

Elemental Composition of Solar
Energetic Particles in 1977 and 1978

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The elemental composition of energetic nuclei ($2 \leq Z \leq 28$) from seven major solar flare events in the September 1977 to May 1978 period has been measured with the cosmic ray detector systems aboard the Voyager 1 and 2 spacecraft. The energetic nuclei abundances differ significantly from those of photospheric material. They are enhanced relative to the photosphere by a factor $\mathcal{F}_i = \mathcal{F}_i^* \cdot f(Z_i)$. \mathcal{F}_i^* is common to all events and has a non-monotonic characteristic dependence on nuclear charge Z . $f(Z_i)$ is a monotonically varying function of Z , differing from event to event. \mathcal{F}_i^* is roughly ordered by 1st ionization potential into two groups of elements, metallics and volatiles.

1. Introduction. Knowledge of the physical characteristics of energetic nuclei fluxes from solar flares contributes to studies of astrophysical acceleration processes and of the elemental composition of thermal solar material.

We present in this report new data on the abundances of energetic nuclei with charge $Z \geq 2$ from seven major solar flares in the September 1977 to May 1978 period.

2. Observations. The observations were performed between 1 and 3 AU with the cosmic ray detector systems (CRS) aboard the Voyager 1 and 2 spacecraft, launched towards the outer heliosphere in fall 1977. The CRS instrument has been described elsewhere (Stone et al., 1977). The measurements discussed here were made with the Low Energy Telescope (LET) system, consisting of four identical LET telescopes on each spacecraft, with a total geometry factor $A\Omega \approx 3.5 \text{ cm}^2\text{sr}$. The charge and total energy of a nucleus was derived from a dE/dx - dE/dx - E analysis. The excellent data quality achieved is demonstrated in Figure 1, an element histogram of solar flare nuclei from Li through Ni summed over the seven solar flare events. The charge resolution ranges from $\sigma_Z \approx 0.08$ units at C to $\sigma_Z \approx 0.27$ units at Fe. The large $A\Omega$ and excellent charge resolution produce gaussian peaks even for the rarer elements such as Na, Al, Ar, Ca, Cr, and Ni, and allow abundance determinations for individual flares. The near absence of B and F events, in spite of their location adjacent to the abundant elements C and O, attests to the negligible background of the data.

3. Results. The abundance ratios relative to oxygen (A_i) of nuclei from Li through Ni are listed in Table 1. The summation time intervals for each event (Table 1: Observation Period) were chosen to exclude the event onset periods, when propagation effects could affect the element composition. The results from Table 1 are displayed in Figure 2. Also shown, for comparison, are photospheric abundances (supplemented with coronal values for Ne and Ar) compiled by Meyer and Reeves (1977), and galactic cosmic ray (GCR) source abundances from Lezniak and Webber (1978).

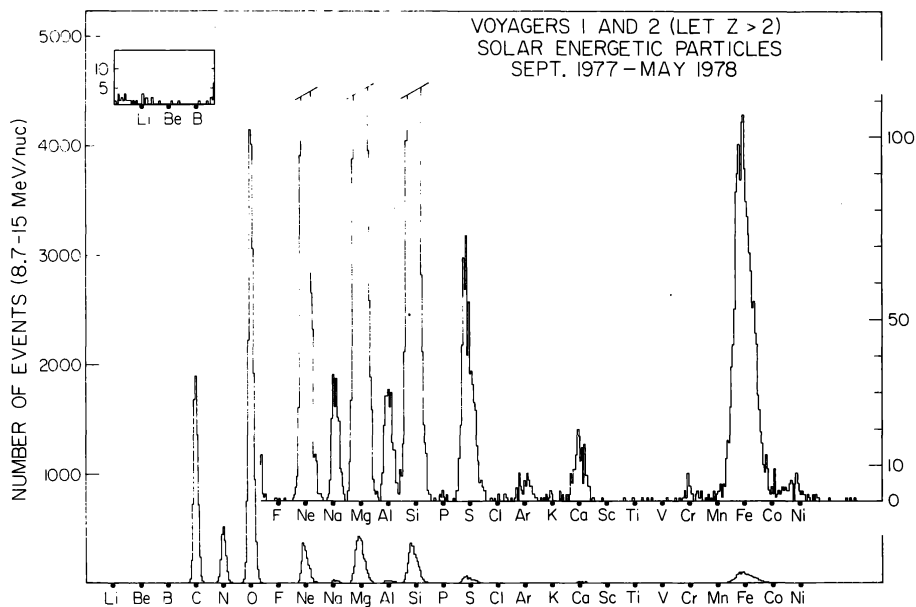


Figure 1. Element histogram ($Z \geq 3$)

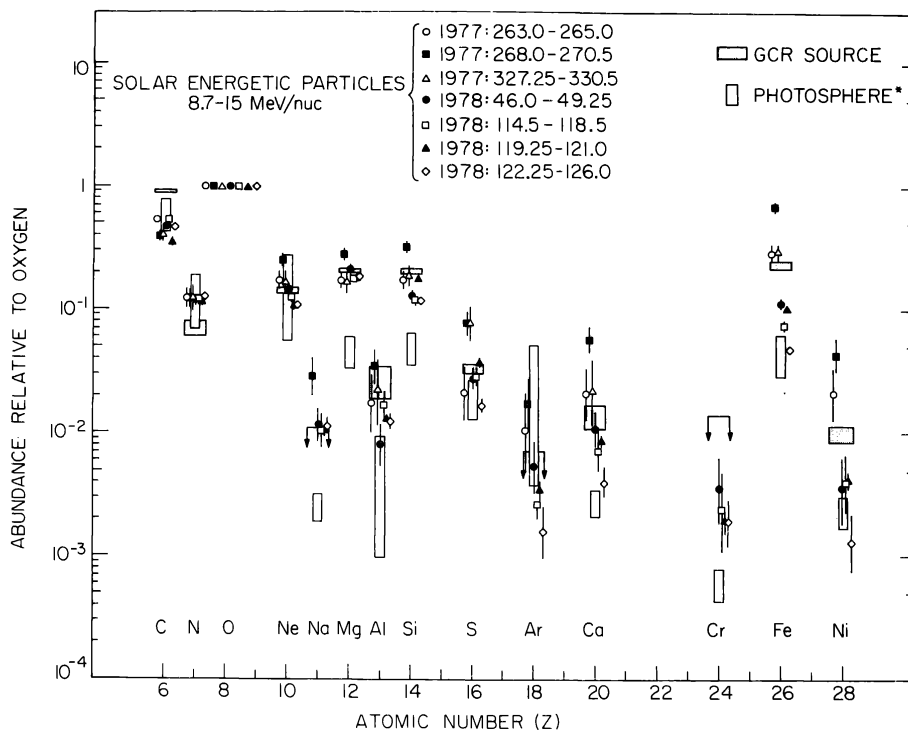


Figure 2. Element abundances relative to oxygen
* Except for Ne and Ar (see text)

Table 1: Solar Energetic Particle Abundances, 8.7 - 15 MeV/nuc*

Z	Element	Event Abundance Ratios (relative to Oxygen)						
		(a)	(b)	(c) [†]	(d)	(e)	(f) [†]	(g) [†]
3	Li	<.007	<.005	<.01	<.002	<.002	<.0015	<.0012
4	Be	<.007	<.005	<.01	<.003	<.003	<.0003	<.0005
5	B	<.007	<.005	<.01	<.002	<.002	<.0004	<.0005
6	C	.53 ± .05	.39 ± .04	.40 ± .06	.47 ± .03	.53 ± .03	.340 ± .006	.46 ± .01
7	N	.12 ± .02	.12 ± .02	.12 ± .03	.12 ± .01	.12 ± .01	.112 ± .003	.13 ± .01
8	O	≡ 1	≡ 1	≡ 1	≡ 1	≡ 1	≡ 1	≡ 1
9	F	<.007	<.005	<.01	<.002	<.002	<.0005	<.0009
10	Ne	.17 ± .03	.25 ± .03	.17 ± .03	.15 ± .01	.12 ± .01	.105 ± .003	.11 ± .01
11	Na	.007 ^{+.009} _{-.005}	.029 ^{+.012} _{-.009}	.011 ^{+.015} _{-.007}	.012 ^{+.004} _{-.003}	.010 ^{+.004} _{-.003}	.010 ± .001	.011 ± .002
12	Mg	.17 ± .03	.28 ± .03	.17 ± .03	.21 ± .02	.18 ± .01	.179 ± .004	.19 ± .01
13	Al	.018 ^{+.012} _{-.008}	.035 ^{+.013} _{-.010}	.022 ^{+.018} _{-.011}	.008 ^{+.004} _{-.003}	.017 ± .004	.013 ± .001	.012 ± .002
14	Si	.18 ± .03	.32 ± .04	.19 ± .04	.13 ± .01	.12 ± .01	.173 ± .004	.12 ± .01
15	P	<.007	<.010	<.01	<.003	<.003	<.0010	<.0005
16	S	.021 ^{+.013} _{-.008}	.078 ± .016	.078 ^{+.027} _{-.021}	.028 ± .005	.029 ± .005	.037 ± .002	.017 ± .002
17	Cl	<.016	<.005	<.01	<.002	<.004	<.0009	<.0005
18	Ar	.011 ^{+.010} _{-.006}	.017 ^{+.010} _{-.007}	.011 ^{+.015} _{-.007}	.005 ^{+.003} _{-.002}	.0008 ^{+.0018} _{-.0007}	.0034 ± .0006	.0016 ^{+.0009} _{-.0006}
19	K	<.007	<.010	<.01	<.003	<.002	<.0013	<.0009
20	Ca	.021 ^{+.013} _{-.008}	.058 ± .013	.022 ^{+.018} _{-.011}	.011 ^{+.004} _{-.003}	.007 ^{+.003} _{-.002}	.0085 ± .0009	.004 ± .001
21	Sc	<.007	<.01	<.01	<.002	<.002	<.0002	<.0005
22	Ti	<.007	<.005	<.01	<.002	<.002	<.0007	<.0005
23	V	<.012	<.005	<.01	<.002	<.002	<.0004	<.0005
24	Cr	<.007	.006 ^{+.008} _{-.004}	.006 ^{+.013} _{-.005}	.004 ^{+.003} _{-.002}	.002 ^{+.002} _{-.001}	.0019 ± .0004	.0018 ^{+.0010} _{-.0007}
26	Fe	.29 ± .04	.70 ± .06	.30 ± .05	.11 ± .01	.075 ± .008	.102 ± .003	.048 ± .004
28	Ni	.021 ^{+.013} _{-.008}	.043 ^{+.014} _{-.011}	.011 ^{+.015} _{-.007}	.004 ^{+.003} _{-.002}	.004 ^{+.003} _{-.002}	.0041 ± .0006	.0013 ^{+.0009} _{-.0006}

Observation Period	(a)	77:263.0-265.0	* All elements except Li, Be, B. Li ⁷ : 8.7-9.4 MeV/nuc Be ⁹ : 8.7-11.3 MeV/nuc B ¹¹ : 8.7-13.0 MeV/nuc
	(b)	77:268.0-270.5	
	(c)	77:327.25-330.5	
	(d)	78:46.0-49.25	
	(e)	78:114.5-118.5	
	(f)	78:119.25-121.0	
	(g)	78:122.25-126.0	

The following features are evident in Figure 2:

- Many energetic nuclei abundances show significant variations from event to event. Although most pronounced for Fe/O, the variations are not restricted to Fe/O.
- Comparison of energetic nuclei abundances with their corresponding element abundances in the photosphere in many cases show large differences, even for ratios like Mg/O, which show little event to event variation.
- Except for C and N, the average solar energetic nuclei composition is very similar to that of the GCR source.

4. Discussion. In order to characterize the relationship between energetic solar nuclei and photospheric material, it is convenient to define an "enhancement factor", \mathcal{E}_i , which is the ratio of the abundance A_i of an energetic nuclei species (relative to oxygen) over the corresponding abundance of photospheric material.

† Abundance ratios are energy dependent for these events.

$$\mathcal{F}_i \equiv \frac{A_i \text{ (energetic nucleus } i)}{A_i \text{ (photospheric element } i)}$$

Out of the seven flare events, we have selected for analysis in depth the four flares (Table 1, columns a,b,d,e) whose abundances show no significant energy dependence in our energy range. The enhancement factors \mathcal{F}_i of nuclear species from these four flare events are presented as data points in Figures 3a-3d. The solid curve, repeated in all panels of Figure 3, represents the average value \mathcal{F}_i^* for the four flares, i.e.,

$$\mathcal{F}_i^* \equiv \frac{A_i^* \text{ (energetic nucleus } i)}{A_i \text{ (photospheric element } i)}$$

where A_i^* is the geometric mean of the four A_i .

It is evident from Figures 3a-3d, that:

- The basic dependence on nuclear charge Z of the enhancement factor is common to the set of flare events and characterized by the average \mathcal{F}_i^* .
- The \mathcal{F}_i (or \mathcal{F}_i^*) functional dependencies are not monotonic with Z , contrary to the conclusion drawn by Dietrich and Simpson (1978)[†] for event (b) Table 1.
- On the average, Na, Mg, Al, and Si are significantly enhanced over C, N, O, and Ne.
- S and Ar are consistently depleted with respect to the Mg group.
- Ca and the Fe group show the largest variations about their average, which is enhanced similar to the Mg group.

If one plots the individual ratios of element abundances over the 4-flare average, A_i/A_i^* , versus Z , as shown in Figure 4, the deviations from the 4-flare average, within statistics, appear to be monotonic functions of Z for all events, although varying from event to event. In particular, the so called Fe-rich events are not a

[†] Also, our results do not support the high B, F, and Cr abundances quoted by Dietrich and Simpson for event (b), Table 1, which they ascribe to fragmentation of heavier nuclei in traversing ~ 0.6 g/cm² of solar material. Our results are consistent with negligible matter traversal and with the upper limit of 0.02 g/cm² quoted by McGuire et al. (1978).

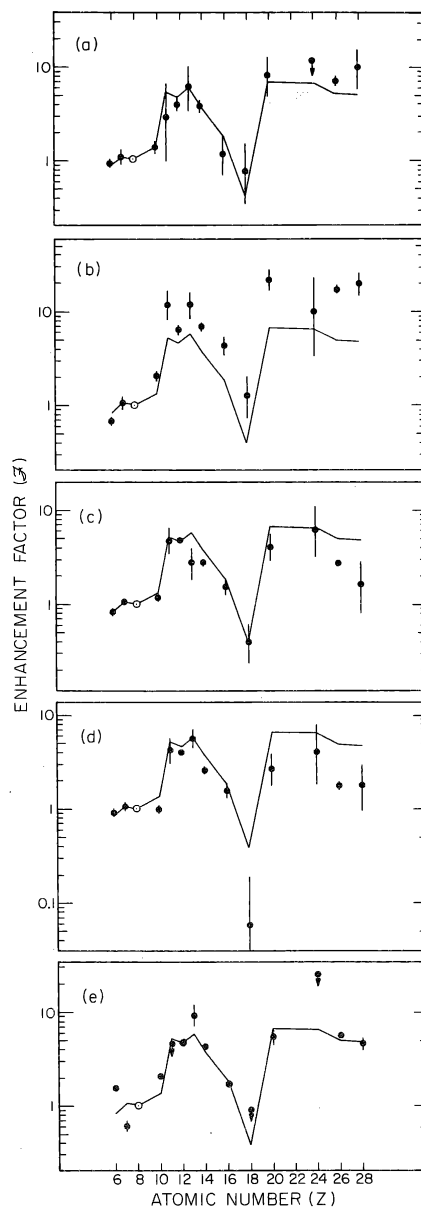


Figure 3. Enhancement factor \mathcal{F}_i .

Solid line: \mathcal{F}_i^* , 4-flare average
Data points:

Panel 3a	=	Table 1, Col. a
3b		b
3c		d
3d		e
3e		GCR

separate class of events, but rather the tail of a continuum of Z-dependent variability. This result suggests a common physical process, introducing a Z-dependent bias, possibly during injection or acceleration. The enhancement factor, therefore, may be represented as a separable function,

$$f_i = f_i^* \cdot f(Z_i)$$

where f_i^* and its characteristic shape are common to all events (and the GCR source!), and $f(Z_i)$ is a monotonically varying function of Z which may vary from event to event.

The physical significance of the characteristic shape of f_i^* is of considerable interest. It is interesting to ask whether f_i^* may be controlled by the ionized fraction of the nuclei before or during acceleration. Figure 5 represents the dependence of f_i^* upon 1st ionization potential. While earlier studies (e.g., Webber (1975)) suggested an approximately inverse dependence on 1st ionization potential, the improved statistical accuracy and broader element coverage of these data lead to a different conclusion. The energetic nuclei appear to divide into roughly two groups with respect to 1st ionization potential, with a dividing line near 10eV. The predominantly metallic group below 10eV shows a typical enhancement factor of ~ 5 , while the second group of essentially volatiles above 10eV is, within statistics, consistent with an enhancement factor ~ 1 .

The relative enhancement of the metallic group may represent an injection or acceleration bias, but it could also be due to a systematic error in the thermal photospheric abundances. It is interesting to note that similar groupings of these elements are associated with other physical considerations.

For example, in photospheric models the elements also separate according to 1st ionization potential (Claas (1951)), with 10eV separating those elements which are ionized ($< 7\text{eV}$) and those which are neutral ($> 13\text{eV}$). Another distinction between the two groups is that the abundances of the metallic elements can be derived from both photospheric (spectroscopic) and meteoritic analysis, while the volatiles have no meteoritic data base.

Additional constraints for the resolution of these questions may come from the fact that the flare averaged abundances and the GCR source abundances agree better with each other than with those of thermal solar matter.

5. Acknowledgements. This work has been supported in part by the National Aeronautics and Space Administration under contract NAS7-100 and grant NGR 05-002-160.

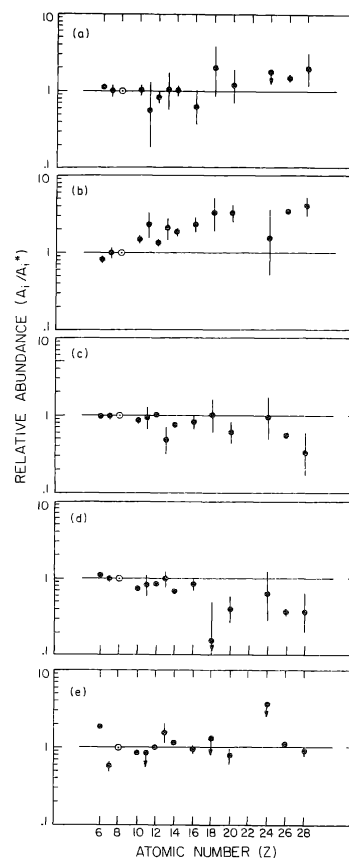


Figure 4. Deviations from 4-flare average

Figure 4 panels correspond to those of Figure 3.

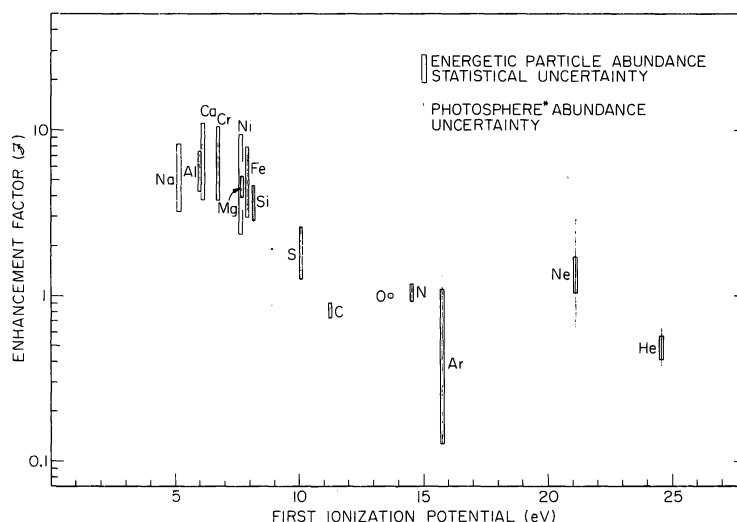


Figure 5. Enhancement factor ζ_i^* (4-flare avg.) vs. 1st ionization potential.

He energy range: 5-7.8 MeV/nuc.; He/O = 62.1 ± 10.7

Energetic particles: Statistical uncertainty includes counting statistics and event to event variations.

*Except for Ne, Ar (see text) and He. He reference abundance used is "local galactic" from Meyer and Reeves (1977).

6. References.

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