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PROCEEDINGS OF SCIENCE

Variations of H-Normalized Heavy-Ion Abundances in Large Solar Energetic $(E > 10$ MeV) Particle Events

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The elemental composition of heavy ions (with atomic number $Z > 2$) (hi-Z) in large gradual $E > 10$ MeV nuc^{-1} SEP events has been extensively studied in the 2-15 MeV nuc^{-1} range to determine the acceleration processes and transport properties of SEPs. These studies invariably are based on abundances relative to those of a single element such as C or O and often neglect H and He, the elements of primary interest for space weather. The total radiation of an SEP event is determined not only by the H and He properties but also by those of hi-Z ions whose abundances and variations relative to H from one event to another are unknown. We report a study to determine those variations in a group of 15 large SEP events over the period 2000 to 2015. Five hi-Z ions (He, C, O, Mg, & Fe) were selected to determine variations of their fluences relative to those of H in the 13.5-50.7 MeV nuc^{-1} energy range for each SEP event. Our average hi-Z abundance ratios slightly exceed those reported by [1] at lower energies, with the Fe event abundances showing the largest standard deviation of an order of magnitude. The event abundances were weakly correlated with H fluences and strongly correlated with speeds Vcme of associated coronal mass ejections (CMEs). These correlations may be evidence of streaming limits in the shock regions of H in the largest events.

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1. Introduction

Space forecasting systems for SEP events benchmark the peak intensities of proton (H) events, usually for $E > 10$ MeV [2,3]. The NOAA Space Weather Prediction Center (SWPC) list of proton events exceeding 10 proton flux units (pfu) at $E > 10$ MeV observed on the *GOES* satellites since 1976 (https://umbra.nascom.nasa.gov/SEP/, hereafter the NOAA SEP list) gives large SEP events important for space weather. Elements with higher atomic number Z are a well known component of SEP events, but in general the Z $>$ 2 (hi-Z) elements are studied separately because their ionic mass to charge state ratio (A/Q) always equals or exceeds 2 [4], in contrast to H, for which A/Q = 1.

SEP events come in two basic types - the smaller impulsive events produced in magnetic reconnection events and ejected in coronal jets and the larger gradual events arising from coronal mass ejection (CME)-driven shocks [1,4]. The relative abundances of the hi-Z elements have been studied for both gradual and impulsive SEP events [4,5] to understand their basic particle acceleration and transport mechanisms. However, the lower energies of these studies are not suitable for space weather purposes, where one wants to know the radiation effects of higher energy ($E > 10$ MeV nuc^{-1}) H, He, and hi-Z elements on space hardware and humans in space. The basic question is: given $E > 10$ MeV proton events of large peak intensities, what are the hi-Z average abundances and their variations among different events?

The compilation of SEP event elemental abundances began with the first observations capable of resolving the hi-Z elements [6]. [7] used the average fluences of 49 SEP events to derive abundances for elements from He to Zn (Z = 30), each normalized to the abundance of O. The energy range of the Z $>$ 2 measurements was 2-12 MeV nuc^{-1}, but H and He, as the primary drivers of the shock Alfven wave field, were measured in the 1-4 MeV nuc^{-1} range. Later work has led to a standard set of coronal elemental abundances based on averages over many gradual SEP events measured in the 5-10 MeV/nuc energy range [1,5,8,9]. These averages are based on the assumption that coronal material is the source of gradual SEP events, which are produced in shock waves driven by CMEs.

One challenge to making abundance measurements is that hi-Z elemental enhancements in SEP events vary in power-law relationships to their A/Q values [10], a result now understood as an effect of interplanetary transport [11]. The power-law exponents can be positive or negative for a given event. The A/Q-dependent power-law relationship for gradual SEP events has recently been tested for extensions to H [12] and He [13], where those abundances are in good agreement for coronal source material temperatures $T < 2$ MK, but can be much higher for sources with $T > 2$ MK in which residual suprathermal ions are likely also accelerated. These results imply significant variations in ratios of hi-Z to H abundances among SEP events, which precludes confident forecasts of hi-Z fluences, given known peak H intensities or fluences.

Another challenge is that hi-Z abundance ratios vary significantly with E. Particle energy spectra of large gradual events generally can be fit by double power laws, defined by a break energy E_B, which scales as $(Q/A)^{\alpha}$, where α varies from 0.2 to 3 among events [14,15]. This is understood in terms of the shock geometry, with $\alpha \sim 0.2$ due to quasi-perpendicular shocks and α up to 2 due to quasi-parallel shocks [16]. The importance of spectral knee energies E_B of H for radiation effects was discussed by [4,17], and we emphasize here that those E_B variations are

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even more important in assessing the radiation impacts of the hi-Z particles. For these reasons it is important to assess empirically the abundance variations of hi-Z elements in large SEP events, as was first called for two decades ago [18].

2. Data Analysis

2.1 Instrument Selection

We limit this investigation to only large SEP events that might be expected to have substantial hi-Z fluences important for space weather purposes. As a second criterion we want to select the high energy ($E > 20$ MeV nuc^{-1}) range both for H, as the basic SEP reference element, and for the most common hi-Z elements. We use H data from the *SOHO*/Energetic and Relativistic Nuclei and Electron (ERNE) experiment [19]. Two sensors comprise the ERNE experiment and were designed to measure lower-energy particles (≤ 12 MeV nuc^{-1}, the LED) and higher energy particles (≥ 12 MeV nuc^{-1}, the HED). Energy ranges for both H and He in the HED are 13.5-25.8 MeV nuc^{-1} and 25.8-50.7 MeV nuc^{-1} [19]. Only two-hour averaged H and He data are available via the public ERNE database, from which we select the combined 13.5-50.7 MeV H channels as the basic H energy range for SEP events.

The *ACE* Solar Isotope Spectrometer (*ACE*/SIS) satisfies the second requirement for high-energy hi-Z elements from He to Zn (Z = 2 to 30) over the energy range from 10 MeV nuc^{-1} to 100 MeV nuc^{-1} [20]. Eight different Si detection layers allow for detection of higher energy particles in 8 energy channels per element from 3.43 MeV nuc^{-1} He (Z = 2) up to 178.96 MeV nuc^{-1} Ni (Z = 28).

2.2 Time Period and Event Selection

The time periods were limited to the available data of both *SOHO*/ERNE, beginning February 1996, and *ACE*/SIS, beginning August 1997. Both datasets covered through December 2017. We examined all events of > 500 pfu (28 candidate events) in the NOAA SEP event list to eliminate any cases with data gaps in the SIS or ERNE coverage. Several SEP events showed large decreases in their ERNE HED H and He 13.5-25.8 and 25.8-50.7 MeV nuc^{-1} intensity profiles around the times of maximum event intensities that were not present in the SIS data. This effect appears due to saturation from the particle prioritization scheme [19] and was not present in the ERNE LED profiles. We used the unaffected *ACE*/SIS He intensities in the 13.6-25.8 and 25.8-41.2 MeV nuc^{-1} range to correct the matching ERNE HED He intensities in the similar energy bands and then scaled the ERNE H intensities to the He intensities based on the H/He ratios outside the saturation times. For the selected 15 events of Table 1, elemental fluences were calculated from the event start to an end time assumed to occur when hi-Z intensities returned to pre-event background levels or to the onset of a subsequent SEP event. Three events of Table 1 (24 November 2000, 15 January 2005, and 13 December 2006) consist of multiple SEP events during when the GOES $E > 10$ MeV intensities remained above 10 pfu for duration of the integration period. The peak flux column consists of the maximum GOES pfu values obtained from the NOAA SEP Event List. The last three columns give solar source longitudes obtained from Table 1 of [21], coronal mass ejection (CME) linear speeds Vcme obtained from the *SOHO* Large Angle and Spectrometric Coronagraph (LASCO)

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Table 1: Selected Large Gradual SEP Events

Year	Month	Start UT	Time UT	Peak pfu	Solar Long.	CME Speed km s^{-1}	Data Qual
2000	Nov	24/0600	29/0200	942	E50	2519	Acc
2001	Apr	02/2000	10/0600	1110	W72	2505	Acc
-	Apr	15/1200	18/0200	951	W85	1199	Acc
-	Oct	01/1200	05/2000	2360	W95	1405	Extr
-	Dec	26/0600	29/0000	779	W54	1446	Acc
2002	Apr	21/0000	29/0600	2520	W84	2393	Extr
2003	Nov	02/1800	04/2000	1570	W56	2598	Extr
2004	Jul	25/1800	30/0000	2086	W33	1333	Extr
2005	Jan	15/0600	24/1200	5040	W25	2049	Extr
-	May	13/1800	18/1400	3140	E11	1689	Extr
-	Sep	07/1400	13/2200	1880	E77	D G	Extr
2006	Dec	13/0400	15/0200	698	W22	1774	Acc
2012	Mar	07/0200	11/0600	6530	E31	2684	Extr
2013	May	22/1200	26/1000	1660	W87	1466	Extr
2015	Jun	21/0000	25/1000	1070	E16	1366	Extr

CME Catalog [22], and whether the H profiles were extrapolated from the SIS He profiles, as discussed above. For the three cases of multiple SEP events, we selected the source location and speed of the CME associated with the largest fluence event.

2.3 Element and Energy Band Selection

The most abundant SEP elements [1,4] relative to H normalized at 1.6 $\times$ 10^6 are He (9.1 $\times$ 10^4), O (1000), C (420), Mg (178), Ne (157), Si (151), and Fe (131). For each selected hi-Z element of He, C, O, Mg, and Fe, we selected combined ranges of *ACE*/SIS energy channels to approximately match the ERNE H and He range of 13.5 to 50.7 MeV nuc^{-1}, given in the second column of Table 2. We subtracted 6-hour averaged pre-event background intensities from event intensities to obtain the fluences. Event fluences for He, C, O, Mg and Fe were divided by the corresponding H fluences Φ_H to obtain the normalized hi-Z abundances α_{He}, α_C, α_O, α_{Mg}, and α_{Fe}. We estimate the effects of energy-range mis-matches on the derived elemental abundances by applying the results of the survey [15] of 46 SEP events. They found hi-Z differential energy spectra to be well fitted by double power-laws of $AE^{-\gamma}$ with break energies E_B averaging $\sim$6 MeV nuc^{-1}, well below our low energy cutoffs. The high-energy power-law spectral exponents γ_b had mean values of $\sim$3.6 for all events. We assume each event here to be characterized by a power law with γ_b = 3.0 or 4.0 and calculate the factors by which our hi-Z elemental abundances are too high relative to those of H due to their differing energy ranges. The abundance multipliers are given in the fifth column of Table 2. With the Fe spectra having the lowest cutoff at 10.7 MeV nuc^{-1}, below the *SOHO*/ERNE H cutoff of 13.5 MeV, they have the highest overestimates by factors of $\sim$1.6 to 2.1. For all 15 SEP events we report the uncorrected average abundances in the nominal elemental energy ranges of column 4 of Table 2. We give the [1] abundances in column 3 and the corrected

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Table 2: SEP Hi-Z Abundances, Multipliers, and Energy Losses

	Energy Range MeV nuc^{-1}	Reames SEP 2-15 MeV nuc^{-1}	This Work (RK) $\sim$13-52 MeV nuc^{-1}	Multiplier $3 < \gamma < 4$	Corrected RK/Reames	Log St.D.
H	13.5-50.7	1.00E+0 $\pm$ 1.3E-1	1.00E+0 $\pm$ 1.04E-1	1.00	1.00	–
He	13.6-41.2	5.80E-2 $\pm$ 3.2E-3	4.77E-2 $\pm$ 6.01E-3	0.95-0.96	0.85-0.87	0.37
C	13.4-54.3	2.68E-4 $\pm$ 6.4E-6	3.17E-4 $\pm$ 3.81E-5	1.03	1.15	0.43
O	13.1-38.9	6.37E-4 $\pm$ 6.4E-6	1.03E-3 $\pm$ 1.27E-4	1.02-1.08	1.50-1.59	0.50
Mg	12.2-48.6	1.13E-4 $\pm$ 2.5E-6	2.26E-4 $\pm$ 2.73E-5	1.24-1.37	1.46-1.61	0.50
Fe	10.7-52.2	8.34E-5 $\pm$ 3.8E-6	2.35E-4 $\pm$ 3.29E-5	1.65-2.04	1.38-1.71	0.94

ratios of our abundances relative to those of [1] in column 6.

3. Results and Discussion

We have averaged the hi-Z (now including He) abundances and their uncertainties of the 15 SEP events, equally weighting the events, as was done by [9] in his compilation of the average 2-15 MeV nuc^{-1} elemental abundances of SEP events. Our values are compared with the updated [1] SEP abundances, both normalized to H = 1, in column 6 of Table 2. We find agreement within a factor $\sim$ 1.6 for all hi-Z elements. The last column shows the standard deviations of the logarithms of abundances among the 15 events for each element. Fe has by far the largest deviation, of nearly a full order of magnitude and about twice that of the other elements. We calculated Pearson CCs of event linear abundances between each hi-Z element pair for the 15 events, and there also the four Fe CCs ranged from 0.25 to 0.65, while CCs $>$ 0.79 for all other hi-Z element pairs. In coronal source regions of the gradual SEP events we consider here, the average A/Q $\approxeq$ 3.7 for Fe and $\leq$ 2.4 for Mg, O, C, and He [1]. Since SEP transport effects are A/Q dependent, it would be surprising if the event abundances of Fe tracked those of the other hi-Z elements.

It is well known that peak SEP event H intensities correlate with associated CME speeds Vcme (e.g., [4]). This should also hold for particle fluences as well as peak intensities, since the two parameters are rather tightly correlated [23]. If hi-Z fluences track those of H in SEP events, we would expect hi-Z fluences also to track Vcme, but the abundance ratios should be roughly independent of Vcme. However, as Figure 1 shows, the abundances generally increase with log Vcme, and the CCs $\sim$ 0.5 (except for Fe) are significant at more than the 90% significance level for the 14 SEP-CME event comparisons. An increase of hi-Z abundances with Vcme would be consistent with a decrease of Φ_H with Vcme, but we also find a positive correlation of CC = 0.591 for log Φ_H with log Vcme. Thus, the increase of Vcme results in both enhanced Φ_H and enhanced hi-Z abundance ratios. This may indicate that H of the larger sample events of Table 1 are streaming limited [4,17,24] by self-generated turbulence, which would produce low-energy plateaus in the H energy spectra for periods around the times of peak intensites [25,26]. The wave turbulence generated by H ions generally affects hi-Zs only at energies below 10 MeV nuc^{-1} [26], which would result in relatively smaller increases in H than in hi-Zs in larger events, leading to the increasing hi-Z abundances in Figure 1. We think it unlikely, but we can not rule out the possibility that the trend of Figure 1 is due to a systematic error in our reconstructions of the saturated H

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profiles of the largest SEP events, such that the reconstructed H profiles and their fluences Φ_H are increasingly underestimated with increasing peak intensities. We found no significant correlation of solar longitudinal variation of the abundance ratios.

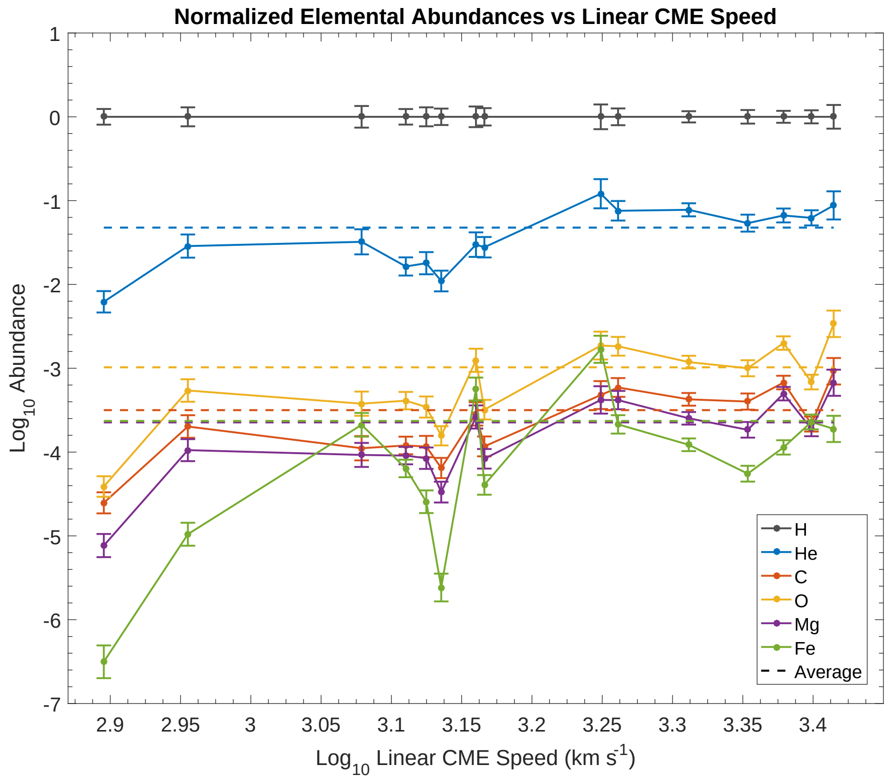

Figure 1: Logs of hi-Z abundance ratios versus the logs of Vcme. Each event is represented by the vertically aligned set of abundances. Color-coded horizontal dashed lines give the event averages.

4. Conclusions

We calculate five hi-Z elemental abundances ϕ_ε of 15 large SEP events in the $\sim$ 13-52 MeV nuc^{-1} energy range. The analysis used proton measurements from the *SOHO*/ERNE detector and He, C, O, Mg, and Fe measurements from *ACE*/SIS. In 10 of the 15 events H and He intensity profiles of the ERNE HED detector were saturated and required reconstruction by comparisons of the closely matched He channels on SIS and ERNE. Except for He, our average values, normalized to H, are higher than those reported by [1] in the 2-15 Mev nuc^{-1} range by factors of $\leq$ 1.6. Standard deviations of the 15 event log abundances were $\sim$ 0.5 for He, C, O, and Mg, but much higher for Fe at 0.94. We found that logs of event abundances strongly correlate with associated CME speeds and suggest that this effect is consistent with increasing streaming limitations of proton intensities in the largest SEP events.

We are not aware of any current SEP forecast program for hi-Z elements beyond He. Future work to determine better hi-Z abundances could be extended to more elements and would benefit from using all measurements from a single spacecraft.

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