvinge, and McDonald 1979 for flare events [i], [ii], [iii], and [iv] of Table 1, and Dietrich and Simpson 1978 for event [ii]). Generally, the various measurements agree within statistical error, except for some rare elements (see Cook *et al.* 1979; McGuire *et al.*). For major elements the largest nonstatistical difference occurs for iron in event (ii) [we obtain Fe/O = 0.70 ± 0.06, while McGuire *et al.* found (Cr + Fe + Ni)/O = 1.17 ± 0.11], and may result from McGuire *et al.* including the event onset period in their averaging time.

III. DISCUSSION

In this *Letter* we concentrate on those flare events ([i], [ii], [iv], and [v] of Table 1) for which the abundance ratios are approximately independent of kinetic energy per nucleon in our energy range, since in these cases the effects of acceleration and propagation biases on the observed abundance ratios may be relatively small.

Figure 1 presents a graphical overview of the solar energetic particle (SEP) abundances for the four selected flare events along with abundances for the photosphere, the corona, an active coronal region, and the solar wind. Although the SEP composition is seen to vary from flare to flare, the average SEP abundances, when normalized to silicon, are similar to those of the other sources for all elements shown except carbon, nitrogen, and oxygen, where the SEP values are persistently low relative to those of the photosphere, as is oxygen in the solar-wind and active-region measurements.

In Figure 2 we examine the systematics of the SEP flare-to-flare composition variations by comparing the SEP elemental composition of the four selected flares to the four-flare average composition. In each of the four flare events the deviations of the SEP abundances from their four-flare average values may be considered monotonic functions of nuclear charge Z in the range $6 \leq Z \leq 28$. In particular, the flare-to-flare abundance variations of carbon, nitrogen, and oxygen are correlated, as are the abundance variations of calcium, iron, and nickel. However, the abundance variations of C, N, and O relative to silicon are anticorrelated with those of Ca, Fe, and Ni. An important exception to the Z ordering of the abundance variations occurs for helium, whose abundance relative to silicon is approximately the same in all four events. The correlations of the SEP elemental abundances seen in Figure 2 suggest that the SEP elemental composition may be described by an average composition and a systematic deviation which varies in strength, but not character, from flare to flare. In particular, the "Fe-rich" events do not stand out as a separate class of event.

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TABLE 1

SOLAR ENERGETIC PARTICLE OBSERVATIONS

Z	ELEMENT	SOLAR ENERGETIC PARTICLE EVENT[a] (i)	(ii)	(iii)	(iv)	(v)	(vi)[e]	(vii)[e]
		Abundance Relative to Silicon[b] (4.6–7.8 MeV/nucleon)						
2.......	He	468±60	433±45	565±49	384±15	386±19	77±3	240±6
		Abundance Relative to Oxygen[c] (5.9–9.3 MeV/nucleon)						
3.......	Li	<0.006	<0.007	<0.003	<0.0011	<0.0008	<0.0050	<0.0016
4.......	Be	<0.0024	<0.005	<0.003	<0.0006	<0.0019	<0.0005	<0.0004
5.......	B	<0.0024	<0.003	<0.003	<0.0006	<0.0014	<0.0004	<0.0004
		Number of Nuclei Detected and Abundance Relative to Silicon[b] (8.7–15 MeV/nucleon)						
6.......	C	151 3.02±0.49	134 1.20±0.15	72 2.12±0.44	519 3.58±0.34	658 4.39±0.40	3727 1.96±0.06	1765 3.90±0.20
7.......	N	35 0.70±0.15	42 0.37±0.07	22 0.65±0.18	133 0.92±0.11	152 1.01±0.12	1230 0.65±0.02	482 1.06±0.07
8.......	O	285 5.70±0.87	347 3.10±0.34	179 5.26±0.98	1113 7.68±0.68	1252 8.35±0.72	10956 5.77±0.14	3797 8.38±0.42
9.......	F	0 <0.04	0 <0.02	0 <0.05	0 <0.013	0 <0.012	3 <0.003[c]	1 <0.007[c]
10......	Ne	49 0.98±0.20	87 0.78±0.11	30 0.88±0.22	162 1.12±0.13	156 1.04±0.12	1153 0.61±0.02	413 0.91±0.06
11......	Na	2 0.040(+0.053, −0.026)	10 0.09(+0.04, −0.03)	2 0.06(+0.08, −0.04)	13 0.090(+0.032, −0.025)	13 0.087(+0.031, −0.024)	112 0.059±0.006	43 0.095±0.015
12......	Mg	49 0.98±0.20	97 0.87±0.12	30 0.88±0.22	236 1.63±0.17	222 1.48±0.16	1956 1.03±0.03	709 1.57±0.09
13......	Al	5 0.10(+0.07, −0.05)	12 0.11(+0.04, −0.03)	4 0.12(+0.09, −0.06)	9 0.06(+0.03, −0.02)	21 0.14±0.03	139 0.073±0.006	47 0.104±0.016
14......	Si	50 1	112 1	34 1	145 1	150 1	1898 1	453 1
15......	P	0 <0.04	1 <0.03[c]	0 <0.05	1 <0.023[c]	1 <0.022[c]	7 <0.006[c]	0 <0.004
16......	S	6 0.12(+0.07, −0.05)	27 0.24±0.05	14 0.41(+0.14, −0.11)	31 0.21±0.04	36 0.24±0.05	401 0.21±0.01	63 0.14±0.02
17......	Cl	2 <0.09[c]	0 <0.02	0 <0.05	0 <0.013	2 <0.031[c]	6 <0.005[c]	0 <0.004
18......	Ar	3 0.06(+0.06, −0.03)	6 0.054(+0.032, −0.021)	2 0.06(+0.08, −0.04)	6 0.041(+0.025, −0.017)	1 0.007(+0.015, −0.006)	37 0.019±0.003	6 0.013(+0.008, −0.005)
19......	K	0 <0.04	1 <0.03[c]	0 <0.05	1 <0.023[c]	0 <0.012	10 <0.008[c]	1 <0.007[c]
20......	Ca	6 0.12(+0.07, −0.05)	20 0.18±0.04	4 0.12(+0.09, −0.06)	12 0.083(+0.032, −0.024)	9 0.060(+0.027, −0.020)	93 0.049±0.005	15 0.033(+0.011, −0.008)
21......	Sc	0 <0.04	1 <0.03[c]	0 <0.05	0 <0.013	0 <0.012	0 <0.001	0 <0.004
22......	Ti	0 <0.04	0 <0.02	0 <0.05	0 <0.013	0 <0.012	4 <0.004[c]	0 <0.004
23......	V	1 <0.07[c]	0 <0.02	0 <0.05	0 <0.013	0 <0.012	2 <0.002[c]	0 <0.004
24......	Cr	0 <0.04	2 0.018(+0.024, −0.012)	1 0.029(+0.068, −0.025)	4 0.028(+0.022, −0.013)	3 0.020(+0.020, −0.011)	21 0.011±0.002	7 0.015(+0.008, −0.006)
26......	Fe	83 1.66±0.30	243 2.17±0.25	54 1.59±0.35	127 0.88±0.11	94 0.63±0.08	1122 0.59±0.02	183 0.40±0.04
28......	Ni	6 0.12(+0.07, −0.05)	15 0.13(+0.04, −0.03)	2 0.06(+0.08, −0.04)	4 0.028(+0.022, −0.013)	5 0.033(+0.023, −0.015)	45 0.024±0.004	5 0.011(+0.008, −0.005)
		SPECTRAL INDEX,[b,d] γ ($dj/dE \sim E^{-\gamma}$)						
6.......	C	3.28±0.13	2.82±0.15	4.72±0.18	3.46±0.07	2.80±0.07	1.14±0.03	2.95±0.04
8.......	O	3.59±0.09	2.90±0.09	4.42±0.12	3.59±0.05	2.90±0.05	1.26±0.02	3.16±0.03
10......	Ne	3.60±0.22	2.31±0.21	4.70±0.36	3.54±0.11	2.92±0.13	1.35±0.06	3.10±0.07
12......	Mg	3.70±0.21	2.52±0.16	3.85±0.26	3.49±0.10	2.81±0.11	1.29±0.04	3.14±0.06
14......	Si	3.14±0.21	2.30±0.18	3.29±0.25	3.75±0.12	3.05±0.14	1.72±0.04	3.45±0.07
26......	Fe	2.75±0.20	2.25±0.11	2.57±0.24	3.64±0.13	2.82±0.18	3.20±0.05	4.15±0.10

[a] Observation periods: (i) 1977 September 20 0000 UT to 1977 September 22 0000 UT; (ii) 1977 September 25 0000 UT to 1977 September 27 1200 UT; (iii) 1977 November 23 0600 UT to 1977 November 26 1200 UT; (iv) 1978 February 15 0000 UT to 1978 February 18 0600 UT; (v) 1978 April 24 1800 UT to 1978 April 28 1200 UT; (vi) 1978 April 29 0600 UT to 1978 May 1 0000 UT; (vii) 1978 May 2 0600 UT to 1978 May 6 0000 UT.

[b] The ($\pm 1\ \sigma$) uncertainties include the effect of particle counting statistics only.

[c] 84% confidence upper limits only are quoted for these elements since possible background contributions have not been assessed.

[d] Spectral indices were obtained by a least-squares fit using six energy bins in the interval 5–15 MeV per nucleon.

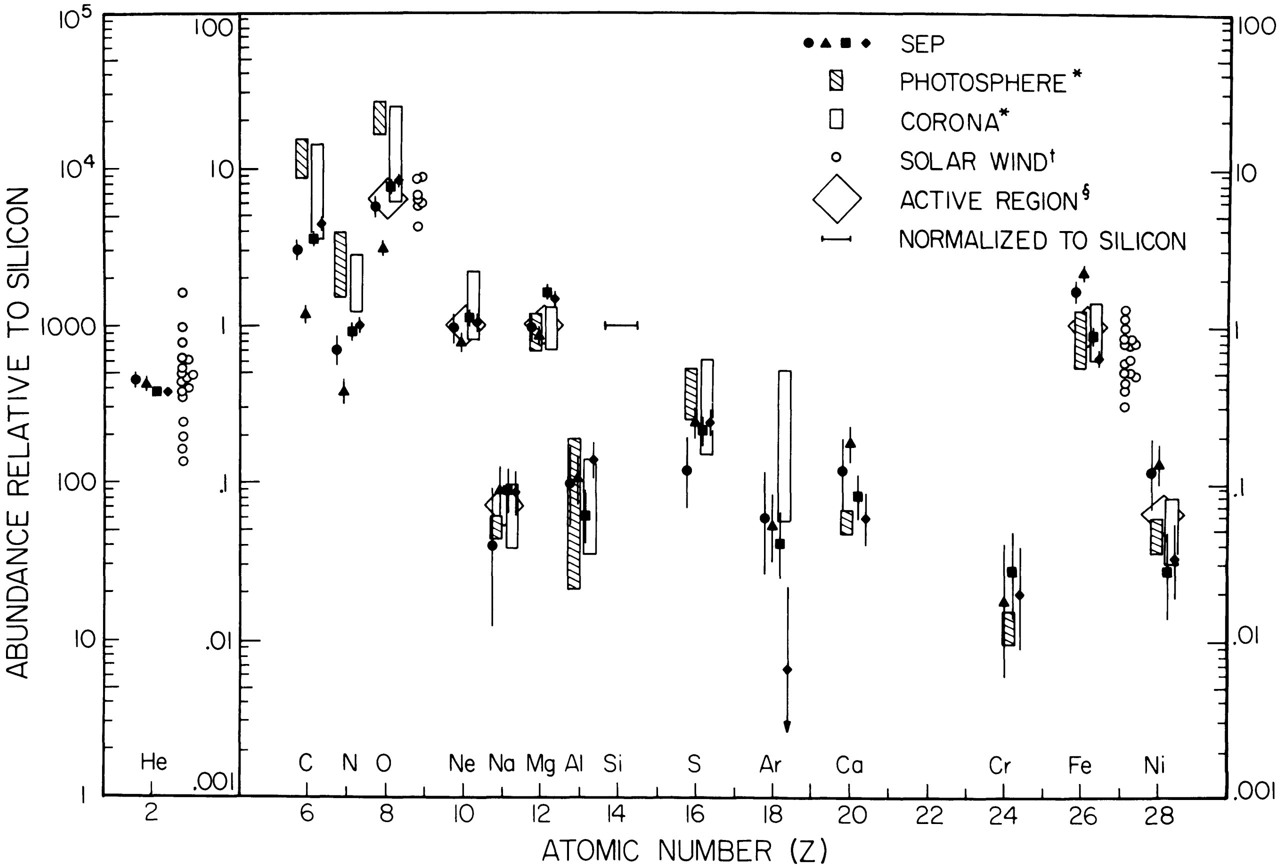

FIG. 1.—Elemental abundances relative to silicon. Symbols ●, ▲, ■, and ♦ indicate the composition of SEP events (i), (ii), (iv), and (v) of Table 1, respectively. References: (*) Meyer and Reeves (1977), (†) Bame *et al.* (1975), (§) Parkinson (1977).

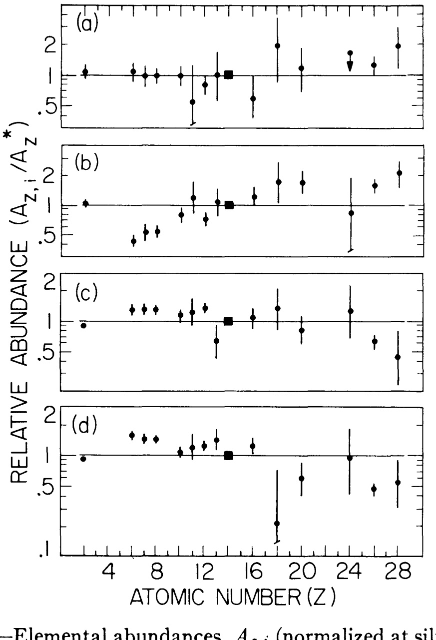

FIG. 2.—Elemental abundances, $A_{z,i}$ (normalized at silicon, ■) from individual flare events i, compared to the four-flare geometric mean abundances, A_z^*. Panels (*a*)–(*d*) correspond to SEP events (i), (ii), (iv), and (v) of Table 1, respectively.

In Figure 3 (see also Table 2) we compare the four-flare average SEP composition to that obtained for the photosphere, the corona, the solar wind, and the galactic cosmic-ray source. Figure 3*a* shows that relative to the photosphere the average SEP abundances of carbon, nitrogen, oxygen, and to a lesser extent sulfur, are depleted with respect to the higher Z elements ($11 \leq Z \leq 28$). The relative depletion of these elements is a persistent effect and has been reported earlier by Teegarden, von Rosenvinge, and McDonald (1973), Webber *et al.* (1975), Cook *et al.* (1979), Mason, Hovestadt, and Gloeckler (1979), and McGuire, von Rosenvinge, and McDonald (1979).

The comparison of coronal abundances (Fig. 3*b*) from the compilation of Meyer and Reeves (1977) to the average SEP composition shows a relative depletion of SEP carbon, nitrogen, and oxygen which is less pronounced than that seen in Figure 3*a*. The large error bars result mostly from the spread of coronal abundance measurements. Several recent coronal measurements (open symbols of Fig. 3*b*) show good agreement with the average SEP composition, even for elements like N and O where large persistent depletions occur in SEPs relative to the photosphere.

Figure 3*c* shows that the solar wind and average SEP abundances are in good agreement. Further, in Figure 1

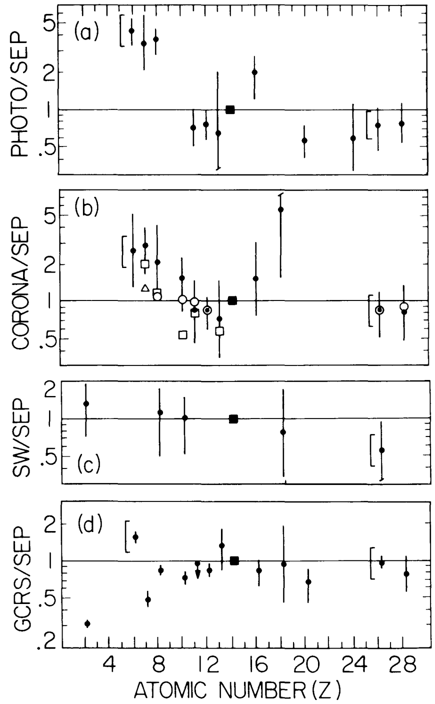

FIG. 3.—Comparison of the four-flare average SEP abundances (normalized at silicon, ■) to abundances from (*a*) the photosphere (● Meyer and Reeves 1977), (*b*) the corona (● Meyer and Reeves 1977, ○ Parkinson 1977, □ Withbroe 1975, and △ inferred from the N/O measurement of McKenzie *et al.* 1978 and Parkinson's O/Si ratio), (*c*) the solar wind (● Boschler and Geiss 1976), and (*d*) the galactic cosmic-ray source (● Lezniak and Webber 1978, except for the argon abundance from Garcia-Munoz and Simpson 1979). The ($\pm 1\ \sigma$) error bars include the estimated uncertainty in the source abundances and the uncertainty due to particle counting statistics in the average SEP abundances. The ($\pm 1\ \sigma$) uncertainty in the average SEP abundances due to the observed flare-to-flare abundance variations is indicated for carbon and iron by brackets.

TABLE 2

RELATIVE ABUNDANCES IN SOLAR ENERGETIC PARTICLES, AND IN THE PHOTOSPHERE, CORONA, SOLAR WIND, AND GALACTIC COSMIC-RAY SOURCE

Z	Element	SEP Four Flare Average[a]	Photosphere[b]	Corona[c] (a)	Corona[c] (b)	Corona[c] (c)	Solar[d] Wind	GCRS[e]
2	He	416±19	...	...	...	...	530±250	129±8
6	C	2.74±0.17	12±3	7(2)	...	...	...	4.32±0.27
7	N	0.70±0.06	2.4(1.6)	2.0±0.8	...	1.4	...	0.34±0.05
8	O	5.80±0.34	21±5	12(2)	6.3	6.6	6.6±3.7	4.85±0.28
10	Ne	0.97±0.07	...	1.5±0.7	1.0	0.5	1.0±0.5	0.69±0.06
11	Na	0.07(1.4)[f]	0.052±0.008	0.06(1.6)	0.07	0.06	...	<0.05
12	Mg	1.20±0.09	0.93±0.25	1.0±0.3	1.0	...	...	1.02±0.08
13	Al	0.10±0.02	0.063(3)	0.07(2)	...	0.06	...	0.13±0.04
14	Si	1	1	1	1	1	1	1
16	S	0.20±0.04	0.39±0.14	0.3(2)	...	...	...	0.16±0.02
18	Ar	0.03(1.9)	...	0.17(3)	...	...	0.024±0.013	0.03±0.01
20	Ca	0.10±0.02	0.057±0.010	...	...	...	...	0.07±0.02
24	Cr	0.02(1.8)	0.0125±0.0030	...	...	...	...	<0.07
26	Fe	1.19±0.09	0.89±0.35	1.0±0.4	1.0	...	0.7±0.5	1.15±0.10
28	Ni	0.06(1.3)	0.048±0.012	0.05(1.6)	0.06	...	...	0.05±0.01

[a] The geometric mean of the abundances from flare events (i), (ii), (iv), and (v) of Table 1. The ($\pm 1\ \sigma$) uncertainties include the effect of particle counting statistics, but not that of flare-to-flare variations.

[b] Meyer and Reeves 1977.

[c] (*a*) Meyer and Reeves 1977, (*b*) Parkinson 1977, (*c*) Withbroe 1975.

[d] Solar-wind abundances relative to silicon were inferred from He/H = 0.04 ± 0.01, O/H = $(5 \pm 2) \times 10^{-4}$, Fe/H = $(5 \pm 3) \times 10^{-5}$, Si/H = $(7.6 \pm 3) \times 10^{-5}$, He/Ne = 530 ± 70, and Ne/Ar = 41 ± 10 (Boschler and Geiss 1976).

[e] GCRS abundances are from Lezniak and Webber 1978, except for the abundance of argon from Garcia-Munoz and Simpson 1979. The abundances have been renormalized from oxygen to silicon.

[f] Numbers in parentheses indicate factors of error.

we see that the O/Si and Fe/Si ratios have a similar range of variation in the solar wind[1] and in the SEPs. We also note that the average solar-wind values of He/Ne = 530 ± 70 and Ne/Ar = 41 ± 10 (Boschler and Geiss 1976) are close to the four-flare average SEP values of He/Ne = 430 ± 20 and Ne/Ar = 32 (+27, −15). While the average elemental compositions of SEPs and solar wind are similar, the isotope ratio $^{20}Ne/^{22}Ne$ has been found to differ in SEPs and solar wind by almost a factor of 2 (Dietrich and Simpson 1979; Mewaldt *et al.* 1979).

The overall similarity of the average SEP elemental composition and the elemental composition measured for the solar wind and corona, and in particular the evidence for a common depletion of oxygen relative to the photosphere, suggests that the differences in the average SEP and photosphere elemental composition may be related to basic plasma processes occurring on the Sun. Other suggestions that SEP composition may be dominated by that of the preaccelerated plasma were made by Zwickl *et al.* (1978) and Briggs, Armstrong, and Krimigis (1979).

Figure 3*d* compares our average SEP elemental composition and that of the galactic cosmic-ray source (GCRS). Previous such comparisons (Mogro-Campero and Simpson 1972; Webber 1975) have been used to support the idea that the GCRS composition may reflect that of energetic nuclei injected by flaring stars into a galactic accelerator (e.g., Cassé and Goret 1978; Montmerle 1979), in which case the GCRS elemental composition would not be a clear signature of recent nuclear processing in presupernovae or in supernova explosions. Figure 3*d* extends Webber's earlier (1975) comparison of SEP and GCRS composition to include the elements argon, calcium, and nickel, and shows that SEP and GCRS abundances are close for elements oxygen through nickel, but that significant differences occur for helium, carbon, and nitrogen.

[1] Some of the variation in the solar-wind abundances may be due to experimental errors (see Bame *et al.* 1975).

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