SOLAR ABUNDANCES AS DERIVED FROM SOLAR ENERGETIC PARTICLES

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ABSTRACT

Recent studies have shown that there are well defined average abundances of heavy (Z>2) solar energetic particles (SEPs), with variations in the acceleration and propagation producing a systematic flare-to-flare fractionation that depends on the charge per unit mass of the ion. Correcting the average SEP abundances for this fractionation yields SEP-derived coronal abundances for 20 elements. Higher resolution SEP studies have also provided isotopic abundances for 5 elements. SEP-derived abundances indicate that elements with high first ionization potentials (>10 eV) are depleted in the corona relative to the photosphere and provide new information on the solar abundance of C and ^{22}Ne. Future SEP observations offer the prospect of a significant reduction of the uncertainties in solar elemental and isotopic abundances.

INTRODUCTION

Ten years following their discovery of heavy cosmic ray nuclei, the Minnesota group detected the first solar flare helium nuclei using the same balloon-borne nuclear emulsion technique[1]. Within three years, Fichtel and Guss[2] used rocket-borne emulsions to detect the first solar energetic particles (SEPs) heavier than He, opening the possibility of a direct determination of the composition of a sample of solar material.

The nuclei recorded in these early emulsion experiments had moderately high energies, typically >50 MeV/nucleon, and appeared to represent an unfractionated sample of solar material. However, subsequent observations by Price and his collaborators[3] using plastic and glass track detectors indicated that the abundance of heavier SEP nuclei were enhanced at lower energies (~1 MeV/nucleon), somewhat compromising their use in the determination of solar abundances. Using an electronic detector, Mogro-Campero and Simpson[4] presented evidence that even at higher energies (25 to 61 MeV/nucleon) the Fe/O ratio averaged over many flares was enhanced relative to the solar ratio.

By 1977 additional emulsion studies of SEP nuclei with 15 to 30 MeV/nucleon by Bertsch and Reames[5] had confirmed that SEP abundance ratios varied significantly from flare to flare. Furthermore, in comparing SEP abundances with those in the photosphere, Hovestadt[6] and Webber[7] had found evidence for a fractionation that appeared to have an exponential dependence on the first ionization potential of the element. As a result, it was thought that the fractionation of SEPs might be too uncertain and too variable to allow an accurate derivation of solar abundances.

There have been a number of new studies in the last ten years, however, which have led to better understanding of the underlying systematics of the flare-to-flare variation so that it is now possible to derive relatively accurate solar abundances. These studies have been aided by improved charge resolution and statistical precision so that abundances can be determined and compared for many elements and many flare events.

For example, abundances of C, N, and O relative to Si for 22 large solar flare events[8] are shown in Figure 1. The flare-to-flare fractionation is clear, with C/Si varying by a factor of ~7 and N/Si and O/Si by a factor of ~4. It was this large variation that understandably prompted concerns about the feasibility of deriving solar abundances from SEP events.

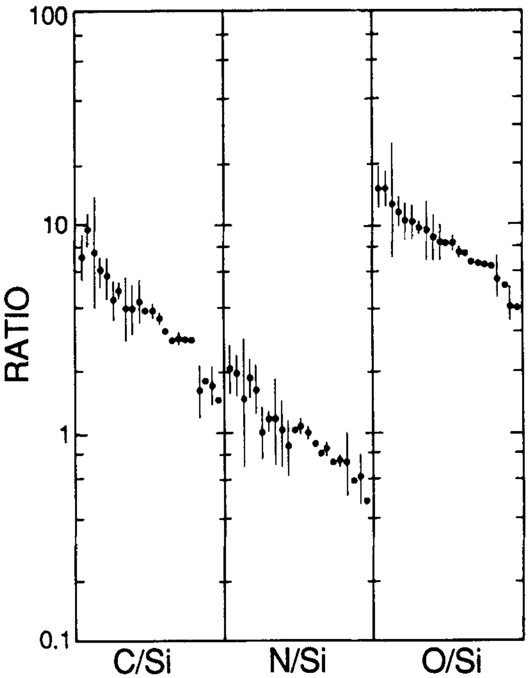


Figure 1. Abundance ratios relative to Si observed in 22 flare events. The sequence of ratios from the various flares is the same in each panel and is ordered in descending value of O/Si.

The improved statistical uncertainties in the data, however, expose the high degree of correlation among the variations of the different ratios, suggesting that there is much less variability in the abundance ratios of adjacent elements. This is shown in Figure 2 for the same SEP data as in Figure 1. Remarkably little variability is observed, indicating that there are well-defined SEP abundances which can be accurately determined with appropriate averaging procedures.

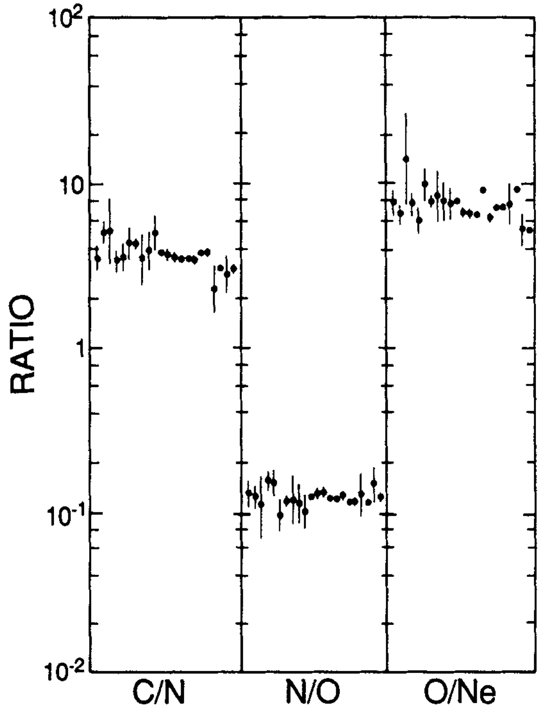


Figure 2. Abundance ratios of nearby elements for the same events as in Figure 1. These ratios exhibit relatively little flare-to-flare variation.

AVERAGE SEP ELEMENTAL ABUNDANCES

Because of the large flare-to-flare variations, several different approaches have been taken by various authors in deriving an average from a specific set of flare observations. In most cases, the intent of the adopted averaging procedure was to minimize the residual effects of the flare-to-flare fractionation. In this way, it was expected that the resulting average SEP abundances would be more representative of solar abundances. Some of the most recently determined average SEP abundances are listed in Table I.

At low energies (1-4.6 MeV/nucleon), Mason *et al.*[9] averaged the daily abundances for those days during which the oxygen flux exceeded 50 $(m^2$ s sr MeV/nucleon$)^{-1}$. There were 37 such days in a four year period. In comparing their results with those at higher energies, Mason *et al.* concluded that there was no indication that the average SEP abundances were energy

Table I. Average SEP Abundances

Z	element	Mason *et al.*[9]	Cook *et al.*[13]	Meyer[15]	McGuire *et al.*[16]	Breneman & Stone[17]
2	He	68	416±19	383(1.27)[a]	53±5	
6	C	0.50	2.74±0.17	2.90(1.30)	0.454±0.018	2710^{+270}_{-240}
7	N		0.70±0.06	0.81(1.33)	0.129±0.008	775^{+54}_{-51}
8	O	≡1	5.80±0.34	6.50(1.13)	1.00±0.031	6230^{+360}_{-340}
9	F				<0.0005	$[0.30^{+0.32}_{-0.30}]$[b]
10	Ne	0.16	0.97±0.07	0.84(1.32)	0.128±0.008	887^{+91}_{-83}
11	Na		0.07(1.4)[a]	0.085(1.47)	0.0083±0.0015	$73.3^{+7.2}_{-6.6}$
12	Mg	0.15	1.20±0.09	1.23(1.28)	0.183±0.010	1206^{+64}_{-61}
13	Al		0.10±0.02	0.089(1.55)	0.0115±0.0018	$87.4^{+4.3}_{-4.1}$
14	Si	0.12	≡1	≡1	0.147±0.009	≡1000
15	P				0.0014±0.0006	$4.61^{+0.62}_{-0.67}$
16	S		0.20±0.04	0.20(1.80)	0.0229±0.0025	$222.^{+8.}_{-7.}$
17	Cl					$2.05^{+0.72}_{-0.68}$
18	Ar	0.08	0.03(1.9)	0.038(1.70)	0.0016±0.0007	$20.7^{+3.5}_{-3.0}$
19	K					$3.3^{+1.7}_{-1.3}$
20	Ca		0.12±0.02	0.076(1.55)	0.0076±0.0016	$68^{+12.}_{-10.}$
21	Sc					$[0.24^{+0.44}_{-0.24}]$[b]
22	Ti					$3.8^{+1.2}_{-1.0}$
23	V					$[0.37^{+0.53}_{-0.37}]$[b]
24	Cr		0.02(1.8)	0.0225(1.90)	0.0024±0.0009	$14.3^{+2.9}_{-2.4}$
25	Mn					$5.2^{+3.0}_{-2.0}$
26	Fe	0.14	1.14±0.08	0.99(1.47)	0.066±0.006	959^{+105}_{-94}
27	Co					< 13.2
28	Ni		0.06(1.3)	0.045(1.75)		$33.8^{+5.2}_{-4.7}$
29	Cu					$[0.39^{+0.59}_{-0.39}]$[b]
30	Zn					$1.06^{+0.56}_{-0.49}$

a) Numbers in parentheses indicate factors of uncertainty.

b) Based on 5 or fewer particles and highly uncertain.

See also Figure 1 for a normalized comparison of all except McGuire *et al.*

dependent, contrary to earlier conclusions by Crawford *et al.*[3]. Mason *et al.*[10] pointed out that some of the earlier conclusions were based on observations from brief rocket flights during the onset of the flare events when the relative abundances and spectra are distorted by the more rapid arrival of higher energy and higher rigidity particles (see also Mewaldt[11] for a discussion of this issue).

The averaging approach chosen by Cook *et al.*[12,13] was to form a logarithmic average of the abundance ratios in four of the seven observed events which exhibited minimal energy-dependence (5-15 MeV/nucleon) in the ratios. It was thought that in such events the acceleration and propagation fractionation might also be minimized.

Meyer[14,15] chose another approach, surveying 53 published observations acquired during 19 active periods and sorting them according to their Z-dependent fractionation. In order to determine a Mass Unbiased Baseline with the smallest statistical uncertainty and with a minimum residual Z-dependent fractionation, Meyer formed an average of 31 of the observations taken during 16 active periods. These were chosen and weighted in such a way that the apparent enhancement of Fe relative to O was consistent with that of Mg and Si, which have similar first ionization potentials. In making this adjustment, Meyer assumed that the unfractionated abundance ratios of Mg, Si, and Fe should be 105:100:88, the same as his Local Galactic abundances.

In determining a Solar Energetic Particle Baseline (SEPB) from their observations of 13 large flare events, McGuire *et al.*[16] averaged the abundances from the 3 flare events with the smallest Fe/O ratios, suggesting that larger ratios might be the result of preacceleration heating. As McGuire *et al.* point out, however, when chosen in this way their SEPB Fe abundance is significantly lower than the coronal abundance.

In their extension of the analysis by Cook *et al.*[12,13], Breneman and Stone[17] derived an average SEP abundance for the largest ten SEP events observed by the Cosmic Ray Subsystems on the two Voyager spacecraft. In forming the average, the contributions from each flare were weighted according to both the statistical uncertainty and flare-to-flare variations[8]. The resulting average has a factor of ~3 higher accuracy than the other recent determinations in Table I.

Even though the various SEP averages in Table I involve different approaches, all are in very good agreement as shown in Figure 3 (except the McGuire *et al.*[16] result, which is not plotted). Thus, there appears to be a well determined average SEP abundance that exhibits little energy dependence in the 1 to 10 MeV/nucleon interval and about which individual flares show varying degrees of Z-dependent fractionation.

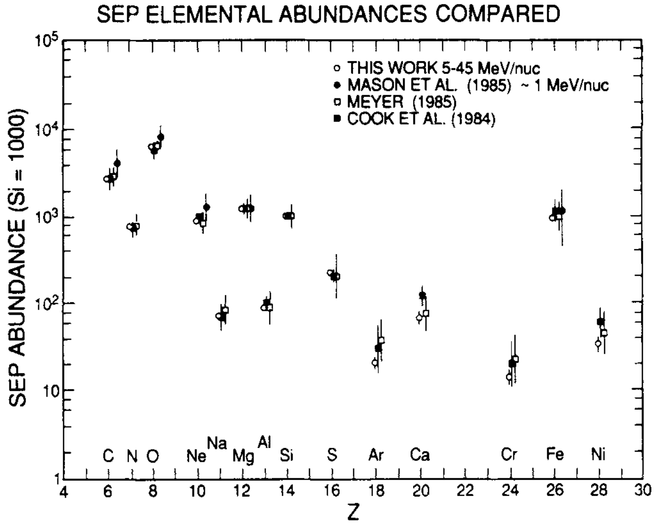


Figure 3. Comparison of different determinations of the average SEP elemental abundances[8]. The different averages are quite consistent. "This work" refers to Breneman and Stone[17].

FLARE-TO-FLARE VARIATIONS

The first indication of the underlying systematics of the flare-to-flare variation in the SEP abundances were the observations by Cook *et al.*[18,12,13] and McGuire *et al.*[19,16] that in comparison to the SEP average, the abundances in a given flare exhibited a fractionation that was a monotonic function of nuclear charge Z. These studies did not attempt to determine whether the fractionation was a function of Z or of other correlated parameters such as mass M or effective ionic charge Q. Of course, when compared with average SEP abundances, individual flares could exhibit either an enhancement or a depletion of heavier ions such as Fe.

If the flare-to-flare variations were due to shock acceleration or interplanetary propagation processes, it might be expected that the fractionation would depend on the charge per unit mass (Q/M) of the ion. Both processes depend upon scattering of the nuclei by fluctuations in the ambient magnetic field, and the scattering mean free path depends on the velocity and the rigidity R of the particle. Since R is the momentum per unit charge and is given by

$$R = \frac{pc}{Qe} = \frac{\gamma\beta Mc^2}{Qe}$$

the mean free path for an ion with a given β will depend on its Q/M.

There are several independent indications that the SEPs in large events are shock accelerated coronal material. The shock is likely associated with the Coronal Mass Ejection usually observed in conjunction with these events[20], and the charge of the accelerated ions is similar to that of coronal material. Luhn *et al.*[21,22] and Luhn[23] measured the charge states of SEP nuclei with ~1 MeV/nucleon in 12 large flare events, finding rather small variations from flare to flare.

Using the measured charge states for C, N, O, Ne, Mg, Si, S, and Fe and estimating others with guidance from the calculations of Shull and van Steenberg[24], Breneman and Stone[17] found that the fractionation of the abundances in individual flares was well represented by $(Q/M)^{\alpha}$ as shown in Figure 4. Power law fits[8] to similar data for 22 flares yielded values for α ranging from -2.4 to 4. The two events with the largest Fe enhancements (α <-1) are likely affected by interplanetary propagation effects in which the higher rigidity particles arrive before those with lower rigidities. Depletion of heavy ions (α>0), however, is likely to result from shock acceleration because their higher rigidities will allow them to more quickly diffuse away from the region of the shock.

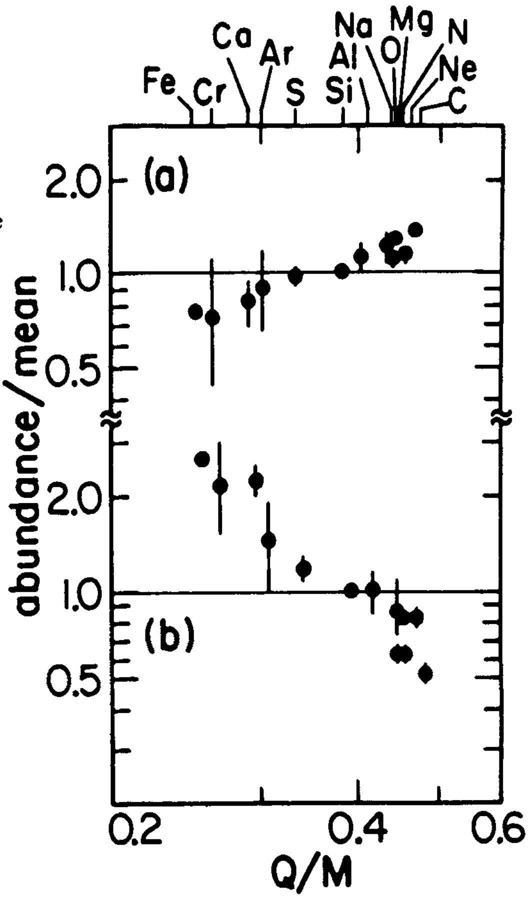


Figure 4. Abundances relative to the average SEP abundances as a function of ionic charge Q per unit mass M, illustrating the Q/M-dependence of the flare-to-flare fractionation[17] for two separate flares.

Flare-to-flare variations in a Q/M-dependent fractionation should produce little variation in the abundance ratios of elements with similar Q/M values. Thus, the lack of variability in the N/O ratios in Figure 2 would be expected because they have almost identical Q/M values (see Figure 4). C/N and O/Ne, with slightly different Q/M, have slightly larger variations.

SEP-DERIVED CORONAL ABUNDANCES

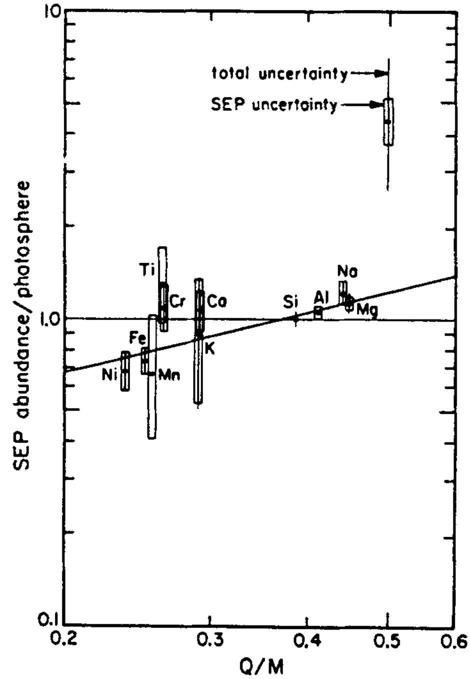
Since the acceleration and propagation processes appear to produce a Q/M-dependent fractionation of individual flares relative to the average SEP abundances, it is likely that these processes result in a similar fractionation of the average abundances relative to the corona from which the ions were accelerated.

In order to estimate this residual Q/M-fractionation, Breneman and Stone compared their average SEP abundances with spectroscopic photospheric abundances[25] as shown in Figure 5. Only Na, Mg, Si, K, Ca, Cr, Fe, and Ni were compared in deriving the residual Q/M-dependence, because the uncertainty in their photospheric abundances was known and no FIP-dependent fractionation between the photosphere and the corona was expected for these low-FIP elements (see below). The best fit power law shown in Figure 5 has $\alpha = 0.66 \pm 0.17$, indicating that the SEP average is mildly depleted of heavier SEP ions relative to the photosphere.

The SEP-derived coronal abundances in Table II were determined by applying this one-parameter correction to the average SEP abundances of all of the elements. Although spectroscopically-derived coronal abundances are not available for all elements and are rather uncertain for others[26], there is very good agreement with the SEP-derived coronal abundances as shown in Figure 6. A similar comparison with solar wind abundances[27,28] in Figure 7 shows equally good agreement. In both cases, the SEP-derived abundances are more accurately known and available for more elements.

The only average SEP abundances in Table I that differed significantly from Breneman and Stone were those derived by McGuire *et al.*[16] from three events with the lowest Fe abundance. It is interesting to compare their average with the SEP-derived corona as shown in Figure 8. The comparison is reasonably consistent with the expected power law dependence on Q/M. According to the interpretation described above, the large depletion of the heavier ions likely results from their greater rigidity and more rapid escape from the shock region, limiting their acceleration times compared to lighter ions. Since higher energy ions also have higher rigidities, the Fe/O abundance for these Fe-depleted events would be expected to exhibit a significant decrease with increasing energy, as observed by McGuire *et al.*[16].

Figure 5. Average SEP abundances relative to the photosphere[25] for the low-FIP elements as a function of Q/M. The power law is a fit to all of the elements except Al, Ti, and Mg, which had unspecified uncertainties in their photospheric abundances[17].



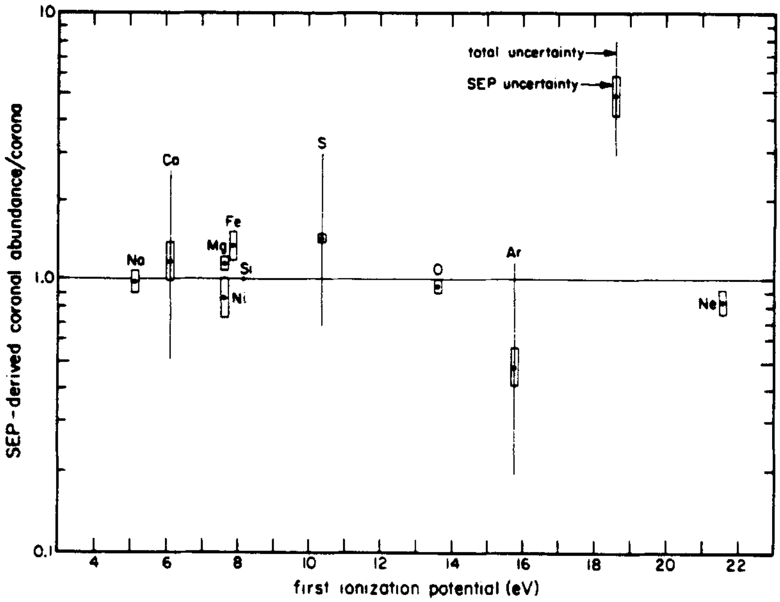


Figure 6. SEP-derived coronal abundances relative to spectroscopic coronal abundances[26]. The two determinations are quite consistent[17].

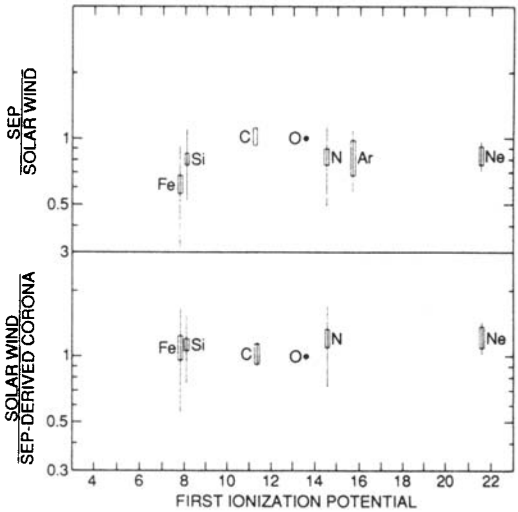
Table II. SEP-Derived Coronal and Photospheric Abundances[17]

Z	element	SEP-derived corona	SEP-derived photosphere
6	C	$2350^{+250.}_{-230.}$	$[6490^{+280.}_{-270.}]^{a}$
7	N	$700^{+52.}_{-49.}$	$[2775^{+53.}_{-50.}]^{a}$
8	O	$5680^{+360.}_{-340.}$	$[22900]^{a}$
9	F	$(0.28^{+0.29}_{-0.28})^{b}$	$[(1.1^{+1.2}_{-1.1})^{b}]^{a}$
10	Ne	$783^{+84.}_{-77.}$	$[3140^{+205.}_{-195.}]^{a}$
11	Na	$67.0^{+6.8}_{-6.2}$	$67.0^{+6.8}_{-6.2}$
12	Mg	1089^{+64}_{-62}	1089^{+64}_{-62}
13	Al	$83.7^{+4.2}_{-4.0}$	$83.7^{+4.2}_{-4.0}$
14	Si	$\equiv 1000$	$\equiv 1000$
15	P	$4.89^{+0.66}_{-0.72}$	$[9.24^{+1.46}_{-1.54}]^{a}$
16	S	$242^{+10.}_{-9.}$	$[460]^{a}$
17	Cl	$2.38^{+0.84}_{-0.80}$	$[9.6^{+3.5}_{-3.3}]^{a}$
18	Ar	$24.1^{+4.2}_{-3.6}$	$[102^{+20.}_{-17.}]^{a}$
19	K	$3.9^{+2.1}_{-1.6}$	$3.9^{+2.1}_{-1.6}$
20	Ca	$82^{+14.}_{-12.}$	$82^{+14.}_{-12.}$
21	Sc	$(0.31^{+0.55}_{-0.31})^{b}$	$(0.31^{+0.55}_{-0.31})^{b}$
22	Ti	$4.9^{+1.6}_{-1.3}$	$4.9^{+1.6}_{-1.3}$
23	V	$(0.48^{+0.69}_{-0.48})^{b}$	$(0.48^{+0.69}_{-0.48})^{b}$
24	Cr	$18.3^{+3.9}_{-3.3}$	$18.3^{+3.9}_{-3.3}$
25	Mn	$6.8^{+3.9}_{-2.7}$	$6.8^{+3.9}_{-2.7}$
26	Fe	$1270^{+170.}_{-150.}$	$1270^{+170.}_{-150.}$
27	Co	<18.1	<18.1
28	Ni	$46.5^{+8.1}_{-7.4}$	$46.5^{+8.1}_{-7.4}$
29	Cu	$(0.57^{+0.87}_{-0.57})^{b}$	$(0.57^{+0.87}_{-0.57})^{b}$
30	Zn	$1.61^{+0.87}_{-0.76}$	$1.61^{+0.87}_{-0.76}$

a) N, F, Ne, Cl, and Ar have been renormalized to oxygen, with stated uncertainties relative to oxygen. In addition, there is a systematic uncertainty of ~6% due to the uncertainty in the FIP fractionation which is assumed to be the same as for oxygen (4.03±0.26). Similarly, P is renormalized to S and assumed to have the same fractionation as S (1.89±0.17), introducing a systematic uncertainty of ~9%. The C fractionation uncertainty is assumed to be a factor of 1.5 in order to include both the O and S fractionation factors. The illustrative calculation of Geiss and Bochsler [29] suggests that the precise ionization fractionation depends on several parameters and may differ by ~30% from those assumed.

b) Abundances for these elements are based on 5 or fewer particles and are highly uncertain.

Figure 7. Average SEP abundances (top) and SEP-derived coronal abundances (bottom) relative to solar wind abundances[27,28]. The error boxes indicate uncertainties in the SEP abundances only, while the total error bars shown include the uncertainties in the solar wind abundances.



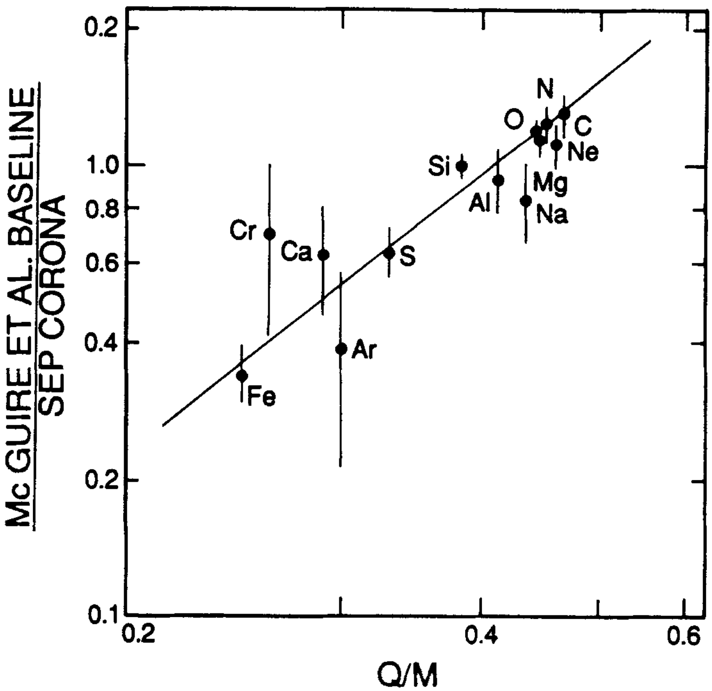


Figure 8. Solar Energetic Particle Baseline abundances from McGuire *et al.*[16] relative to the SEP-derived coronal abundance, exhibiting a Q/M-dependent fractionation.

FIP-DEPENDENT FRACTIONATION AND SEP-DERIVED PHOTOSPHERIC ABUNDANCES

In comparing their SEP average abundances with those of the photosphere, Cook *et al.*[18,13] found a FIP-dependent fractionation that appeared to be a step function. Those elements having a first ionization potential (FIP) of >11 eV were depleted by a factor of ~4 relative to those with lower FIPs. Since the FIP-dependent fractionation was observed in all of the large SEP events, they suggested that it was characteristic of the coronal material from which the SEPs originated and resulted from the plasma physics of coronal formation.

Meyer[14,15] subsequently compared his statistically more accurate Mass Unbiased Baseline described above with his Local Galactic abundances (mainly photospheric), clearly demonstrating a step-function dependence on FIP. He considered several alternative fractionation mechanisms, but concluded that only a FIP-dependent selection process seemed consistent with the observations.

The same step function dependence shows up even more clearly in the comparison of the SEP-derived coronal abundances with spectroscopically-derived photospheric abundances[25], as shown in Figure 9 from Breneman and Stone[17]. Although the photospheric abundances of many of the high FIP elements are not well known, there is a remarkable consistency in their apparent depletion in the corona by a factor of ~4. Only C appears to be more depleted, and as discussed below, this is likely because the photospheric abundance of C is lower than assumed in the Grevesse compilation[25].

The origin of the FIP-dependent fractionation is not understood. The fractionation is unlikely to occur in the corona because all of the elements are highly ionized at coronal temperatures and the first ionization potential would seem immaterial. However, the elements with high FIP are primarily neutral at photospheric temperatures, suggesting that the fractionation takes place in the transition from the photosphere to the corona.

In the dynamical ionization model of Geiss and Bochsler[29] for the formation of coronal material, the high-FIP elements which are neutral in the photosphere and cannot be ionized from the ground state by the intense flux of H Ly-alpha photons are depleted because their ionization times are longer than the time individual atoms spend in a rising spicule. The degree of depletion depends on the first ionization time (FIT) of the element, which is closely related to its FIP. Although the applicability of this approach to coronal formation has yet to be demonstrated, the FIT calculations indicate that the ionized fractions of N, O, Ne, and Ar should be similar.

Since O had been observed spectroscopically in both the corona and the photosphere, yielding a depletion factor of 4.03 ± 0.26, Breneman and Stone applied the same depletion factor to all of the high-FIP elements in order to

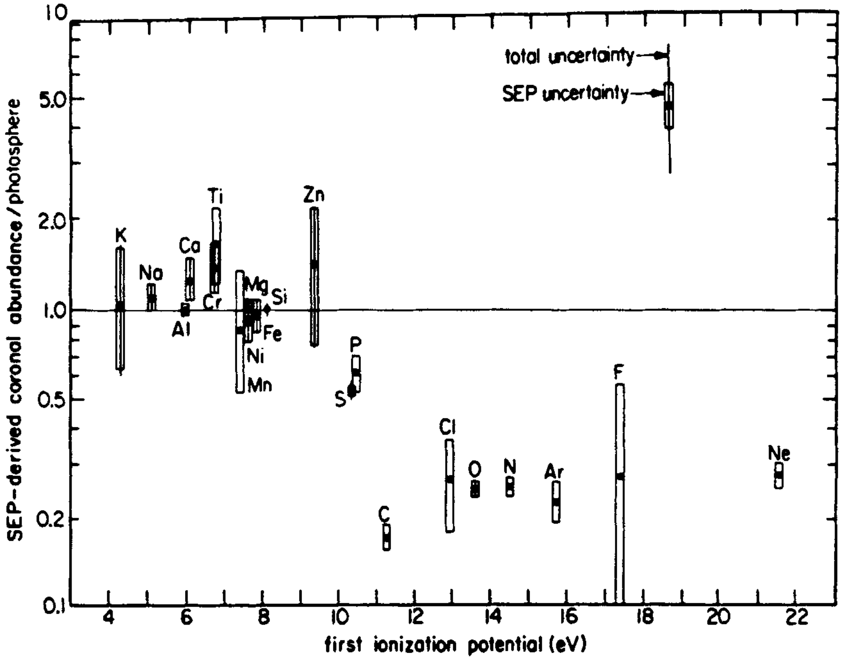


Figure 9. SEP-derived coronal abundances relative to spectroscopic photospheric abundances[25], showing a step-function dependence on the first ionization potential[17].

determine the SEP-derived photospheric abundances shown in Table II. Since the Geiss and Bochsler FIT calculation indicates that the ionization fraction of the high-FIP elements may vary by 30% from that of O, there is a corresponding systematic uncertainty in the SEP-derived photospheric abundances for those elements.

The FIP- or FIT-dependent fractionation of C is more uncertain, with the FIT calculation indicating that it should be less fractionated than O. Breneman and Stone[17] assumed a fractionation that is the average of that observed for S (1.89 ± 0.17) and O (4.03 ± 0.26), with an uncertainty of a factor of 1.5 so as to include both values as indicated in Table II and shown in Figure 10. If the fractionation of C and O are the same, then the C/O ratio would be 0.41 ± 0.02, as in the corona, but if C is fractionated like S, then the photospheric C/O ratio would be only 0.19 ± 0.02. In either case, as shown in Figure 10, the C/O ratio is significantly lower than the typically assumed value of 0.6 in the Grevesse compilation[25].

Also shown in Figure 10 are two more recent measurements which have confirmed the lower C abundance. Infrared spectroscopy[30] indicates a photospheric ratio of 0.43 ± 0.04, consistent with the SEP-derived value assuming that C is fractionated like O, while the solar wind C/O ratio[27] agrees quite well with the SEP-derived coronal value of 0.41 ± 0.02.

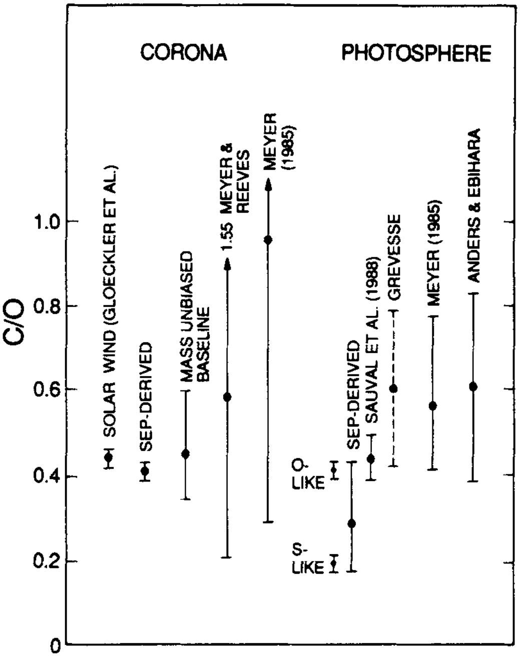


Figure 10. Comparison of various determinations of the C/O ratio in the corona[15,17,27,41,42] (left side) and the photosphere[17,25,30,31,41] (right side). The SEP-derived coronal value is shown for both O-like and S-like FIP-fractionation.

Although the accuracy of SEP-derived photospheric abundances for high-FIP elements is currently limited by the lack of a complete model for the fractionation process, the accuracy for the low-FIP elements which appear to be unfractionated in the corona is currently limited by statistics. As shown in Figure 9, the SEP-derived abundances for these elements are in reasonable agreement with spectroscopically-determined abundances[25], including an Fe/Si ratio of 1.32 which is distinctly larger than the meteoritic ratio[31] of 0.90.

SEP-DERIVED ISOTOPIC ABUNDANCES

With the advent of higher resolution energetic particle spectrometers, it has become possible to identify individual SEP isotopes and to directly determine the isotopic composition of solar material. The most comprehensive observations were during the flare event of September 23, 1978[32,33]. The elemental composition during this event exhibited the usual Q/M-dependence with $\alpha = 1.95 \pm 0.44$, indicating a depletion of heavier SEP isotopes relative to the corona[34]. Because the masses of the different isotopes of an element differ by $\lesssim 10\%$, relatively small corrections for the observed Q/M-fractionation are needed to obtain coronal isotopic ratios from the SEP ratios.

The corrected isotopic abundances from Mewaldt and Stone[34] are listed in Table III, along with the corresponding solar system values from Anders and Ebihara[31]. These ratios are shown in Figure 11, together with solar wind abundance ratios[35] and C, Ne, and Mg SEP ratios obtained by Dietrich and Simpson[36,37] by averaging over 3 to 10 flare events. Except for $^{22}Ne/^{20}Ne$, the SEP-derived ratios are in agreement with the Anders and Ebihara compilation.

Table III. Isotopic Abundances Observed in SEPs and Derived for the Corona[34]

Isotope Ratio	Measured Value in SEPs[33]	Value Derived for the Corona	Anders and Ebihara[31]
$^{3}He/^{4}He$	$\leq 2.6 \times 10^{-3}$	$\leq 1.9 \times 10^{-3}$	4.3×10^{-4}
$^{13}C/^{12}C$	$0.0095^{+.0042}_{-.0029}$	$0.0111^{+.0049}_{-.0034}$	0.0111
$^{14}C/^{12}C$	< 0.0014	<0.0019	0.00
$^{15}N/^{14}N$	$0.008^{+.010}_{-.005}$	$0.009^{+.012}_{-.006}$	0.0037
$^{17}O/^{16}O$	≤ 0.0021	≤ 0.0024	0.00037
$^{18}O/^{16}O$	$0.0015^{+.0011}_{-.0007}$	$0.0019^{+.0014}_{-.0009}$	0.00204
$^{21}Ne/^{20}Ne$	≤ 0.014	≤ 0.015	0.0024
$^{22}Ne/^{20}Ne$	$0.109^{+.026}_{-.019}$	$0.131^{+.032}_{-.024}$	0.073
$^{25}Mg/^{24}Mg$	$0.148^{+.046}_{-.026}$	$0.160^{+.050}_{-.028}$	0.129
$^{26}Mg/^{24}Mg$	$0.148^{+.043}_{-.025}$	$0.173^{+.050}_{-.030}$	0.142

As shown in Figure 11, distinctly different Ne isotopic abundances are found in various samples of solar system material. The SEP-derived values are consistent with neon-A (planetary neon), but not with solar wind neon. There also appears to be a difference between the SEP-derived value and neon-C which is ascribed to SEP Ne implanted in lunar materials over millions of years. Mewaldt and Stone[34] suggest that the neon-C ratio should be multiplied by ~ 1.1 to correct for the estimated Q/M-fractionation, somewhat improving the agreement with the contemporary SEP results.

The origin of the difference between the SEP-derived and solar wind ratios for $^{22}Ne/^{20}Ne$ is unknown and puzzling, since both are samples of the solar corona with consistent elemental composition as shown in Figure 7. When the SEP results were first reported in 1979[32,36] it was thought that the difference might be due to flare-to-flare variations. However, the Q/M-dependence of much of this variation has since been recognized, resulting in the corrections discussed above. The consistency of the corrected ratio from the event of September 23, 1978, with the 10-flare average also suggests that the SEP-derived abundance of ^{22}Ne in Table III is typical.

Several other explanations for the difference can be hypothesized. If the solar wind value is representative of the corona then there must be an additional fractionation process that is independent of Q/M and systematically enhances the acceleration of just ^{22}Ne in SEPs, since there is

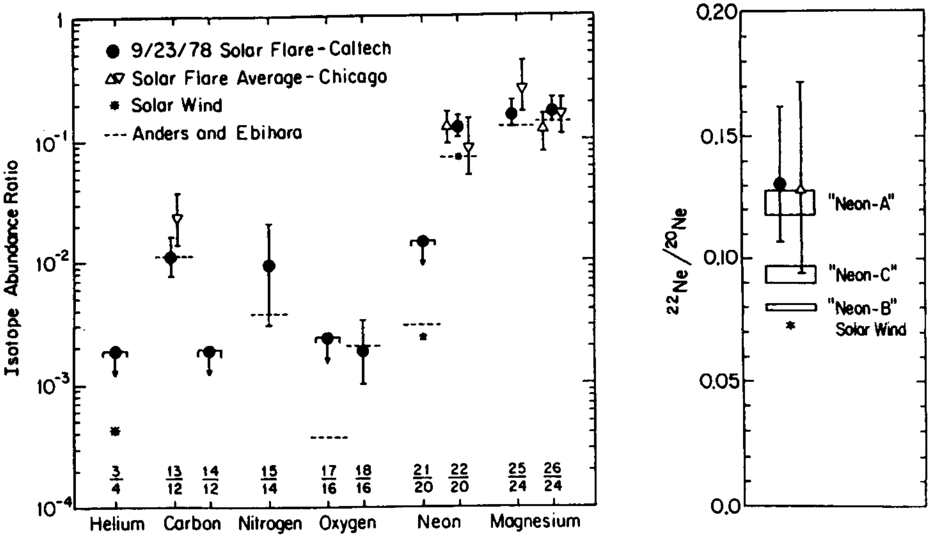


Figure 11. Comparison of SEP-derived coronal isotopic abundances[33,36–38] with the solar wind[35] and with the Anders and Ebihara[31] compilation (left panel). Comparison of the SEP-derived coronal abundance of ^{22}Ne with various meteoritic components[39,40] (right panel). Both panels are from Mewaldt and Stone[34].

no indication of similar enhancements of other heavier isotopes. However, if the SEP value is representative of the corona, then the solar wind samples collected by the Apollo foils[35] must have been fractionated by some unidentified process. Although Fe/Ne varies by a factor of 10 in the solar wind, there is no indication that $^{22}Ne/^{20}Ne$ would be expected to vary by a factor of 2.

Finally, the SEP and solar wind values might be representative of different regions of the corona, since the SEPs likely originate from closed coronal regions while the solar wind originates from open regions such as coronal holes. Addressing these various possibilities will likely require new observations of both the solar wind and SEPs.

FUTURE PROSPECTS

Significant progress has been made in the last decade in deriving solar elemental and isotopic abundances from SEP abundances, although for the rarer elements and for most isotopes the precision is seriously limited by the statistics of the total number of SEP nuclei recorded during a flare event. Considerable improvement can be expected with the launch of new energetic particle spectrometers over the next decade, most with geometrical factors much larger than the ~ 1 cm^2 sr characteristic of instruments during the last decade.

In the next several years a new solar isotope spectrometer (EHIC) built by the University of Chicago and having a geometrical factor of ~ 1.5 cm^2 sr will be launched into a polar orbit, in time for the next maximum in solar activity. This will be followed in several more years by the launch of larger instruments on the Wind and Geotail spacecraft. The Japanese solar isotope spectrometer on Geotail will have a geometrical factor of ~ 60 cm^2 sr, while the Goddard instrument on Wind includes both an isotope spectrometer with ~ 10 cm^2 sr and an element spectrometer with ~ 75 cm^2 sr which should return statistically useful measurements of elements heavier than Ni. Although both instruments will be launched after maximum solar activity, their larger geometrical factors will allow useful measurements of even modest sized flare events.

Currently in the planning phase is an Advanced Composition Explorer (ACE) which could be launched in the mid-1990's. Instruments on ACE would include spectrometers for measuring the mass and the charge state of both solar wind and solar energetic particles, providing the first opportunity for coordinated observations and comparisons of these two samples of solar material. The collecting power for the SEP isotope spectrometers would be ~10 to ~100 times that of previous instruments, allowing the determination of many elemental and isotopic abundances with a statistical precision of the order of one percent.

Just as the discovery of heavy galactic cosmic rays 40 years ago offered the promise of determining the composition of a sample of matter from nearby regions of the Galaxy, the discovery of heavy solar energetic particles 27 years ago offered a similar promise for a sample of solar matter. During the last decade considerable progress has been made in realizing this latter promise, with the prospect of even more progress during the next decade.

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