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CORONAL ELEMENT ABUNDANCES DERIVED FROM SOLAR ENERGETIC PARTICLES

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ABSTRACT

The large gradual solar-energetic-particle (SEP) events, where abundances are commonly measured, are produced when coronal mass ejections (CMEs) drive shock waves through the corona and the interplanetary medium. The shock accelerates particles from the highly-ionized, ~1.5 MK, plasma in a manner that depends only weakly upon the Q/A of the ion, except at very high energies. Averaging the ~1 MeV/amu abundances over many events compensates for the acceleration effects to produce abundances that appear to correspond directly to those in the coronal source for all observed elements, including H. The resulting abundances reflect the 4 x enhancement of ions with low values of first ionization potential (FIP) arising from ion-neutral fractionation that occurs as the atoms are transported up from the photosphere. A different pattern of fractionation is found for ions that are shock-accelerated from the high-speed solar wind emerging from coronal holes.

INTRODUCTION

It is ironic that the largest and most violent of solar events has been a source of significant information on the element abundances of the quiet corona. Energetic ions accelerated to > 1 MeV/amu in major solar events and observed on spacecraft near Earth have provided some of the most complete information on coronal abundances of the elements. The first observation of energetic heavy ions from the Sun was made over 30 years ago by Fichtel and Guss /1/ using nuclear emulsion detectors flown on sounding rockets. Elements up to and including Fe were measured/2/ a few years later by the same technique. In 1985, Meyer /3/ reviewed the measurements of these solar-energetic-particle (SEP) abundances. He found that the abundances, averaged over many events, could be organized into two groups depending upon the first ionization potential (FIP) of the element, indicating an ion-neutral fractionation of material transported into the corona. Superimposed on the average abundances were flare-to-flare abundance variations that were increasingly large for heavier elements. This "mass bias" was presumed to be an effect of the acceleration process.

Most of the early measurements of energetic-particle abundances were made in events that we now call major proton events (MPEs). It turns out that the particles in these events are not accelerated in solar flares but rather by shock waves driven by large coronal mass ejections (CMEs) /4,5/. In some cases these events are produced by "disappearing filament" events that occur outside active regions, without related flares /5/. The particles that *do* come from impulsive flares have unusual abundance enhancements that cause them to be described as ^{3}He rich or Fe rich /4,5/. These abundance enhancements arise from wave-particle interactions in the flare plasma. Very high ionization states of the energetic Fe ions (+20) in impulsive-flare events provide evidence of heating of the flare plasma to temperatures of > 10 MK. It has been important to distinguish the the two classes of events, impulsive and gradual, and the underlying acceleration mechanisms, in order to correctly relate the observed abundances to those in the solar corona. However, since event classes are discussed elsewhere in this issue /5/, I will discuss only the abundances in MPEs (or gradual events) below, and assume that SEPs and MPEs are synonymous.

An entirely different population of energetic particles is accelerated at shock waves produced outside 1 AU at corotating interaction regions (CIRs) where high-speed solar wind streams overtake low-speed streams. Particles accelerated from the high speed stream show a different dependence of the abundances on FIP indicating a difference in the ion-neutral fractionation process beneath coronal holes /6/.

SEP ABUNDANCES

In 1985 Breneman and Stone /7/ parameterized the acceleration bias in large SEP events in terms of the charge/mass ratio, Q/A, of the ions instead of the mass, A. They found that the enhancement or suppression of ions in a given event was approximately a power law in Q/A, with the power varying from event-to-event. Unfortunately, these authors used an incorrect value for the photospheric abundance of Fe based upon measurements of Fe I (which comprises only ~5% of the photospheric Fe) /8/. More recent measurements of the abundance of Fe / *e.g.* 9/ suggest that the meteoritic abundance of Fe from the C1 chondrites is appropriate for the photosphere. This means that the large correction that Breneman and Stone applied to convert from the average SEP to coronal abundances is not correct. Using the meteoritic abundance of Fe for the photosphere, the average SEP abundances are almost identical to the coronal abundances; no correction is required.

It is clear that the power-law in Q/A is only an approximation of the acceleration bias, however, since the abundance H does not fit this dependence. Recently Mazur /10/ has fit the energy spectra of H, He, O and Fe in 10 large SEP events using several theoretical acceleration models. For all cases, he finds that toward lower energy, the event-to event variations in the abundances diminish and the abundances themselves approach coronal values.

In our present understanding of diffusive shock acceleration /11/, particles receive an increment in velocity each time they cross the shock as they are scattered back and forth by self-generated waves. The resonance scattering between particles and waves depends upon the gyrofrequency of the particle, hence upon Q/A. Leakage of the particles from the acceleration region, dependent upon the scattering, will be small at low energies, but will increase at high energies where the intensity of both particles and resonant waves diminishes. Thus it is not surprising that abundances at low energies reflect those of the source material while those at high energies vary widely depending upon both the Q/A of the species and the properties of the shock.

With this understanding, I have determined the average H/He ratio in the 1-4 MeV/amu interval for all of the same SEP events where Reames, Richardson and Barbier /6/ reported abundances of elements He and above. These low-energy high-statistics abundances were then combined with the high-resolution SEP abundance measurements of Breneman and Stone /7/ and are listed in Table 1 and shown in the upper panel of Figure 1, normalized to the photospheric (meteoritic) abundances /8/. Aside from averaging over events, *no* corrections of any kind have been made for acceleration effects. Comparing Fe with Mg and Si in the figure, it seems clear that no corrections are required; Fe has nearly the same FIP as Mg and Si, but a much different value of Q/A.

Table 1. Abundances of Elements.

	Z	Mean SEP Corona (O=1000)	Mean SEP Corona (Si=1000)	Photosphere (Meteoritic) (Si=1000)	Ref.
H	1	$(1.17\pm0.089)\times10^6$	$(7.55\pm0.57)\times10^6$	2.79×10^7	-
He	2	55000. ±3000.	$(3.55\pm0.19)\times10^5$	2.72×10^6	6
C	6	471. ± 14.	3040. ± 90.	10100.	6,7
N	7	128. ± 4.	826. ± 26.	3130.	6,7
O	8	1000. ± 30.	6450. ±190.	23800.	6,7
Ne	10	151. ± 5.	974. ± 32.	3440.	6,7
Na	11	11.8 ± 1.1	76. ± 7.	57.4	7
Mg	12	203. ± 8.	1310. ± 52.	1074.	6,7
Al	13	14.0 ± 0.7	90. ± 5.	84.9	7
Si	14	155. ± 7.	1000. ± 45.	1000.	6,7
P	15	0.74± 0.11	4.7± 0.7	10.4	7
S	16	35.6 ± 1.1	230. ± 7.	515.	6,7
Cl	17	0.33± 0.11	2.1± 0.7	5.24	7
Ar	18	3.3 ± 0.5	21. ± 3.	101.	7
K	19	0.53± 0.24	3.3± 1.5	3.77	7
Ca	20	12. ± 1.6	77. ± 10.	61.1	7
Ti	22	0.61± 0.16	3.8± 1.1	2.4	7
Cr	24	2.3 ± 0.4	15. ± 3.	13.5	7
Fe	26	155. ± 15.	1000. ±100.	900.	6,7

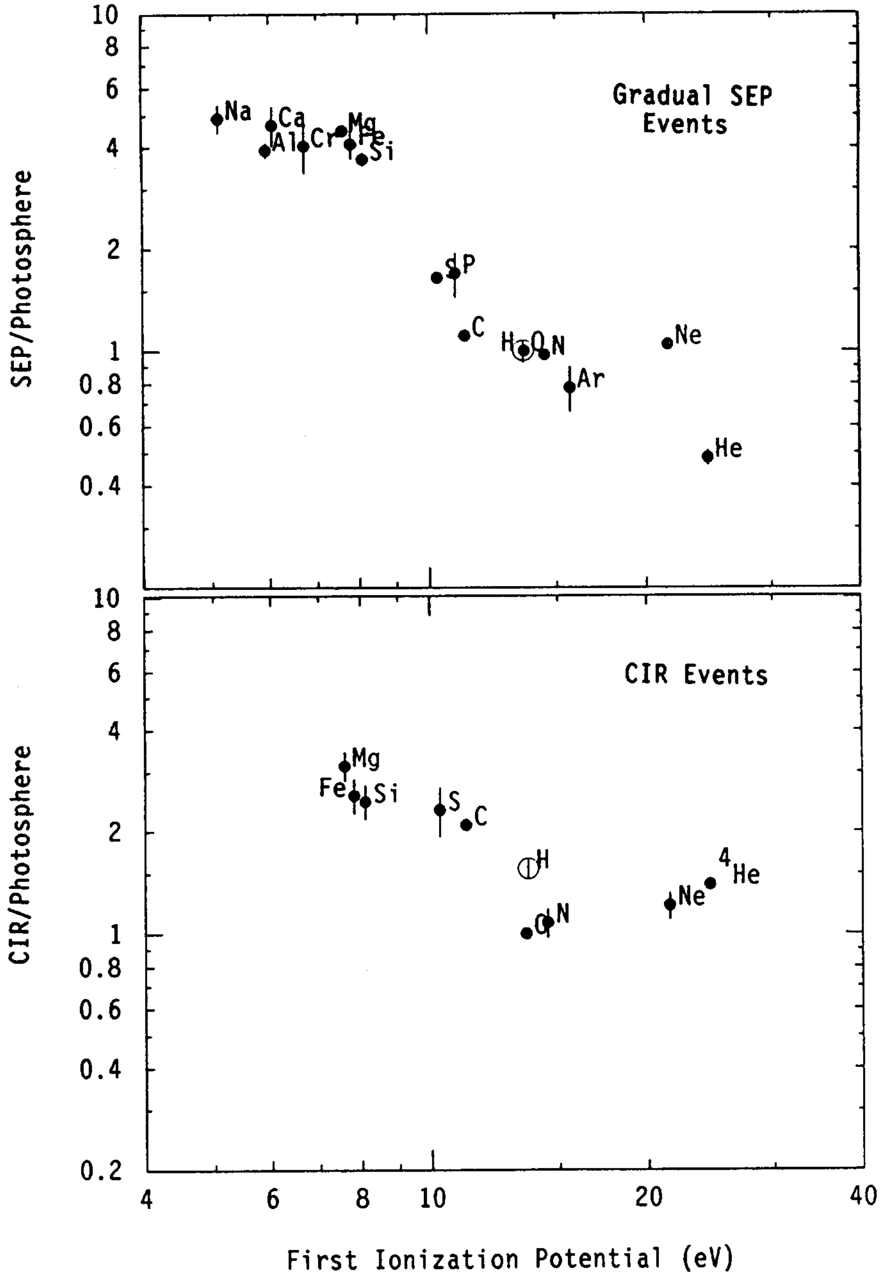

Fig. 1. The ratio of the mean abundances of energetic ions in gradual SEP events (upper panel) and in CIR events (lower panel) to those in the photosphere (meteoritic) are shown as a function of FIP. These abundances represent the FIP dependence of ion-neutral fractionation of the corona near active regions and beneath coronal holes, respectively. The large open circle represents H.

CIR ABUNDANCES

CIRs are formed where high-speed solar-wind streams overtake low-speed streams. Two shocks may be formed at CIRs, a forward shock propagates outward into the low-speed stream and a reverse shock propagates inward in the high-speed stream. Generally the shocks form outside 1 AU. Energetic particles accelerated from the high-speed solar wind at the reverse shock can be observed streaming sunward, in the plasma rest frame, in the high-speed region. During solar minimum, CIRs can persist for many solar rotations and recurrent increases in the energetic particles are seen every 27 days.

Differences in the FIP dependence of the abundances of energetic CIR ions from those in SEP events were discussed by Reames, Richardson and Barbier /6/. The differences are especially characterized by increased C/O and He/O ratios in the averaged CIR abundances. The C/O and He/O ratios are positively correlated with the maximum solar-wind speed in the high-speed region /12/.

I have determined the average 1-4 MeV/amu in the sample of CIR events studied previously /6/. The mean value of this ratio, H/He = 11.4± 0.7 is included with the other abundances and shown in the lower panel of Figure 1. Since the CIR shocks are different from those in SEPs, and the energy spectra are steeper, even near 1 MeV/amu, it is not entirely clear that H/He has reached its asymptotic low-energy value for this case. The distribution of H/He ratios, and their mean values, are shown in Figure 2 for both CIR and SEP events.

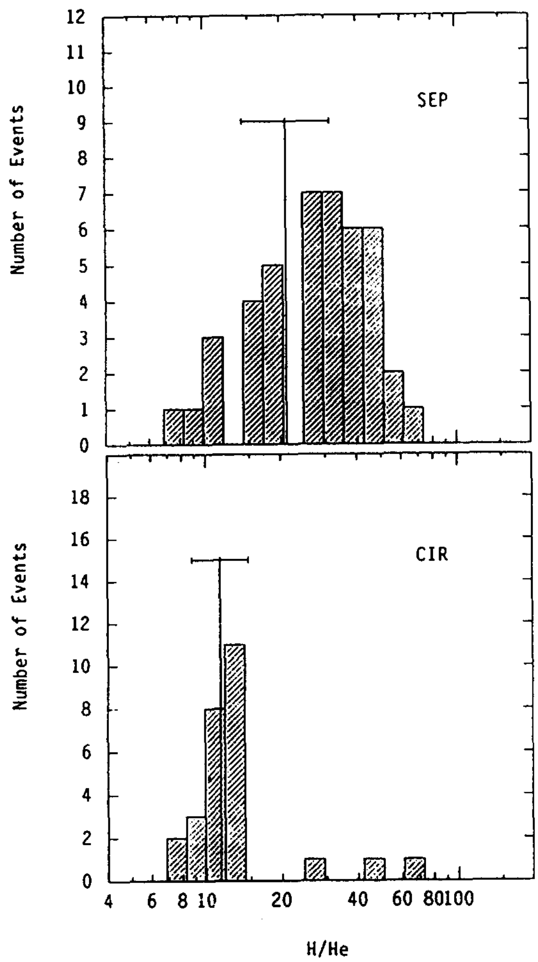

Fig. 2. Distributions of H/He for gradual SEP events and for CIR events.

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