Hydrogen and the Abundances of Elements in Gradual Solar Energetic-Particle Events

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Abstract Despite its dominance, hydrogen has been largely ignored in studies of the abundance patterns of the chemical elements in gradual solar energetic-particle (SEP) events; those neglected abundances show a surprising new pattern of behavior. Abundance enhancements of elements with $2 \leq Z \leq 56$, relative to coronal abundances, show power-law dependence, versus their average mass-to-charge ratio $A/Q$, that varies from event to event and with time during events; the ion charge states $Q$ depend upon the source plasma temperature $T$. For most gradual SEP events, shock waves have accelerated ambient coronal material with $T < 2$ MK to produce a decreasing power-laws in $A/Q$; here the proton abundances agree rather well with the power-law fits extrapolated from elements with $Z \geq 6$ at $A/Q > 2$ down to hydrogen at $A/Q = 1$. Thus the abundances of the elements with $Z \geq 6$ fairly accurately predict the observed abundance of H, at a similar velocity, in most SEPs. However, for those gradual SEP events where ion enhancements follow positive powers of $A/Q$, especially those with $T > 2$ MK where shock waves have reaccelerated residual suprathermal ions from previous impulsive SEP events, proton abundances commonly exceed the extrapolated expectation, usually by a factor of order 10. This is a new and unexpected pattern of behavior that is unique to the abundances of protons. This proton behavior is a signature that can help distinguish the presence or absence of shock acceleration when Fe-rich impulsive material is observed.

Keywords: Solar energetic particles · Solar system abundances · Coronal Mass Ejections · Solar flares
1. Introduction

Hydrogen is, by far, the most abundant element in typical astrophysical settings, including the Sun, where the pattern of element abundances is believed to have changed little during the 4.6 billion years since its formation. As elements evaporate from the solar photosphere up into the corona, those that are ionized, \textit{i.e.} with first ionization potential (FIP) $< 10$ eV, are preferentially enhanced by a factor of about 4 relative to the elements with FIP $> 10$ eV that are initially neutral atoms. Once in the 1-MK corona, all elements are highly ionized, and at altitudes where the plasma becomes collisionless, ion acceleration by electromagnetic fields can be sustained. The effects of those fields on acceleration and transport depends upon the magnetic rigidity of the ions, which, when compared at a constant velocity, varies as the ion mass-to-charge ratio $A/Q$. Thus it is not surprising that the effects of acceleration and transport on the abundances of solar energetic particles (SEPs) are found to vary as power laws in $A/Q$. The surprise is that scientists have advanced this picture of abundance variations of the elements for decades without including the abundance of hydrogen. Do protons ever fit this abundance pattern?

Early measurement of abundances, averaged over the large SEP events we now call “gradual” events, began to show clear evidence of the FIP effect (\textit{e.g.} Webber, 1975; Meyer, 1985; Reames, 1995, 2014) especially for the elements from He or C through Fe. Once typical element ionization states $Q$ first became available (Luhn \textit{et al.} 1984), event-to-event variations in some events were found to be power-law functions of $A/Q$ for elements with atomic numbers $6 \leq Z \leq 30$ by Breneman and Stone (1985), but H was also omitted from more-recent similar studies by Reames (2016a, 2016b, 2018b). Even the inclusion of He is rather complicated (Reames 2017c). Power-law behavior of abundances in “impulsive” SEP events was proposed by Reames, Meyer, and von Rosenvinge (1994) using abundances of elements with $2 \leq Z \leq 26$ and the extension to high $Z$ shows an especially strong behavior as the third power of $A/Q$ for $2 \leq Z \leq 82$ (Reames, 2000, 2017a; Mason \textit{et al.}, 2004; Reames and Ng, 2004; Reames, Cliver, and Kahler, 2014a).

The terms “impulsive” and “gradual” have come to refer to the dominant physical process of particle acceleration in these SEP events as evidence for two mechanisms has evolved (Reames, 1988, 1999, 2013, 2015, 2017a; Gosling, 1993). The evidence of
unique physics in the small “impulsive” SEP events was first shown by huge 1000-fold enhancements of $^3\text{He}/^4\text{He}$ (Serlemitsos and Balasubrahmanyan, 1975; Mason, 2007; Reames, 2017a). While $^3\text{He}/^4\text{He} \approx 5 \times 10^{-4}$ is found in the solar wind, even the early measurements found SEP events with $^3\text{He}/^4\text{He} \approx 1.5 \pm 0.1$. A few events even have $^3\text{He}/\text{H} > 1$ (Reames, von Rosenvinge, and Lin, 1985). The events were associated with streaming non-relativistic electrons and type III radio bursts (Reames, von Rosenvinge, and Lin, 1985; Reames and Stone, 1986). In the most complete theory, the streaming electrons produce electromagnetic ion-cyclotron (EMIC) waves in resonance with the gyrofrequency of $^3\text{He}$ to produce the unique enhancements (Temerin and Roth, 1992; Roth and Temerin, 1997). Further complicating the behavior, power-law enhancements of elements, also 1000-fold, between He and the heavy elements up to Pb (Reames, 2000, 2017a; Mason \textit{et al}., 2004; Reames and Ng, 2004; Reames, Cliver, and Kahler, 2014a) were found and were better explained by particle-in-cell simulations of magnetic reconnection (Drake \textit{et al}., 2009) which produce the power-law dependence on $A/Q$ from rigidity dependence during acceleration. Impulsive SEP events are associated with narrow coronal mass ejections (CMEs) related to solar jets (Kahler, Reames, and Sheeley, 2001; Bučík \textit{et al}., 2018) driven by magnetic reconnection involving open field lines.

In “gradual” or long-duration SEP events, particles are accelerated at shock waves driven out from the Sun by fast, wide CMEs (Kahler \textit{et al}., 1984). These shock waves accelerate SEPs (Lee, 1983, 2005; Zank, Rice, and Wu, 2000; Cliver, Kahler, and Reames, 2004; Ng and Reames, 2008; Gopalswamy \textit{et al}., 2012; Lee, Mewaldt, and Giacalone, 2012; Desai and Giacalone, 2016; Reames, 2017a), requiring shock speeds above $500 \text{–} 700 \text{ km s}^{-1}$ (Reames, Kahler, and Ng, 1997), and accelerating ions over an extremely broad region of the heliosphere (Reames, Barbier, and Ng, 1996; Rouillard \textit{et al}., 2012; Cohen, Mason, Mewaldt, 2017; Reames, 2017b). Generally, the shock waves sample the 1 – 2 MK coronal plasma (Reames, 2016a, 2016b, 2018b). Power-law dependence in gradual events can come from rigidity-dependent scattering of ions during transport (Parker, 1963; Ng, Reames, and Tylka, 1999, 2001, 2003, 2012; Reames, 2016a, 2016b) which results in dependence upon $A/Q$ when ion abundances are compared at the same particle velocity. If Fe scatters less than O in transit, for example, Fe/O will
increase early in an event and be depleted later on; this dependence on time and space traveling along the field $B$ also become longitude dependence because of solar rotation.

However, SEP abundances become complicated because shock waves can also reaccelerate residual ions from a seed population that includes pre-accelerated ions from the ubiquitous small impulsive SEP events, complicating the SEP abundance story. Mason, Mazur, and Dwyer (2002) noted the presence of modest enhancements of $^3$He in large SEP events that would otherwise be called gradual and the complexity of the seed population was soon realized (Desai et al., 2003; Tylka et al., 2005; Tylka and Lee, 2006; Bučík et al., 2014, 2015, 2018; Chen et al., 2015; Reames 2016a, 2016b). Thus gradual SEP events sometimes exhibit the abundance enhancement patterns of impulsive SEP events which we can recognize from power-law enhancements increasing with $A/Q$ and source plasma temperatures of $\approx 3$ MK (Reames, Cliver, and Kahler, 2014a, 2014b, 2015; Reames, 2019a, 2019b) which actually dominate 24% of gradual events (Reames 2016a, 2016b). The $^3$He/$^4$He ratio is also enhanced in these events (Reames, Cliver, and Kahler, 2014b) but its extreme variation with energy and from event to event (Mason 2007) makes Fe/O a more stable and reliable indicator of impulsive material. Hence we prefer Fe/O rather than $^3$He/$^4$He to identify impulsive SEP events and reaccelerated impulsive ions (Reames, Cliver, and Kahler, 2014a). Recently, the abundance patterns of H (Reames, 2019b) and $^4$He (Reames 2019a) have been found for impulsive SEP events.

Protons have been studied for many aspects of gradual SEP events (e.g. Reames, 2017a), including acceleration (Lee, 1983, 2005; Zank, Rice, and Wu, 2000; Ng and Reames, 2008), transport (Parker, 1963; Ng, Reames, and Tylka, 1999, 2001, 2003, 2012), time variations (Reames, Ng, and Tylka, 2000; Reames, 2009), and energy spectra (Reames and Ng, 2010), but not for FIP or power-law abundance patterns. If we seek guidance from the case of the solar wind, we find variations are seen in H/He with solar-wind speed and phase in the solar cycle (Kasper et al., 2007). However, while the solar wind is coronal in origin and does display a FIP effect (e.g. Schmelz et al. 2012), it is clear that SEPs have a different source than the solar wind (Mewaldt et al., 2002; Desai et al., 2003; Reames, 2018a) that may be related to differing open- and closed-field origins (Laming, 2009, 2015) of the two coronal samples (Reames, 2018a, 2018b). For our purposes, the SEP reference coronal abundances (derived from averaged gradual SEP
events) and the solar photospheric abundances are provided in Appendix A. We define an element “enhancement” to be its observed abundance, normalized to O, divided by its corresponding reference abundance, similarly normalized.

To what extent can we organize the abundance of H within the scheme of the other elements in gradual SEP events? We consider the gradual events studied and listed by Reames (2016a) using observations made by the Low-Energy Matrix Telescope (LEMT) on the Wind spacecraft, near Earth (von Rosenvinge et al., 1995; Reames et al., 1997; see also Chapt. 7 of Reames, 2017a). LEMT primarily measures elements He through Pb in the region of 2 – 20 MeV amu\(^{-1}\). The element resolution of LEMT up through Fe is shown in detail by Reames (2014). LEMT resolves element groups above Fe as shown by Reames (2000, 2017a). Unlike other elements, the protons in LEMT are limited to a small interval sampled near \(\approx 2.5\) MeV bounded by the front-detector (dome) threshold (von Rosenvinge et al., 1995; Reames et al., 1997).

Throughout this text, whenever we refer to the element He or its abundance, we mean \(^4\)He, unless \(^3\)He is explicitly stated.

2. Power-laws in \(A/Q\)

The theory of diffusive transport provides support for our expectation that element enhancements in gradual events will vary approximately as power laws in \(A/Q\). It is common to expect that the scattering mean free path \(\lambda_X\) of species \(X\) depends upon as a power law on the particle magnetic rigidity \(P\) as \(P^\alpha\) and upon distance from the Sun \(R\) as \(R^\beta\) so that the expression for the solution to the diffusion equation (Equation C3 in Ng, Reames, and Tylka 2003 based upon Parker 1963) can be used to write the enhancement of element \(X\) relative to oxygen as a function of time \(t\) as

\[
\frac{X}{O} = L^{-3/(2-\beta)} \exp \{ (1-1/L) \tau/t \} \ r^S
\]

where \(L = \lambda_X \lambda_O = r^\alpha = \left( \frac{A_X/Q_X}{A_O/Q_O} \right)^\alpha \) and \(\tau = 3R^2 / [ \lambda_O (2-\beta)^2 v ]\) for particles of speed \(v\). Since we compare different ions at the same velocity, their rigidities can be replaced by their corresponding values of \(A/Q\). The factor \(r^S\) is included to represent
any $A/Q$-dependent power-law enhancement at the source. For shock acceleration of impulsive suprathermal ions, it describes the power-law enhancement of the seed particles expected from acceleration in impulsive SEP events (e.g. Drake et al., 2009). For shock acceleration of the ambient coronal material, $S = 0$.

To simplify Equation (1), we can achieve a power-law approximation if we expand $\log x = (1-1/x) + (1-1/x)^2/2 + \ldots$ (for $x > 1/2$). Using only the first term to replace $1-1/L$ with $\log L$ in Equation (1), we have

$$X/O \approx L^{(\tau/t \cdot 3/(2-\beta))} r^S$$

(2)

as an expression for the power-law dependence of enhancements on $A/Q$ for species $X$.

More generally, we can write Equation (2) in the form $X/O = r^p$, where the exponent $p$ is linear in the variable $1/t$, so that

$$p = \alpha \tau / t + S - 3\alpha / (2-\beta)$$

(3)

the average parameters are directly measurable from the time behavior of SEP-abundance observations (Reames, 2016b). Fits to the time behavior of typical gradual SEP events show that late in events where impulsive material is not present $p \approx -1$ to $-2$ (Reames, 2016b) while the average power-law for impulsive events suggests $S \approx 3$ (Reames, Cliver, and Kahler, 2014a, Mason, et al. 2004). The ions in small impulsive events generally propagate scatter free (Mason et al., 1989), but in the more intense gradual events any shock-accelerated impulsive suprathermal ions are scattered, so that the power for the heavy-element enhancements is reduced (Reames, 2016b).

Thus we can expect that the enhancements will vary as a power law in $A/Q$, but the pattern of the average value of $Q$ for each element depends upon the source plasma temperature $T$ of the ions. Figure 1 shows two examples of observed abundance enhancements for SEP events matched against regions of the theoretical plots of $A/Q$ versus $T$ based upon Mazzotta et al. (1998).
Figure 1. Observed element enhancements (left) are compared with theoretical plots of $A/Q$ versus $T$ (right) for 8-hr periods in 14 November 1998 (upper panels) and 22 May 2013 (lower panels) SEP events. Temperatures are chosen that best match the observed groupings of elements (Reames 2016a).

For the event at $T \approx 2.5$ MK in the upper left panel of Figure 1, the almost fully ionized elements C, N, and O occur grouped with He, while Ne, Mg, and Si, with two orbital electrons, are grouped at an interval above them. For the example in the lower panels, with $T \approx 0.7$ MK, partially ionized C, N, and O have moved well above He and are now grouped with Ne, while Mg and Si have moved far above Ne and have joined S.
approaching Ar and Ca. We will see that the $\chi^2$ values of fits can be quite sensitive to these variations.

Given a temperature and the associated values of $A/Q$, we can determine, by least-squares fitting, the best fit line and the associated value of $\chi^2/m$, where $m$ is the number of degrees of freedom. Repeating this fitting for every $T$ of interest, we can plot $\chi^2/m$ versus $T$ (e.g. Figure 2d) to choose the most likely temperature and fit line (Reames 2016a, 2016b, 2018b). In the present paper, we include only the elements $Z \geq 6$ in the fits, and compare that best fit line with He and extrapolated to H. In the fits an error of 15% is assumed for random abundance variations in addition to the statistical errors.

3. Low-$T$ Events and Decreasing Powers of $A/Q$

Guided by the power-law fits of gradual events for $Z \geq 2$ by Reames (2016a), we first examine events with $T < 2$ MK which seem to represent shock acceleration of the ambient solar coronal plasma.

Figure 2 shows analysis of the event of 24 August 1998 from a source at longitude E09 on the Sun. The extrapolated values of the least-squares power-law fits for elements with $Z \geq 6$ for the six 8-hr time intervals agree rather well with the measured enhancement for H plotted at $A/Q = 1$. In this event, the abundances of the elements with $Z \geq 6$ actually predict the abundances of H and He.
Figure 2. Intensities of H, He, O, and Fe (a), normalized abundance enhancements H/O and Fe/O (b), and best-fit temperatures (c) are shown versus time for the 24 August 1998 SEP event. Panel (d) shows $\chi^2/\text{m}$ versus $T$ for each 8-hr interval while (e) shows enhancements, labeled by $Z$, versus $A/Q$ for each 8-hr interval shifted $\times 0.1$, with best-fit power law for elements with $Z \geq 6$ extrapolated down to H at $A/Q = 1$. Colors correspond for the six intervals in (c), (d), and (e) and symbols in (c) and (d); times are also listed in (e). Event onset is flagged with solar longitude in (a) and event number from Reames (2016a) in (b).

Figure 3 shows the event of 23 January 2012 from a source at W21 on the Sun with an associated CME speed of 2175 km s$^{-1}$. The enhancements versus $A/Q$ are quite flat during the early periods so $T$ is poorly determined. Here again the abundance of H is fairly well predicted by the abundances of elements with $Z \geq 6$. 
Figure 3. Intensities of H, He, O, and Fe (a), normalized abundance enhancements H/O and Fe/O (b), and best-fit temperatures (c) are shown versus time for the 23 January 2012 SEP event. Panel (d) shows $\chi^2/m$ versus $T$ for each 8-hr interval while (e) shows enhancements, labeled by $Z$, versus $A/Q$ for each 8-hr interval shifted x0.1, with best-fit power law for elements with $Z \geq 6$ extrapolated down to H at $A/Q = 1$. Colors correspond for the eight intervals in (c), (d), and (e) and symbols in (c) and (d); times are also listed in (e). Event onset is flagged with solar longitude in (a) and event number from Reames (2016a) in (b).

Figure 4 shows analysis of the first two of the “Halloween” events on 26 and 28 October 2003 from W38 and E08 with CME speeds of 1537 and 2459 km s$^{-1}$, respectively. Extrapolation of the least-squares fits for $Z \geq 6$ to $A/Q = 1$ fit H rather well, even when the slope reverses for the last interval in Figure 4e. These events have been studied
previously for their protons (Mewaldt et al. 2005) and their heavier ions (Cohen et al. 2005) separately.

**Figure 4.** Intensities of H, He, O, Fe, and $50 \leq Z \leq 56$ ions (a), normalized abundance enhancements H/O and Fe/O (b), and derived source temperatures (c) are shown versus time for the 26 and 28 October 2003 SEP events. Panel (d) shows $\chi^2/m$ versus $T$ for each 8-hr interval while (e) shows enhancements, labeled by $Z$, versus $A/Q$ for each 8-hr interval shifted $\times 0.1$, with best-fit power law for elements with $Z \geq 6$ extrapolated down to H at $A/Q = 1$. Colors correspond for the eight intervals in (c), (d), and (e) and symbols in (c) and (d); times are also listed in (e). Event onsets are flagged with solar longitude in (a) and event number from Reames (2016a) in (b).
4. High-\( T \) Events with Increasing Powers of \( A/Q \)

\( H \) seemed to fit the abundance pattern of the preceding events. However, there is another class of events where it does not; examples have already been seen for impulsive SEP events (Reames 2019b).

Figure 5 is an example of an event with positive power-law slope and \( T \approx 2.5 \) MK for an event from W63 on the Sun with a CME speed of 1556 km s\(^{-1}\). These properties suggest the presence of impulsive suprathermal ions with \( S > 0 \) in the seed population. The proton enhancement in this event is an order of magnitude higher than expected from the extrapolation of the fit for the ions with \( Z \geq 6 \). This behavior was seen recently for the impulsive events where there is additional reacceleration of ions by shock waves (Reames 2019b) and we will find this behavior common for many gradual SEP events with positive powers of \( A/Q \) and with \( T > 2 \) MK since they are dominated by reaccelerated impulsive SEP ions.
Figure 5. Intensities of H, He, O, Fe, and $50 \leq Z \leq 56$ ions (a), normalized abundance enhancements H/O and Fe/O (b), and temperatures (c) are shown versus time for the 6 November 1997 SEP event. Panel (d) shows $\chi^2/m$ versus $T$ for each 8-hr interval while (e) shows enhancements, labeled by $Z$, versus $A/Q$ for each 8-hr interval shifted ×0.1, with best-fit power law for elements with $Z \geq 6$ (solid) joined to H by dashed lines. Colors correspond for the six intervals in (c), (d), and (e) and symbols in (c) and (d); times are also listed in (e). Dashed lines join H with its associated elements in panel (e). Event onset is flagged with solar longitude in (a) and event number from Reames (2016a) in (b).

For comparison, we show in Figure 6 the next event in the series of Halloween events, immediately following the events in Figure 4. The source of this event is a CME with a speed of 2029 km s$^{-1}$ from longitude W02 on the Sun on 29 October 2003.
Figure 6. Intensities of H, He, O, Fe, and 50 ≤ Z ≤ 56 ions (a), normalized abundance enhancements H/O and Fe/O (b), and temperatures (c) are shown versus time for the 29 October 2003 SEP event. Panel (d) shows χ²/m versus T for each 8-hr interval while (e) shows enhancements, labeled by Z, versus A/Q for each 8-hr interval shifted ×0.1, with best-fit power law for elements with Z ≥ 6 (solid) joined to H by dashed lines. Colors correspond for the five intervals in (c), (d), and (e) and symbols in (c) and (d); times are also listed in (e). Dashed lines join H with its associated elements in panel (e). Event onset is flagged with solar longitude in (a) and event number from Reames (2016a) in (b).

Unlike its immediate predecessors (shown in Figure 4) the event in Figure 6 shows a 2.5 MK seed population of impulsive SEP ions with an order-of-magnitude ex-
cess of protons. This event is not influenced by the properties of its immediate predecessor in Figure 4.

5. Other Variations

From the foregoing one might conclude that hydrogen enhancements agree with those of other elements when the shock waves accelerate ambient coronal material and H exceeds expectations by a factor of about 10 when impulsive SEP ions are reaccelerated. That does describe most gradual SEP events. However, there are some events with combinations of behavior that are more complex.

Figure 7 shows analysis of the event of 2 April 2001 driven by a CME with a speed of 2505 km s\(^{-1}\) from W78 on the Sun. Abundances early in the event indicate a temperature of 2.5 MK, but the proton excess is quite modest, perhaps a factor of 2 above expectations. During the middle of the event the temperature rises slightly to 3.2 MK and the factor-of-10 proton excess is seen.

The final three periods shown in Figure 7e illustrate that temperature determination becomes impossible when the abundance enhancements are flat, independent of \(A/Q\). We can measure temperature when there is either increasing or decreasing dependence on \(A/Q\), but we cannot determine \(A/Q\) or \(T\) when there is no variation and the enhancements are independent of \(A/Q\). Nevertheless, it is clear that the proton enhancements are a factor of 10 above the other elements here as well.
Figure 7. Intensities of H, He, O, Fe, and 50≤ Z ≤ 56 ions (a), normalized abundance enhancements H/O and Fe/O (b), and temperatures (c) are shown versus time for the 2 April 2001 SEP event. Panel (d) shows $\chi^2/m$ versus $T$ for each 8-hr interval while (e) shows enhancements, labeled by $Z$, versus $A/Q$ for each 8-hr interval shifted $\times 0.1$, with best-fit power law for elements with $Z \geq 6$ extrapolated down to H at $A/Q = 1$ (solid) or joined to H by dashed lines. Colors correspond for the eight intervals in (c), (d), and (e) and symbols in (c) and (d); times are also listed in (e). Dashed lines join H with its associated elements in panel (e). Event onset is flagged with solar longitude in (a) and event number from Reames (2016a) in (b).

Figure 8 shows the event of 29 September 2013 from W33 with a CME speed of 1179 km s$^{-1}$. This event shows classic evolution where Fe/O decreases with time.
Figure 8. Intensities of H, He, O, and Fe ions \((a)\), normalized abundance enhancements \(\text{H/O and Fe/O} \,(b)\), and temperatures \((c)\) are shown \textit{versus} time for the 29 September 2013 SEP event. \textit{Panel} \((d)\) shows \(\chi^2/m\) versus \(T\) for each 8-hr interval while \((e)\) shows enhancements, labeled by \(Z\), \textit{versus} \(A/Q\) for each 8-hr interval shifted \(\times 0.1\), with best-fit power law for elements with \(Z \geq 6\) extrapolated down to \(\text{H at } A/Q = 1\) \textit{(solid)} or joined to \(\text{H by dashed lines}}. Colors correspond for the six intervals in \((c), (d),\) and \((e)\) and symbols in \((c)\) and \((d)\); times are also listed in \((e)\). Dashed lines join \(\text{H with its associated elements in panel} \,(e)\). Event onset is flagged with solar longitude in \((a)\) and event number from Reames (2016a) in \((b)\).

The event in Figure 8 shows a consistent temperature of 1.5 MK indicating a lack of hotter material with impulsive suprathermal ions, yet the proton enhancement is sig-
nificantly above expectation early, when the enhancements are rising with $A/Q$, but are well within expectations when the enhancements are falling with $A/Q$.

Does the large proton excess depend upon the presence of impulsive material or on the slope of the power law? Figure 8e suggests that only the slope matters, but Figure 7e shows predicted proton abundances for both positive slope and $T = 2.5$ MK.

### 6. Proton Excess and Distributions in $A/Q$ and $T$

We have seen several examples of events that show typical behavior of proton enhancement in gradual SEP events and a few events that show atypical behavior. What remains is to examine the probability distributions for a wide range of cases. Since the behavior can vary with time during an event we must look at the distributions of the basic 8-hr averages, nearly 400 intervals within the SEP events originally studied by Reames (2016a).

The upper panel of Figure 9 shows the distribution of proton enhancements during the 8-hr intervals as a function of the slope, or power of $A/Q$, of the fit. Clearly, the peak of the distribution lies at a negative slope near -1, where most intervals have a proton enhancement within a factor of about 3 of having the value correctly predicted by the ions with $Z \geq 6$ or modest excesses. Grouping the intervals by temperature, in the lower panels of Figure 9, shows that intervals with $T \geq 2.5$, on the right, identify with the positive slope involving reaccelerated impulsive ions with typical power-of-10 proton excesses. Lower temperatures of ambient coronal plasma in the lower left panel have a much better chance of predicting the proton intensity using only the $Z \geq 6$ ions, but there are some event intervals with positive slope that usually occur early in these events.
Figure 9. In all panels, the enhancement of H relative to that expected from the power-law fit of elements \( Z \geq 6 \) is shown versus the “slope” or power of \( A/Q \) from the fit of elements \( Z \geq 6 \). The upper panel shows a histogram of the distribution of all 398 8-hr intervals in this space with symbol color and size showing the number at each location. The lower left panel shows the distribution of intervals with \( T = 0.79 \), 1.0, and 1.26 MK. The lower right panel shows the distribution of intervals with \( T = 2.5 \) and 3.2 MK.
7. Discussion

The abundances we study depend upon two underlying factors. First, elements suffer the “FIP effect” as they are brought into the corona to produce the reference SEP abundances tabulated in Appendix A. Second, their acceleration and transport depend, not only upon particle rigidity, but approximately as a power law on rigidity. Similar processes apply, not only to SEPs, but even to energetic ions in corotating interaction regions where shock waves accelerate ions, from the solar wind in this case, to produce enhancements that usually decline with \( A/Q \) (Reames, 2018c) like most SEP events here. All ions experience this process, but the protons in shock acceleration have a dual role; they are not only accelerated like other ions, but they must generate waves as they stream away so as to scatter subsequent ions back and forth across the shock (Bell 1978; Lee, 1983, 2005; Ng and Reames, 2008; Desai and Giacalone, 2016). Are extra protons sometimes required for the latter task? If we adjust the abundance normalization from O to H, events with formerly “excess protons” are now seen as unable to accelerate the expected number of heavy ions given the available protons and the wave spectrum they have produced.

When we compare ions at the same velocity, as we do for studies of abundance enhancements, the ions interact with different parts of the proton-generated wave spectrum. For example, for 2.5 MeV protons the wave spectrum is approximately generated by streaming 2.5 MeV protons, for 2.5 MeV amu\(^{-1}\) He, C, or O with \( A/Q = 2 \) the spectrum is generated by streaming 10 MeV protons, for 2.5 MeV amu\(^{-1}\) Fe at \( A/Q = 4 \) the spectrum is generated by streaming 39 MeV protons, and for 2.5 MeV amu\(^{-1}\) heavy ions with \( A/Q = 10 \) the spectrum is generated by streaming 224 MeV protons. Thus the proton spectrum and the slope of the \( A/Q \)-dependence of heavy ion enhancements are related. Probably, any downward breaks in the proton spectrum will especially tend to depress heavy ions perhaps such as may be occurring for the \( 50 \leq Z \leq 56 \) ions in Figures 6 and 7. Breaks can also disrupt the power-law lower in \( A/Q \) as seen by the break at Mg in the multi-spacecraft study of the SEP event of 23 January 2012 (Reames 2017b).

Do the excess protons come from the same ion population as the heavy ions? Recently, Reames (2019b) suggested that two components contributed to the shock acceleration in “impulsive” SEP events with significant excess protons, the heavy ions may
come from residual impulsive suprathermal ions with positive power of $A/Q$, while the protons come from the ambient plasma with a negative power of $A/Q$ (see Figure 9 in Reames 2019b). However, excess protons are seen rather often and in similar amounts, making this dual-source explanation less probable, since two components might be expected to produce a larger range of relative variation. Also, two components would not explain the event in Figure 8 where a proton excess and positive power of $A/Q$ coexists for ions with an ambient 1.5 MK source plasma temperature. Apparently, more protons are required to support shock conditions that can produce or can maintain a strong positive power of $A/Q$ in the enhancements of heavy elements, even when injected abundances already have a positive power of $A/Q$ initially. However, cases do exist where positive powers of $A/Q$ extrapolate to predict the observed proton enhancement (Figures 4 and 7).

We summarize the general behavior of gradual SEP events as follows:

(i) Most time intervals in most gradual SEP events (> 60 %) have source temperatures $0.7 \leq T \leq 1.6$ MK and abundances that decrease as a power of $A/Q$. Proton enhancements are predicted by the power-law pattern of the other elements.

(ii) Time periods during those events (> 20%) dominated by pre-accelerated impulsive ions, with $T > 2$ MK and abundances that increase as a power of $A/Q$, usually have proton enhancements a factor of about 10 above the expected values.

In SEP events overall, three situations can exist. Proton abundances can be consistent with the expectations of a power law in $A/Q$ in (i) “pure” small Fe-rich impulsive SEP events (Reames, 2019b) and in (ii) “pure” large gradual SEP events with decreasing powers of $A/Q$ with few impulsive ions. However, proton abundances significantly exceed expectations primarily in (iii) “compound” SEP events where shock waves reaccelerate impulsive SEP material. This new three-way behavior of proton abundances can help identify the physical processes involved. Thus, Fe-rich SEPs with expected proton abundances were probably accelerated in a magnetic reconnection region without involvement of shocks, while Fe-rich SEPs with a 10-fold excess of protons were probably reaccelerated by a shock wave. This is a powerful new insight.
In contrast to H, He shows substantial source abundance variations $30 \leq \text{He/O} \leq 100$ in both impulsive and gradual events (Reames, 2017c, 2019a) with a few impulsive SEP events showing extreme suppression of $\text{He/O} \approx 2$ (Reames, 2019a). These variations in He may result from FIP-related inefficient ionization of He during transport up into the corona (Laming, 2009). H and He do not share the same behavior; this is why we study H/O and He/O rather than He/H. In view of the comparisons of other elements (e.g. Reames 2018a), it is not surprising that variations of H and He in SEP events also seem to differ completely from variations of H and He in the solar wind.

**Disclosure of Potential Conflicts of Interest**

The author declares he has no conflicts of interest.
Appendix A: Reference Abundances of Elements

The average element abundances in gradual SEP events are a measure of the coronal abundances sampled by SEP events (Reference gradual SEPs in Table 1). They differ from photospheric abundances (Table 1) by a factor which depends upon FIP (e.g. Reames 2018a; 2018b). Ion “enhancements” are defined as the observed abundance of a species, relative to O, divided by the reference abundance of that species, relative to O.

Table 1 Reference gradual SEP abundances, photospheric, and impulsive SEP abundances are shown for various elements.

| Element | Z  | FIP [eV] | Photosphere1 | Reference Gradual SEPs2 | Avg. Impulsive SEPs3 |
|---------|----|---------|--------------|------------------------|----------------------|
| H       | 1  | 13.6    | (1.74±0.17)×10^6 | (1.6±0.2)×10^6 | -                     |
| He      | 2  | 24.6    | 15600±7000   | 57000±5000   | 53000±30000**         |
| C       | 6  | 11.3    | 550±76       | 420±10      | 386±8                |
| N       | 7  | 14.5    | 126±35       | 128±8       | 139±4                |
| O       | 8  | 13.6    | 1000±161     | 1000±10     | 1000±10              |
| Ne      | 10 | 21.6    | 210±54       | 157±10      | 478±24               |
| Mg      | 12 | 7.6     | 64.5±9.5     | 178±4       | 404±30               |
| Si      | 14 | 8.2     | 61.6±9.1     | 151±4       | 325±12               |
| S       | 16 | 10.4    | 25.1±2.9     | 25±2        | 84±4                 |
| Ar      | 18 | 15.8    | 5.9±1.5      | 4.3±0.4     | 34±2                 |
| Ca      | 20 | 6.1     | 4.0±0.7      | 11±1        | 85±4                 |
| Fe      | 26 | 7.9     | 57.6±8.0     | 131±6       | 1170±48              |
| Zn-Zr   | 30-40 | - | - | 0.04±0.01 | 2.0±0.2 |
| Sn-Ba   | 50-56 | - | - | 0.0066±0.001 | 2.0±2 |
| Os-Pb   | 76-82 | - | - | 0.0007±0.0003 | 0.64±0.12 |

1 Lodders, Palme, and Gail (2009), see also Asplund et al. (2009).
* Caffau et al. (2011).
2 Reames (1995, 2014, 2017a).
3 Reames, Cliver, and Kahler (2014a)
** Reames (2019a).
References

Asplund, M., Grevesse, N., Sauval, A.J., Scott, P.: 2009, The chemical composition of the sun, *Ann. Rev. Astron. Astrophys.* 47, 481 doi: 10.1146/annurev.astroph.46.060407.145222

Bell, A.R.: 1978, The acceleration of cosmic rays in shock fronts. I, *Mon. Not. Roy. Astron. Soc.*, 182, 147 doi: 10.1093/mnras/182.2.147

Breneman, H.H., Stone, E.C.: 1985, Solar coronal and photospheric abundances from solar energetic particle measurements, *Astrophys. J. Lett.* 299, L57, doi: 10.1086/184580

Bučík, R., Innes, D.E., Chen, N.H., Mason, G.M., Gómez-Herrero, R., Wiedenbeck, M.E.: 2015, Long-lived energetic particle source regions on the Sun, *J. Phys. Conf. Ser.* 642, 012002 doi: 10.1088/1742-6596/642/1/012002

Bučík, R., Innes, D.E., Mall, U., Korth, A., Mason, G.M., Gómez-Herrero, R.: 2014, Multi-spacecraft observations of recurrent $^3$He-rich solar energetic particles, *Astrophys. J.* 786, 71 doi: 10.1088/0004-637X/786/1/71

Bučík, R., Innes, D.E., Mason, G.M., Wiedenbeck, M.E., Gómez-Herrero, R., Nitta, N.V.: 2018, $^3$He-rich solar energetic particles in helical jets on the Sun, *Astrophys. J.* 852 76 doi: 10.3847/1538-4357/aa9d8f

Caffau, E., Ludwig, H.-G., Steffen, M., Freytag, B., Bonofacio, P.: 2011, Solar chemical abundances determined with a CO5BOLD 3D model atmosphere, *Solar Phys.* 268, 255. doi:10.1007/s11207-010-9541-4

Chen, N.H., Bučík R., Innes D.E., Mason G.M. 2015, Case studies of multi-day $^3$He-rich solar energetic particle periods, *Astron. Astrophys.* 580, 16 doi: 10.1051/0004-6361/201525618

Cliver, E.W., Kahler, S.W., Reames, D.V.: 2004, Coronal shocks and solar energetic proton events, *Astrophys. J.* 605 902 doi: 10.1086/382651

Cohen, C.M.S., Mason, G.M., Mewaldt, R.A.: 2017, Characteristics of solar energetic ions as a function of longitude, *Astrophys. J.* 843, 132 doi: 10.3847/1538-4357/aa7513

Cohen, C.M.S. Stone, E.C., Mewaldt, R.A., Leske, R.A., Cummings, A.C., Mason, G.M., Desai, M.I., von Rosenvinge, T.T., Wiedenbeck, M.E.: 2005, Heavy ion abundances and spectra from the large solar energetic particle events of October-November 2003 *J. Geophys. Res* 110 A916 doi: 10.1029/2005JA011004

Desai, M.I., Giacalone, J.: 2016, Large gradual solar energetic particle events, *Living Reviews of Solar Physics*, doi: 10.1007/s41116-016-0002-5.

Desai, M.I., Mason, G.M., Dwyer, J.R., Mazur, J.E., Gold, R.E., Krimigis, S.M., Smith, C.W., Skoug, R.M.: 2003, Evidence for a suprathermal seed population of heavy ions accelerated by interplanetary shocks near 1 AU, *Astrophys. J.* 588, 1149, doi: 10.1086/374310

Drake, J.F., Cassak, P.A., Shay, M.A., Swisdak, M., Quataert, E.: 2009, A magnetic reconnection mechanism for ion acceleration and abundance enhancements in impulsive flares, *Astrophys. J. Lett.* 700, L16 doi: 10.1088/0004-637X/700/1/L16

Gopalswamy, N., Xie, H., Yashiro, S., Akiyama, S., Mäkelä, P., Usoskin, I.G.: 2012, Properties of Ground level enhancement events and the associated solar eruptions during solar cycle 23, *Space Sci. Rev.* 171, 23 doi: 10.1007/s11214-012-9890-4

Gosling, J.T.: 1993, The solar flare myth, *J. Geophys. Res.* 98, 18937 doi: 10.1029/93JA01896

Kahler, S.W., Reames, D.V., Sheeley, N.R., Jr.: 2001, Coronal mass ejections associated with impulsive solar energetic particle events, *Astrophys. J.*, 562, 558 doi: 10.1086/323847
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D. V. Reames

Kahler, S.W., Sheeley, N.R., Jr., Howard, R.A., Koomen, M.J., Michels, D.J., McGuire R.E., von Rosenvinge, T.T., Reames, D.V.: 1984, Associations between coronal mass ejections and solar energetic proton events, J. Geophys. Res. 89, 9683, doi: 10.1029/JA089iA11p09683

Kasper, J.C., Stevens, M.L., Lazarus, A.J., Steinberg, J.T., Ogilvie, K.W.: 2007, Solar wind helium abundance as a function of speed and heliographic latitude: variation through a solar cycle, Astrophys. J. 660, 901 doi: 10.1086/510842

Laming, J.M.: 2009, Non-WKB models of the first ionization potential effect: implications for solar coronal heating and the coronal helium and neon abundances, Astrophys. J. 695, 954 doi: 10.1088/0004-637X/695/2/954

Laming, J.M.: 2015, The FIP and inverse FIP effects in solar and stellar coronae, Living Reviews in Solar Physics, 12, 2 doi: 10.1007/lrsp-2015-2

Lee, M.A.: 1983, Coupled hydromagnetic wave excitation and ion acceleration at interplanetary traveling shocks, J. Geophys. Res., 88, 6109 doi: 10.1029/JA088iA08p06109

Lee, M.A.: 2005, Coupled hydromagnetic wave excitation and ion acceleration at an evolving coronal/interplanetary shock, Astrophys. J. Suppl., 158, 38 doi: 10.1086/428753

Lee, M.A., Mewaldt, R.A., Giacalone, J.: 2012, Shock acceleration of ions in the heliopause, Space Sci. Rev., 173, 247, doi: 10.1007/s11214-012-9932-y

Lodders, K., Palme, H., Gail, H.-P.: 2009, Abundances of the elements in the solar system, In: Trümper, J.E. (ed.) Landolt-Börnstein, New Series VI/4B, Springer, Berlin. Chap. 44, 560.

Luhn, A., Klecker B., Hospes, D., Gloeckler, G., Ipavich, F.M., Scholer, M., Fan, C.Y. Fisk, L.A.: 1984, Ionic charge states of N, Ne, Mg, Si and S in solar energetic particle events, Adv. Space Res. 4, 161 doi: 10.1016/0273-1177(84)90307-7

Mason, G.M.: 2007 3He-rich solar energetic particle events, Space Sci. Rev. 130, 231 doi: 10.1007/s11214-007-9156-8

Mason, G.M., Mazur, J.E., Dwyer, J.R.: 2002, A new heavy ion abundance enrichment pattern in 3He-rich solar particle events, Astrophys. J. Lett. 565, L51 doi: 10.1086/39135

Mason, G.M., Mazur, J.E., Dwyer, J.R., Jokippi, J.R., Gold, R.E., Krimigis, S.M.: 2004, Abundances of heavy and ultraheavy ions in 3He-rich solar flares, Astrophys. J. 606, 555 doi: 10.1086/382864

Mason, G.M., Ng, C.K., Klecker, B., Green, G.: 1989, Impulsive acceleration and scatter-free transport of about 1 MeV per nucleon ions in 3He-rich solar particle events, Astrophys. J. 339, 529 doi: 10.1086/167315

Mazzotta, P., Mazzitelli, G., Colafrancesco, S, Vittorio, N.: 1998, Ionization balance for optically thin plasmas: Rate coefficients for all atoms and ions of the elements H to Ni, Astron. Astrophys Suppl. 133, 403 doi: 10.1051/aas:1998330

Mewaldt, R.A., Cohen, C.M.S., Leske, R.A., Christian, E.R., Cummings, A.C., Stone, E.C., von Rosenvinge, T.T., Wiedenbeck, M.E.: 2002, Fractionation of solar energetic particles and solar wind according to first ionization potential, Advan. Space Res. 30 79 doi: 10.1016/S0273-1177(02)00263-6

Mewaldt, R.A., Cohen, C.M.S., Labrador, A.W., Leske, R.A., Mason, G.M., Desai, M.I., Looper, M.D., Mazur, J.E., Selesnick, R.S., Haggerty, D.K.: 2005, Proton, helium, and electron spectra during the large solar particle events of October-November 2003, J. Geophys. Res. 110 A09S18 doi: 10.1029/2005JA011038

Meyer, J.-P.: 1985, The baseline composition of solar energetic particles, Astrophys. J. Suppl. 57, 151, doi: 10.1086/191000

Ng, C.K., Reames, D.V.: 2008, Shock acceleration of solar energetic protons: the first 10 minutes, Astrophys. J. Lett. 686, L123 doi: 10.1086/592996

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Ng, C.K., Reames, D.V., Tylka, A.J.: 1999, Effect of proton-amplified waves on the evolution of solar energetic particle composition in gradual events, *Geophys. Res. Lett.* 26, 2145 doi: 10.1029/1999GL900459

Ng, C.K., Reames, D.V., Tylka, A.J.: 2001, Abundances, spectra, and anisotropies in the 1998 Sep 30 and 2000 Apr 4 large SEP events, *Proc. 27th Int. Cosmic-Ray Conf.* (Hamburg), 8, 3140

Ng, C.K., Reames, D.V., Tylka, A.J.: 2003, Modeling shock-accelerated solar energetic particles coupled to interplanetary Alfvén waves, *Astrophys. J.* 591, 461, doi: 10.1086/375293

Ng, C.K., Reames, D.V., Tylka, A.J.: 2012, Solar energetic particles: Shock acceleration and transport through self-amplified waves, *AIP Conf. Proc.* 1436 212, doi: 10.1063/1.4723610

Parker, E.N.: 1963 *Interplanetary Dynamical Processes*, Interscience, New York.

Reames, D.V.: 1988, Bimodal abundances in the energetic particles of solar and interplanetary origin, *Astrophys. J. Lett.* 330, L71 doi: 10.1086/185207

Reames, D.V.: 1995, Coronal Abundances determined from energetic particles, *Adv. Space Res.* 15 (7), 41.

Reames, D.V.: 1999, Particle acceleration at the sun and in the heliosphere, *Space Sci. Rev.* 90, 413 doi: 10.1023/A:1005105831781

Reames, D.V.: 2000, Abundances of trans-iron elements in solar energetic particle events, *Astrophys. J. Lett.* 540, L111 doi: 10.1086/312886

Reames, D.V.: 2009, Solar release times of energetic particles in ground-level events, *Astrophys. J.* 693, 812 doi: 10.1088/0004-637X/693/1/812

Reames, D.V.: 2013, The two sources of solar energetic particles, *Space Sci. Rev.* 175, 53, doi: 10.1007/s11214-013-9958-9

Reames, D.V.: 2014, Element abundances in solar energetic particles and the solar corona, *Solar Phys.* 289, 977 doi: 10.1007/s11207-013-0350-4

Reames, D.V.: 2015, What are the sources of solar energetic particles? Element abundances and source plasma temperatures, *Space Sci. Rev.* 194: 303, doi: 10.1007/s11214-015-0210-7.

Reames, D.V.: 2016a, Temperature of the source plasma in gradual solar energetic particle events, *Solar Phys.* 291 911, doi: 10.1007/s11207-016-0854-9

Reames, D.V.: 2016b, The origin of element abundance variations in solar energetic particles, *Solar Phys.* 291 2099, doi: 10.1007/s11207-016-0942-x

Reames D.V.: 2017a, *Solar Energetic Particles*, Lecture Notes in Physics 932, Springer, Berlin, ISBN 978-3-319-50870-2, doi: 10.1007/978-3-319-50871-9.

Reames, D.V.: 2017b, Spatial distribution of element abundances and ionization states in solar energetic-particle events, *Solar Phys.* 292 133 doi: 10.1007/s11207-017-1138-8 (arXiv 1705.07471).

Reames, D.V.: 2017c, The abundance of helium in the source plasma of solar energetic particles, *Solar Phys.* 292 156 doi: 10.1007/s11207-017-1173-5 (arXiv: 1708.05034)

Reames, D.V., 2018a The “FIP effect” and the origins of solar energetic particles and of the solar wind, *Solar Phys.* 293 47 doi: 10.1007/s11207-018-1267-8 (arXiv 1801.05840)

Reames, D.V.: 2018b, Abundances, ionization states, temperatures, and FIP in solar energetic particles, *Space Sci. Rev.* 214 61, doi: 10.1007/s11214-018-0495-4 (arXiv: 1709.00741)

Reames, D.V.: 2018c, Corotating shock waves and the solar-wind source of energetic ion abundances: Power laws in A/Q, *Solar Phys* 293 144 doi: 10.1007/s11207-018-1369-3 (arXiv: 1808.06132)
Reames, D.V.: 2019a, Helium suppression in impulsive solar energetic-particle events, *Solar Phys.* submitted (arXiv: 1812.01635)

Reames, D.V.: 2019b, Hydrogen and the abundances of elements in impulsive solar energetic-particle events, *Solar Phys.* submitted (arXiv 1901.04369)

Reames, D.V., Ng, C.K.: 2004, Heavy-element abundances in solar energetic particle events, *Astrophys. J.* 610, 510 doi: 10.1086/421518

Reames, D.V., Ng, C.K.: 2010, Streaming-limited intensities of solar energetic particles on the intensity plateau, *Astrophys. J.* 723 1286 doi: 10.1088/0004-637X/723/2/1286

Reames, D.V., Stone, R.G.: 1986, The identification of solar $^3$He-rich events and the study of particle acceleration at the sun, *Astrophys. J.*, 308, 902 doi: 10.1086/164560

Reames, D.V., Barbier, L.M., Ng, C.K.: 1996, The spatial distribution of particles accelerated by coronal mass ejection-driven shocks, *Astrophys. J.* 466 473 doi: 10.1086/177525

Reames, D.V., Barbier, L.M., von Rosenvinge, T.T., Mason, G.M., Mazur, J.E., Dwyer, J.R.: 1997, Energy spectra of ions accelerated in impulsive and gradual solar events, *Astrophys. J.* 483, 515 doi: 10.1086/304229

Reames, D.V., Cliver, E.W., Kahler, S.W.: 2014a, Abundance enhancements in impulsive solar energetic-particle events with associated coronal mass ejections, *Solar Phys.* 289, 3817 doi: 10.1007/s11207-014-0547-1

Reames, D.V., Cliver, E.W., Kahler, S.W.: 2014b, Variations in abundance enhancements in impulsive solar energetic-particle events and related CMEs and flares, *Solar Phys.* 289, 4675 doi: 10.1007/s11207-014-0589-4

Reames, D.V., Cliver, E.W., Kahler, S.W.: 2015, Temperature of the source plasma for impulsive solar energetic particles, *Solar Phys.* 290, 1761 doi: 10.1007/s11207-015-0711-2

Reames, D.V., Kahler, S.W., Ng, C.K.: 1997, Spatial and temporal invariance in the spectra of energetic particles in gradual solar events, *Astrophys. J.* 491, 414 doi: 10.1086/304939

Reames, D.V., Meyer, J.P., von Rosenvinge, T.T.: 1994, Energetic-particle abundances in impulsive solar flare events, *Astrophys. J.* Suppl. 90, 649 doi: 10.1086/191887

Reames, D.V., Ng, C.K., Tylka, A.J.: 2000, Initial time dependence of abundances in solar particle events, *Astrophys. J. Lett.* 531 L83 doi: 10.1086/312517

Reames, D.V., von Rosenvinge, T.T., Lin, R.P.: 1985, Solar $^3$He-rich events and nonrelativistic electron events - A new association, *Astrophys. J.* 292, 716 doi: 10.1086/163203

Roth, I., Temerin, M.: 1997, Enrichment of $^3$He and Heavy Ions in Impulsive Solar Flares, *Astrophys. J.* 477, 940 doi: 10.1086/303731

Rouillard, A., Sheeley, N.R. Jr., Tylka, A., Vourlidas, A., Ng, C.K., Rakowski, C., Cohen, C.M.S., Mewaldt, R.A., Mason, G.M., Reames, D., et al.: 2012, The longitudinal properties of a solar energetic particle event investigated using modern solar imaging, *Astrophys. J.* 752, 44 doi: 10.1088/0004-637X/752/1/44

Schmelz, J.T., Reames, D.V., von Steiger, R., Basu, S.: 2012, Composition of the solar corona, solar wind, and solar energetic particles, *Astrophys. J.* 755 33 doi: 10.1088/0004-637X/755/1/33

Serlemitsos, A.T., Balasubrahmanyan, V.K.: 1975, Solar particle events with anomalously large relative abundance of $^3$He, *Astrophys. J.* 198, 195 doi: 10.1086/153592

Telerin, M., Roth, I.: 1992, The production of $^3$He and heavy ion enrichment in $^1$He-rich flares by electromagnetic hydrogen cyclotron waves, *Astrophys. J. Lett.* 391, L105 doi: 10.1086/186408
Tylka, A.J., Cohen, C.M.S., Dietrich, W.F., Lee, M.A., Maclennan, C.G., Mewaldt, R.A., Ng, C.K., Reames, D.V.: 2005, Shock geometry, seed populations, and the origin of variable elemental composition at high energies in large gradual solar particle events, Astrophys. J. 625, 474 doi: 10.1086/429384

Tylka, A.J., Lee, M.A.: 2006, Spectral and compositional characteristics of gradual and impulsive solar energetic particle events, Astrophys. J. 646, 1319 doi: 10.1086/505106

Webber, W.R.: 1975, Solar and galactic cosmic ray abundances - A comparison and some comments. Proc. 14th Int. Cosmic Ray Conf, Munich, 5 1597

von Rosenvinge, T.T., Barbier, L.M., Karsch, J., Liberman, R., Madden, M.P., Nolan, T., Reames, D.V., Ryan, L., Singh, S., Trexel, H.: 1995, The Energetic Particles: Acceleration, Composition, and Transport (EPACT) investigation on the Wind spacecraft, Space Sci. Rev. 71 152 doi: 10.1007/BF00751329

Zank, G.P., Rice, W.K.M., Wu, C.C.: 2000, Particle acceleration and coronal mass ejection driven shocks: A theoretical model, J. Geophys. Res., 105, 25079 doi: 10.1029/1999JA0004551