Hydrogen Abundances and Shock Waves

9

Abstract

How well do protons fit into the abundance patterns of the other elements? Protons have $Q = 1$ and $A/Q = 1$ at all temperatures of interest. When does their relative abundance fit on the power law in A/Q defined by the elements with $A/Q > 2$? For small “pure” impulsive events, protons fit well, but for larger CME-associated impulsive events, where shock waves boost the intensities, protons are enhanced a factor of order ten by addition of seed protons from the ambient plasma. During most large gradual SEP events with strong shock waves, protons again fit the power law, but with weaker or quasi-perpendicular shock waves, dominated by residual impulsive seed particle abundances at high Z , again protons are enhanced. Proton enhancements occur when moderately weak shock waves happen to sample a two-component seed population with dominant protons from the ambient coronal plasma and impulsive suprathermal ions at high Z ; thus proton-enhanced events are a surprising new signature of shock acceleration in jets. A/Q measures the rigidity dependence of both acceleration and transport but does not help us distinguish the two. Energy-spectral indices and abundances are correlated for most gradual events but not when impulsive ions are present; thus we end with powerful new correlations that probe both acceleration and transport.

There are substantial variations in the abundances of elements from event to event in SEPs. It was a leap of faith to assume that most of those variations could be explained by differing source plasma temperatures plus a smooth power-law dependence upon A/Q . Only the element He seems to vary, because of its FIP, from the average coronal abundance underlying SEPs. However, we have not yet considered protons. Should we expect protons to fit the power law?

Proton abundances in the solar wind, as measured by He/H, vary by a factor of about five with the solar cycle depending on the wind speed (Kasper et al. 2007).

Most of this variation is in H, since more modest variations of He/O are seen in the solar wind as functions of time and of solar-wind speed (Collier et al. 1996; Bochsler 2007; Rakowsky and Laming 2012). However, in Chap. 8 we have seen that SEP abundances are not related to those of the solar wind. Different physics.

With the exception of protons, elements in SEPs are “test particles” which are influenced by the electromagnetic fields they encounter but are too rare to alter those fields significantly. When streaming protons reach sufficient intensities, they can amplify or generate resonant waves of sufficient intensities to alter the behavior of all ions that follow behind. The power-law of enhancements vs. A/Q might be expected to break down when different particle species encounter different interplanetary scattering conditions at different resonant frequencies that have been varying with space and time (Chap. 5; Reames et al. 2000; Ng et al. 1999, 2003, 2012). For what circumstances does the power law from high Z predict the intensity of protons?

9.1 Impulsive SEP Events

Figure 9.1 begins the study with two very small impulsive SEP events. For these small events, an extension, down to protons at $A/Q = 1$, of the power law fit of enhancement vs. A/Q from the elements with $Z \geq 6$, fits extremely well for the energies shown in the figure, despite some scatter of the elements that define the fit. These cases seem typical for the smallest impulsive SEP events (Reames 2019b).

Of the 111 impulsive SEP events studied and listed by Reames et al. (2014), 70 had measurable proton intensities not buried in background. It is interesting that even for the “He-poor” impulsive events (see Fig. 4.12; Reames et al. 2014; Reames 2019a) we find that the fit lines often predict the proton abundances accurately, as shown in Fig. 9.2. Here, the protons fit the power law in Event 35 while the suppression of He seems completely unrelated. This is the case for most of the small He-poor impulsive SEP events. However, as a counter-example, protons exceed the expected value in Event 34, perhaps because of background from a small prior event in this case.

Figure 9.3 shows two well-known large impulsive SEP events (see e.g. Fig. 3.2). In both events, protons exceed the values predicted by the power-law fit by more than an order of magnitude. For Event 49 the pre-event background of protons might contribute, in principle, but they do not explain the proton excess. For Event 37, the very low intensity of pre-event protons could certainly not be a factor. Events 37 and 49 have associated CMEs with speeds of 1360 and 840 km s⁻¹, respectively (Reames et al. 2014).

In the case of Event 37, particle angular distributions present some evidence that protons undergo additional scattering, which may depend upon rigidity, in comparison with other ions of the same velocity (Reames 2019b). However, other events show no evidence of this, so it is not a common factor that causes proton excesses. Most impulsive SEP events are nearly scatter-free. The presence of significant CME speeds suggests that shock waves are the important factor.

Fig. 9.1 Intensities of H, He, O, and Fe (lower-left) and normalized abundance enhancements H/O and Fe/O (upper-left) are shown versus time for two impulsive SEP events. Event numbers 3 and 4, marking the event onset times, refer to the list of Reames et al. (2014); the solar source coordinates are also listed. The right panels show enhancements, relative to average SEP coronal abundances, labeled by Z , versus A/Q for each event, with best-fit power law for elements with $Z \geq 6$ (blue line) extrapolated down to protons at $A/Q = 1$ (Reames 2019b)

It is when we consider the size or intensity of events that differences begin to become clearer as seen in Fig. 9.4. The ratio of observed proton enhancement to that expected from the least-squares fit, i.e. the proton excess, is shown on the abscissa. A value of 1.0 implies that the protons agree with the fit from $Z > 2$ ions. Figure 9.4a shows that, for small events with higher anisotropy, protons are more likely to fit. Figure 9.4b shows that small events tend to fit while increasingly larger ones do not. Figure 9.4c shows a histogram of the overall distribution for impulsive SEP events.

Statistically, for 24% of the events in Fig. 9.4 protons are within one standard deviation of the least-squares fit line. However, a possible explanation for the proton excess in larger impulsive SEP events comes when we consider the speed of associated CMEs, if any, found by Reames et al. (2014) as shown in Fig. 9.5. Fast CMEs tend to be associated with those intense events where protons fall a factor of ten or more above the fitted line. Events with CME speeds above $\approx 500 \text{ km s}^{-1}$ are likely to drive shock waves that can boost the energies and intensities of the SEPs from the impulsive event and also dip into ambient coronal protons. Excess protons

Fig. 9.2 Intensities of H, He, O, and Fe (lower-left) and normalized abundance enhancements H/O and Fe/O (upper-left) are shown versus time for two He-poor impulsive SEP events. Event numbers 34 and 35, marking the event onset times, refer to the list of Reames et al. (2014); the solar source coordinates are also listed. The right panels show enhancements, relative to SEP coronal abundances, labeled by Z , versus A/Q for each event, with best-fit power law for elements with $Z \geq 6$ (blue line) extrapolated down to protons at $A/Q = 1$ (Reames 2019b)

may be evidence of a shock wave driven by the CME associated with the same jet that produced energetic ions, i.e. jets with fast CME-driven shock waves accelerate protons from the ambient plasma along with the reaccelerated $Z > 2$ impulsive seed particles with $T \approx 3$ MK from the reconnection.

In impulsive SEP events, at a source temperatures of ≈ 3 MK, He and C are fully ionized and O is nearly so. Thus variations in the abundances of these ions, such as He/C, reflect variations in the source itself, rather than in acceleration or transport. Figure 9.6 shows how various properties of impulsive events associate with relative O/C vs. He/C variations. The larger impulsive events with fast CMEs and proton excesses have higher average reference He/O. These events are less ^3He -rich, perhaps because larger events have depleted the available ^3He (Sect. 2.5.2). CMEs with speeds above 500 km s^{-1} are easily capable of accelerating ions that are pre-accelerated in the magnetic reconnection region of the impulsive jet event. Smaller events do not have proton excesses, but may or may not have suppressed He.

Fig. 9.3 Intensities of H, He, O, and Fe (lower-panels) and normalized abundance enhancements H/O and Fe/O (center-panels) are shown versus time for two large impulsive SEP events. Event numbers 37 and 49, marking the event onset times, refer to the list of Reames et al. (2014); the solar source locations are also listed. The upper panels show enhancements, relative to SEP coronal abundances, labeled by Z , versus A/Q for each event, with best-fit power law for elements with $Z \geq 6$ (blue line) extrapolated down to protons at $A/Q = 1$ (Reames 2019b)

Fig. 9.4 Panel (a): the front/back directional anisotropy of protons during the first 6 h of impulsive SEP events is shown versus the observed enhancement of H relative to that expected from the power-law fit for elements $Z \geq 6$ for 70 impulsive SEP events; the symbol size and color show the peak 2-MeV proton intensity of each event. Panel (b) shows the peak proton intensity versus the observed/expected H ratio for each event, and panel (c) shows a histogram of the distribution of observed/expected H enhancement ratio. An observed/expected enhancement of H = 1 is shown as a solid line in panels (a) and (b) (Reames 2019b)

9.2 Gradual SEP Events

For gradual SEP events, the power-law fit to the abundance enhancements versus A/Q often varies with time during an event, so we consider 8-h intervals which usually provide adequate statistics for abundance measurements.

Fig. 9.5 The peak proton intensity of impulsive SEP events is shown versus the observed/expected H ratio for each event. The color and size of the circle show the speed of the associated CME, if any is seen. An observed/expected H enhancement = 1 is shown as a solid line

Figure 9.7 shows the analysis of two events of the “Halloween” series in October 2003 (Reames 2019c). This analysis is similar to that described for Fig. 5.13. Least-squares power-law fits of abundance enhancements are shown for each time interval in Fig. 9.7e using A/Q values for the temperature minimum of χ^2/m determined in Fig. 9.7d and shown in Fig 9.7c. As in all similar fits, the observed abundances are divided by the reference coronal abundances to determine enhancements, all relative to O. Fit lines determined for the elements with $Z > 2$ are extended to $A/Q = 1$ and compared with protons in Fig 9.7e. Here the agreement is reasonably good, even when there are sudden large changes in slope as in the case between the last two time periods near the bottom of panel Fig 9.7e.

A typical gradual event where protons exceed the prediction is an event with impulsive suprathermal seed ions and $T \approx 3$ MK, as shown in Fig. 9.8. Here, the dashed lines down to $A/Q = 1$ in Fig. 9.8e show a broken power law with significant proton excesses.

We see the distribution of all 8-h gradual-event intervals in Fig. 9.9. The *upper panel* shows a histogram of the distribution of proton excess versus slope or power of the A/Q of the fit while the lower panels show the distribution for different source temperatures.

For most gradual-event periods, with source plasma temperatures below 2 MK and declining slope versus A/Q , the proton intensities are predicted within a factor of order 2 or 3, by the ions with $Z > 2$. However, the $\sim 25\%$ of gradual events with $T > 2$ MK and positively sloping intensities versus A/Q , have persistent large proton excesses; these are the events dominated by impulsive seed ions.

Fig. 9.6 Each panel shows normalized abundances of O/C versus He/C with errors $<20\%$ for impulsive SEP events with temperature, proton excess, 2 MeV proton intensity, CME speed, and $^3He/^4He$ ratio highlighted by color and size of the points, as indicated. Dashed lines indicate reference abundances of $He/O = 57$ and 91 . Note that the larger events with faster CMEs have higher average He/O and have limited $^3He/^4He$ (Reames 2019d)

Fig. 9.7 Panel (a) shows intensities of H, He, O, Fe, and $50 \leq Z \leq 56$ ions (energies in MeV amu^{-1}), (b) normalized abundance enhancements H/O and Fe/O, and (c) derived source temperatures are shown versus time for the 26 and 28 October 2003 SEP events. Panel (d) shows χ^2/m versus T for each 8-h interval while (e) shows enhancements, labeled by Z , versus A/Q for each 8-h 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 (2016) in (b) (Reames 2019c). Event 21 is a GLE

The lower panel in Fig. 9.10 shows source temperature in a plot of O/C vs. He/C for gradual SEP events at the same scale as that for impulsive SEP events in Fig. 9.6. Upper panels show temperature, proton excess, and 20-MeV proton intensity on panels of normalized Fe/O vs. He/C.

Fig. 9.8 Panel (a) shows intensities of H, He, O, Fe, and $50 \leq Z \leq 56$ ions, (b) normalized abundance enhancements H/O and Fe/O, and in (c) temperatures are shown versus time for the 14 November 1998 SEP event. Panel (d) shows χ^2/m versus T for each 8-h interval while (e) shows enhancements, labeled by Z, versus A/Q for each 8-h interval shifted $\times 0.1$, 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 (2016) in (b) (Reames 2019c)

The upper panels in Fig. 9.10 show that events in the higher temperature range ≈ 3 MK, which involve reaccelerated impulsive seed ions, also have the large proton excesses as we saw in Fig. 9.9. These events have modest intensities of 20-MeV protons and lower average shock speeds (Reames 2019d). Like the impulsive events

Fig. 9.9 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-h 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 (Reames 2019c)

Fig. 9.10 The lower panel shows normalized abundances of O/C versus He/C for 8-h intervals during gradual SEP events with temperature as the size and color of the points. The upper panels show Fe/O vs. He/C with temperature, proton excess, and 20-MeV proton intensity for each interval highlighted by color and size of the points. Dashed lines indicate reference abundances of $\text{He/O} = 57$ and 91

with CMEs in Fig. 9.6 they have higher He/C ratios. In contrast, the biggest gradual events, with the highest intensities of 20-MeV protons, lie on the low-He/C side of Fig. 9.10 and they lack proton excesses. These measurements drift to lower values of Fe/O with time during each event at constant He/C.

The lowest panels of Figs. 9.6 and 9.10 compare impulsive and gradual events, respectively, at the same scale. The gradual events have much smaller intrinsic abundance variations, such as He/C, especially if we restrict the sample to $T > 2$ MK impulsive suprathermal seed particles. This comparison was already seen in Fig. 5.19 and will be discussed below. Sampling seed ions from a pool fed by many small impulsive events reduces the abundance variation.

9.3 Waves Coupling Proton Velocity with A/Q

When we compare ions at the same velocity, as we do when we study the power-law dependence on A/Q , those ions interact with different parts of the ambient or proton-generated wave spectrum. Neglecting pitch angle variations, for example, 2.5 MeV protons resonate with waves generated by streaming 2.5 MeV protons. However, 2.5 MeV amu^{-1} He, C, and O with $A/Q = 2$ resonate with waves generated by streaming 10 MeV protons, and 2.5 MeV amu^{-1} Fe at $A/Q = 4$ resonates with the wave spectrum generated by streaming 39 MeV protons; at $T = 1$ MK, 2.5 MeV amu^{-1} Fe has $A/Q = 6.1$ and resonates with protons near 90 MeV. Thus the shape of the A/Q dependence is related to the shape of the proton spectrum and its time dependence, since high-energy protons arrive earlier to modify the wave spectrum that resonates with the ions with high A/Q . The time behavior in large events is complicated and its A/Q dependence has not been modeled extensively.

There are some gradual events that have excess protons early in the events but the expected numbers of protons later. In these events, the initial abundance ratios are affected by hard proton spectra as described in the large gradual event of 30 September 1998 discussed in Sect. 5.1.4 and shown in Fig. 5.2. Here high-energy protons arrive first and create resonant waves that scatter He and the heavier ions of a given velocity while the protons of that velocity are just beginning to be scattered by self-generated waves. This process suppresses He/H initially in Fig. 5.2, i.e. it effectively increases H/He and creates excess protons. An excess of protons actually means that for a given proton intensity the heavier ions are suppressed (see Reames 2020a).

9.4 Compound Seed Particles

The SEP events with shock acceleration may sample a complex seed population. Are the protons sampled from the same component of this seed population as the other ions? When the heavy-ion abundances increase with A/Q , they may be sampled from

Fig. 9.11 (a) Element enhancements, labeled by Z , versus A/Q for impulsive Event 54 (20 February 2002), together with possible sources for shock acceleration from pre-accelerated impulsive ions (blue, SEP1) and ambient corona or pre-event plasma (red). Helium may receive comparable contributions from both sources in this event (Reames 2019b, d). Panel (b) shows possible selection of seed particle H (solid) and O (dashed) from ambient (red) and harder pre-accelerated impulsive (blue SEP1) spectra by shock waves with different threshold energies (Reames 2020a)

pre-accelerated impulsive suprathermal ions that have $T \approx 3$ MK. The protons in that population are already suppressed, but ambient coronal material is also available for shock acceleration. This situation has been described by Reames (2019b, d, 2020a) and shown in Fig. 9.11a. Here, impulsive Event 54 on 20 February 2002 (from the

list in Reames et al. 2014) with a CME of 954 km s^{-1} may include shock-accelerated protons predominantly from the ambient corona (red source) plus ions with $Z \geq 2$ mainly from a local impulsive jet magnetic-reconnection source (blue source labeled SEP1). The red components show a decreasing slope in A/Q , typical of shock-accelerated coronal plasma, while the original slope of the blue component retains most of its steep positive dependence on A/Q . The lower temperature of the (red) coronal material in Fig. 9.11a decreases Q and raises the A/Q for heavier ions like C, O, and etc.

Figure 9.11b shows possible seed-particle spectra of H and O (representing other heavy ions) with appropriate abundances for ambient thermal ions and for an assumed harder spectrum of pre-accelerated impulsive suprathermal ions (labeled as SEP1). The combination of spectral hardness and abundances of the seeds allow weaker shocks to sample both populations while strong shocks are dominated by the more-abundant ambient ions throughout.

This is a possible explanation for the impulsive events with observed proton excesses, but Fig. 9.11 applies to gradual SEP events as well. Of course, for gradual SEP events the shocks must just happen to encounter the pools of impulsive suprathermal ions in order to include them. Also, the extremely fast, wide shocks in most gradual events may sweep up ambient coronal material so efficiently that the impulsive suprathermal ions become negligible, and all ions, including protons, fit on the same power law of the SEP ions. However, the smaller gradual events with weaker shock waves favor the residual impulsive suprathermal ions swept up from a large region by the wide shock; only protons from the ambient coronal plasma are able to predominate. The preference for the higher-velocity seed particles is enhanced when quasi-perpendicular shock waves are involved where ions downstream must be fast to overtake the shock to continue the acceleration (Tylka et al. 2005; Tylka and Lee 2006).

In Fig. 9.10 (and also in Fig. 9.6) the proton excess shows a tendency to increase as a function of He/C. It is possible that events with high proton excess accelerated from ambient coronal material also have a component of He from the same source as the protons.

Figure 9.12 shows the distinction between the similar process in impulsive and gradual events. Both involve moderately weak shocks. In both, impulsive suprathermal seed ions with $T \approx 3 \text{ MK}$ dominate high Z while ambient plasma dominates the protons and occasionally the He. The essential difference is that each impulsive event probably involves a single jet source, for which seed abundances may vary locally from event to event, while the wide shock in the gradual events sweeps up suprathermal residue from a pool of many (N) impulsive jet sources that has been accumulating, reducing abundance variations by a factor of $\sqrt{N}$. The residue from many jets has been observed to collect in large regions for substantial periods of time, so that these ^3He -rich, Fe-rich pools of suprathermal ions are often seen (see regions labeled A and B in Fig. 2.8, for example; Desai et al. 2003; Bučík

Fig. 9.12 Suggested explanations for (a) the broad distribution of source abundances in impulsive events from variations in single localized jet events where ejecta may (SEP2) or may not (SEP1) drive shocks, and (b) the narrow distribution in high- T gradual events where pre-accelerated impulsive seed populations from a pool of many small individual jets are averaged by a large shock (SEP3). Abundance distributions shown (from Fig. 5.19) are equivalent to those that were shown in the lower panels of Figs. 9.6, and 9.10

et al. 2014, 2015, 2018a, b; Chen et al. 2015). The number of small flares increases logarithmically with decreasing size, leading Parker (1988) to propose that nanoflares were sufficiently numerous to heat the solar corona. Jets, being the open-field version of flares, may increase similarly, so that many small jets, perhaps we should call them microjets or even nanojets, contribute the seed population for the gradual SEP events with high- Z enhancements and $T \approx 3$ MK.

While the model impulsive SEP event involves a single jet, we can certainly imagine a region of magnetic reconnection that is extensive enough to involve several individual jets at a given time. Element abundances from these compound regions might tend toward average impulsive SEP abundances as the gradual events do. Perhaps this is why the smallest impulsive SEP events tend to have the largest abundance variations—they involve smaller regions with less averaging.

Fig. 9.13 Histograms compare the speed (left panels) and width (right panels) distributions of CMEs associated with impulsive (upper panels) and gradual (lower panels) SEP events. The “?” indicates events with no known CME association, often for lack of coverage (Reames 2019d)

9.5 CME Associations of Impulsive and Gradual Events

Figure 9.13 reviews the CME associations of impulsive and gradual SEP events. Simply by selecting events based upon the Fe/O ratio to initially define our impulsive events (Fig. 4.1), we have found significant differences in the nature and properties of the associated CMEs involved.

In Fig. 9.14, we examine the events based upon source plasma temperature T . The events with $T > 1.9$ MK that involve reaccelerated impulsive ions tend to involve slower, weaker CMEs. Events with the fastest CMEs and shocks accelerate the cooler ambient plasma.

The smaller gradual events with the hotter (≈ 3 MK) reaccelerated impulsive-SEP source plasma not only involve slower, weaker CMEs, but may also involve quasi-perpendicular shock waves (not shown). These events with $T \approx 3$ MK tend to arrive early in solar cycle 23 and the weaker solar cycle 24. Faster CMEs that occur later in cycle 23 tend to be dominated by cooler ambient coronal plasma of which they

Fig. 9.14 CME speed is shown for gradual SEP events as a function of time, with source plasma temperatures indicated in the lower panel. CME speed distributions for gradual SEP events, with $T < 1.9$ MK (SEP4) and $T > 1.9$ MK (SEP3), are shown in the middle and upper panels, respectively (Reames 2019d)

sample deeply—these more powerful events have less need for pre-accelerated ions. Like all SEP events, all solar cycles are not the same.

9.6 Four Subtypes of SEP Events

Thus, inclusion of protons in SEP abundance patterns leads to the suggestion of four types of SEP events (after Reames [2019d](#), [2020a](#)):

1. SEP1—Pure Impulsive: “Pure,” shock-free impulsive SEP events accelerate ions in islands of magnetic reconnection in solar jets. Element abundance enhancements increase as a power law in A/Q from H to elements as heavy as Pb derived from $T \approx 3$ MK plasma; they can be distinguished initially by Fe/O that is over four times the coronal value and confirmed by the lack of any proton excess. He/O is normally high, but may be greatly suppressed in occasional events perhaps by a rapid rise of ionized material that may be too fast to allow much ionization of high-FIP He. Abundant electrons streaming out from the event generate waves that are resonantly absorbed by ^3He ; these electrons produce a type III radio burst. Plasma may also be ejected from the event, producing a narrow CME that is too slow to drive a significant shock wave.
2. SEP2—Impulsive + Shock: An impulsive event occurs when the narrow CME from a jet, that of an otherwise pure impulsive SEP1 event, drives a fast shock wave. The shock wave samples all available ions, those from the ambient plasma and residual energetic ions from the SEP1 event. The abundant ambient protons form the wave structure at the shock and dominate at $Z = 1$, but the pre-enhanced, pre-accelerated, $T \approx 3$ MK ions dominate the $Z > 2$ region because they are favored by the weak shock. This appears as a large 10-fold proton excess.
3. SEP3—Weak Gradual with Impulsive Seeds: A moderately-fast, wide CME from an eruptive event drives a moderately-fast shock wave producing a gradual SEP event. The sampled shock region may be quasi-perpendicular (or just weak) so its dominant contribution from sampling of ambient plasma is limited mainly to protons, while preferring the faster residual impulsive suprathermal ions surviving in pools of a dozen or more previous impulsive SEP events from small jets that combine to produce well-defined average impulsive-SEP abundances for $Z > 2$. These gradual events have substantial proton excesses plus the $T \approx 3$ MK, high- Z signature of the impulsive seed particles.
4. SEP4—Pure Gradual: A fast, wide CME from an eruptive event drives a fast shock wave that expands broadly, producing an energetic gradual SEP event that lasts many days. If the shock is quasi-parallel or samples deeply into the tail of the thermal distribution of the ambient plasma with $T < 2$ MK, it will produce a “pure” gradual event with dominant coronal ion abundances modified by a power-law dependence on A/Q that may be enhanced or suppressed during ion transport. Protons generally fit with other ions although some regions of unusual transport may produce modest local excesses or depletions of protons. Any impulsive suprathermal ions present are also accelerated by the shock, but their contribution is overwhelmed by the accelerated ambient coronal ions; these shocks do not need pre-accelerated ions. Small, weak shocks may also join this category when they find no suprathermal ions to accelerate.

The inclusion of protons in abundance studies has provided surprising new information on the underlying physics in SEP events. More generally, the study of power-law patterns in the A/Q -dependence of element abundance enhancements has provided an important new source of information on the difficult-to-obtain temperature and origin of the ions accelerated as SEPs, on the physical processes involved, and on the nature of the solar corona.

9.7 Spatial Distributions

Proton abundances can clarify the pattern of abundances and their spatial distribution, even when H is not included in the power-law fit of the abundances. Figure 9.15 shows power-law fits as a function of time for three widely separated spacecraft for the 23 January 2012 SEP event. Protons were not included in the original study of this event (Reames 2017) and the power-law fits seemed to be disrupted by a spectral break, and of poor quality. However, when we include H in Fig. 9.15, it is clear that the power-law fits of high- Z elements point directly toward the protons in most cases. H validates the power-law behavior and marks this as an SEP4-class event—viewed from any longitude.

Early in the event in Fig 9.15d, the power-law fits are extremely flat at the well-connected *Wind* spacecraft, i.e. the SEP abundances are nearly coronal, so it is difficult to determine a plasma temperature. Later, as the higher-rigidity heavy ions at higher A/Q leak away, the increasing slope defines a temperature of 1.3 ± 0.3 MK (see Fig. 3 of Reames 2019c).

Intensities are considerably lower at the STEREO spacecraft than at *Wind* and, unfortunately, geometry factors are also an order-of-magnitude smaller for the STEREO instruments, so the STEREO abundances are more poorly defined, especially STEREO B. However, the trends in the data are clear.

By the time the shock (S in Fig. 9.15a, b) has reached about 2 AU, STEREO A shares a magnetic reservoir (Sect. 5.7) with *Wind*, and all ion intensities become spatially uniform, declining with time as the magnetic “bottle” containing them expands. Reservoirs treat differing energies and rigidities of ions invariantly. STEREO B does not sample this reservoir and intensities there are much lower late in the event.

9.8 Rigidity-Dependence: Acceleration or Transport?

By now, one might conclude that the average acceleration by shocks has minimal dependence upon rigidity (i.e. upon A/Q). If we exclude reacceleration of impulsive suprathermal ions, which have a built-in dependence on A/Q , the dependence we find in SEP4 events, for example, could be explained easily by transport from the shock. Scattering is one big adjustable parameter. However, there does seem to be a net negative slope to the SEP4 power-law fits for the small and moderate events. This is shown in Fig. 9.16, where the lower panel shows source temperature vs. the

Fig. 9.15 Power-law abundances distributions are shown for the three-spacecraft configuration of STEREO B, *Wind*, and STEREO A shown at the top. (a) Time profiles of few MeV/n ^4He , O, and Fe are compared for STEREO A and *Wind* during the 23 January 2012 SEP4 event. (b) Similar time profiles of ^4He , O, and Fe are compared for STEREO B and *Wind* during the event. (c–e) shows abundance enhancements, labeled by Z , versus A/Q for relative time intervals beginning at the time listed, with best-fit power law for elements with $Z \geq 6$ extrapolated down to H at $A/Q = 1$ for (c) daily intervals on STEREO A, (d) 8-h intervals on *Wind*, and (e) daily intervals on STEREO B. Abundances at STEREO A and B are for 4–6 MeV amu^{-1} ions, and those at *Wind* are typically for 3–5 MeV amu^{-1} ions. In (a), *Wind* and STEREO A enter an equal-intensity, magnetic reservoir on 27 January, long after shock passage

Fig. 9.16 The *lower panel* shows T vs. the power-law slope of enhancement vs. A/Q , averaged over each gradual SEP event, with the proton excess shown as the point size and color. Impulsive-sourced SEP3 events stand out as orange or red in the upper-right corner. The *upper panel* shows the fluence of $>30 \text{ MeV}$ protons vs. the average slope of A/Q only for SEP4 events with $T < 2 \text{ MK}$ (Reames 2020b, © Springer)

power-law slope of A/Q , averaged over each event, with proton excess as point size and color. If we eliminate the obvious SEP3 events by requiring $T < 2 \text{ MK}$, we obtain the event-size distribution in the upper panel of Fig. 9.16. This distribution suggests that small events, with minimal wave generation, tend to have negative slopes of A/Q , while large events, with significant wave generation, have average slopes that are net neutral or positive (Reames 2020b).

At the outset we should say that this discussion may seem a bit circular since we actually derived the reference coronal abundances by averaging over gradual SEP events. However, when we compared these average SEP abundances with those in the photosphere (Chap. 8) we found a FIP effect that was compatible with current theory and which could not support any significant residual power-law in A/Q . However they were obtained, the reference abundances are not arbitrary and we cannot simply redefine them. For example, solar wind abundances do not work as a reference for SEPs; temperature minima are not formed.

Naively, we would expect that ions scatter against Alfvén waves, back and forth across the shock, with a mean free path proportional to the ion's rigidity. This would surely produce rigidity dependence in the acceleration, making the acceleration time vary inversely with rigidity until an equilibrium spectrum is attained. Jones and Ellison (1991) discuss the issue of reduced rigidity dependence in reference to the Earth's bow shock, where Monte Carlo calculations (Ellison et al. 1990) showed that shock smoothing could compensate for the expected rigidity dependence. Shock smoothing allows ions with longer mean free paths to encounter a larger shock-velocity difference, compensating for the slower acceleration otherwise.

In fact, shock waves are not simple planar structures; they are complex surfaces, modulated by waves that vary in space and time. Particle-in cell (PIC) simulations show these variations (e.g. Trotta et al. 2020) and small-scale variations have been observed in interplanetary shocks by the *Cluster* spacecraft (e.g. Kajdič et al. 2019). These variations include upstream waves produced by reflected particles, some including variations in θ_{Bn} . While these considerations have not been applied to coronal shocks or to the rigidity dependence of SEPs, they are interesting and could be important. A/Q dependence of abundances may, in fact, allow some measure of shock structure, with some shocks relatively enhancing heavier-element abundances and others suppressing them. Perhaps future simulations of shock acceleration of SEPs will aid the study these effects.

The power law in A/Q that we observe in SEPs is a result of the combined rigidity dependence of both acceleration and transport. In an effort to separate these processes, we first consider very small gradual events, where the proton intensities do little to disrupt the transport. Perhaps SEPs from small gradual events even travel scatter-free like those from small impulsive events. Figure 9.17 shows properties of the small gradual SEP event of 17 June 1998. During the first day of this event the ions show very little scattering in their angular distributions for H and He shown in panels (d) and (c), respectively. The best power-law fit for the abundance enhancements vs. A/Q measured on 17 June are shown in Fig 9.17f has a slope of -1.07 ± 0.14 . Perhaps this represents the rigidity dependence of the acceleration by this shock that is unmodified by transport. Small SEP4 events in Fig. 9.16 have slopes in the region of -1 to -2 , which may be the rigidity dependence from acceleration alone in these events.

At the opposite extreme, we can consider huge gradual SEP events where proton intensities are so high as to reach the streaming limit (Sect. 5.1.5), impeding the flow of low-energy ions and causing flattened or rounded low-energy spectra during the early plateau period (Sect. 5.1.5; Reames and Ng 2010; Ng et al. 2012).

Fig. 9.17 Selected particle intensities (a) and enhancements (b) are shown vs. time, along with angular distributions (in °) relative to the magnetic field B for H (d) and He (c) in the small 17 June 1998 gradual SEP event. The plot of χ^2/m vs. T in (e) selects $T = 1$ MK as the best fit for abundance enhancements vs. A/Q , shown in (f), with each element noted by Z . The time period measured is listed and is shown by the bar above the curves in (a) (Reames 2020b, © Springer)

Figure 9.18 shows the behavior of element abundances during two of the large events studied by Reames and Ng (2010). For these events and other streaming-limited events the power of A/Q changes markedly from positive to negative after shock passage. Early in the events, low-rigidity ions are strongly scattered but, at a given velocity, higher-rigidity ions like Fe can penetrate the turbulence more easily than low-rigidity ions like H. However, a small but consistent proton excess in the 5 November 2001 event, on the left in Fig. 9.18, may indicate that the wave spectrum is not a perfect power law.

For the 5 November 2001 event the power or slope is positive 0.8–1.2 before the shock and $-0.6 - -1.0$ after. For the 28 October 2003 event the power is 1.3–2.1 before and $-0.4 - -0.5$ after. There is little doubt that scattering during transport increases this power early in these events, trapping the lower-rigidity ions near the

Sun, but the suppressed values after the shock passage might represent, not the source, but also the depletion of the high-rigidity ions that escaped previously. In a study of SEP abundances, Reames (2014) found that abundances were very stable in reservoirs late in events, but they showed a strong energy dependence which was not present in the overall abundance averages used for FIP studies. Self-consistent models of wave generation and scattering of ions during acceleration and transport are not yet available to help resolve these issues.

9.9 Correlations Between Spectra and Abundances

When shock waves sweep up coronal material for acceleration, the pattern of abundances at a given velocity is related to spectral indices of the ions. Both features result from the same rigidity-dependent scattering, as does the interplanetary transport, which can also maintain or disrupt the relationship. Non-relativistically, spectra of form E^y with enhancements of $(A/Q)^x$ has been found to obey $y = x/2 - 2$ (Reames 2020b). The power of velocity is $x - 4$. The origin of this fundamental relationship is not understood theoretically. It relates to the “injection problem” and describes the way a shock selects ions of different A/Q from the solar plasma.

The analysis of a moderate-sized, well-behaved event is shown in Fig. 9.19. For events of this size, the spectra seem to be determined early in the event, subsequent action of the shock only maintains the same spectral shape and abundance pattern; the spectrum is no harder at the shock peak (also true for the event in Fig. 9.15). A weakening shock only maintains the spectrum of a previous stronger shock, as we saw in Eq. (5.9). Apparently transport has little effect on the properties of this event.

Analysis of a more complex example is shown in Fig. 9.20. Here the spectral index and the power of A/Q change rapidly throughout the event, only roughly tracking the expected relationships. For this event O spectra vary from E^{-1} to E^{-5} while abundances vary from $(A/Q)^{+1}$ to $(A/Q)^{-2}$. Fe spectra vary less, probably because of their higher rigidity. The abundances follow the classic pattern of high-Z enhancement early and suppression later, because Fe scatters less than O during transport, for example. This is a large event and wave amplification is certainly a factor. However, it is also true that its longitude suggests that we are connected to the strong nose of the shock early and to the weaker flanks later. Spatial vs. temporal effects, acceleration vs. transport, it is not easy to tell, but comparing smaller and larger events suggests that transport is the new factor that dominates this behavior, since smaller events show no significant longitude dependence (e.g. Fig. 9.15). Differences in the spectral indices of O and Fe are also a clue. We lack event simulations that explore these abundance variations. Other examples are shown by Reames (2020c), including SEP3 events and events dominated by the streaming limit.

For the large SEP4 events, we can use 2-h time intervals and improve the resolution of the complex temporal evolution. Spectral and abundance correlations are shown for two SEP4 GLEs in Fig. 9.21. Eight-hour spectral fits for these events are shown in Reames (2020c). Event 15 was also shown in Fig. 9.18 (see also

Fig. 9.19 (a) Intensities, for listed ions and energies in MeV amu⁻¹ and (b) derived source temperatures are shown versus time for gradual SEP Event 4 (list of Reames 2016), on 24 August, 1998. Fits are shown for (c) enhancements of elements, listed by Z, versus A/Q, and for energy spectra of (d) O and (e) Fe. Correlation plots are shown for spectral indices of (f) Fe versus O and of (g) O versus A/Q. Colors for time intervals correspond in (b), (c), (d), (e), (f), and (g). In (f) the solid line is diagonal, $y = x$, in (g) it is $y = x/2 - 2$ (Reames 2020c)

Fig. 5.1) as an example of an event with a streaming-limited plateau formed when Alfvén waves generated by streaming protons limit the intensities of low-rigidity ions (Sects. 5.1.2 and 5.1.5; Reames and Ng 2010; Ng et al. 2012).

The O and Fe spectra we are using have similar energy amu^{-1} but rigidities of O span the range of about 180–360 MV and Fe spans about 370–700 MV at $T \approx 1.3$ MK. Thus the proton-generated waves preferentially trap the low-rigidity O near the shock, making the early O spectra flatter, but these waves have less effect on Fe spectra. Persistently flatter slopes of O than Fe are clearly seen in Fig. 9.21h and also in Fig. 9.21d to a lesser extent. The spectra recover just before the shock arrives.

Behind the shock in Event 15 we see evidence of adiabatic trapping in a magnetic reservoir (Sect. 5.7) where all of the red points in Fig. 9.21c, d pile together, indicating invariant spectra. Spectral shapes are invariant in the reservoir. These points fall near the lines of expected correlation.

Strictly speaking, the complexity in the disrupted correlation of spectra and abundances like those in Fig. 9.21 come from a breakdown in our power-law assumption for these quantities because of proton-generated waves at high intensities. The O and Fe spectra are still observed to be power laws over the observed range of each species, but they have different powers, whereas for small and medium SEP4 events, with no significant transport component, a single power spans from O through Fe. The proton-generated waves are rigidity dependent, but they vary with time and a single power no longer spans from O to Fe.

Time variation is an important factor. At a given time the wave spectrum near the shock may produce a power-law wave-spectral modification. However, this wave spectrum varies with time (Ng et al. 2003). The relative scattering delay and trapping of the low-energy ions during the evolution of the event can mix low-rigidity ions produced at one time and place with higher-rigidity ions from another time and place involving much different wave spectra. This causes the complexity we see in Fig. 9.21.

In Fig. 9.22 we compare the spectra and abundances of the first four 8-h periods in 45 gradual SEP events of all kinds (listed in Reames 2016). SEP3 events with $T > 2$ MK are indicated by red. Figure 9.22a shows that He spectra tend to be a bit harder than O spectra. In Fig. 9.22b, Fe spectra show larger variation vs. O, especially for SEP4 events. In Fig. 9.22c, the orange and red ($T > 2$ MK) SEP3 events have high powers of A/Q that are uncorrelated with spectral indices, since those powers are largely determined by the strong positive enhancements of the impulsive seeds prior to shock acceleration. If we remove the red and orange SEP3 events from Fig. 9.22c, the remaining SEP4 events follow broadly along the expected correlation; of course, some are distorted along the lines we would expect from the rather extreme examples in Figs. 9.20 and 9.21.

Fig. 9.20 (a) Intensities and (b) derived source temperatures are shown versus time for gradual SEP Event 40, of 29 September, 2013. Fits are shown for (c) enhancements of elements, listed by Z, versus A/Q, and for energy spectra of (d) O and (e) Fe. Correlation plots are shown for spectral indices of (f) Fe versus O and of (g) O versus A/Q. Colors for time intervals correspond in (b), (c), (d), (e), (f), and (g). In (f) the solid line is diagonal, $y = x$, in (g) it is $y = x/2 - 2$ (Reames 2020c)

Fig. 9.21 Shows two GLEs, Event 15 of 4 November, 2001 on the left, and Event 23 of 2 November, 2003 on the right with 2-h time resolution. Panels (a) and (e) show intensities of listed species and energies (in MeV amu⁻¹) versus time; (b) and (f) show derived temperatures versus time, providing time-tagged symbols and colors for the upper panels; (c) and (g) show time evolution of O spectral index versus power of A/Q; (d) and (h) show time evolution of Fe versus O spectral indices. S denotes the time of shock passage (Reames 2020c)

Fig. 9.22 Shown are (a) spectral indices of He versus O, (b) spectral indices of Fe versus O, and (c) spectral indices of O versus powers of A/Q for the first four 8-h periods in 45 gradual SEP events listed by Reames (2016). The size and color of each point is determined by the source plasma temperature T as shown by the scale. Events with $T > 2$ MK are SEP3-class events dominated by reaccelerated impulsive suprathermal ions with enhanced abundances already determined before shock acceleration. In (a) and (b) the solid line is diagonal, $y = x$, in (c) it is $y = x/2 - 2$ (Reames 2020c)

9.10 Open Questions

1. What physical parameters determine the magnitude of the large excess of protons in some impulsive and gradual SEP events?
2. Why is reduced He/C associated with the largest gradual SEP events?
3. What causes a few ^3He -rich events to have greatly suppressed $^4\text{He}/\text{C}$?
4. How does the rigidity dependence of SEP4 shock acceleration depend upon shock structure? Can we measure it?
5. Will the next generation of SEP simulations include abundances of $Z > 1$ ions? Only protons are a significant hazard, but getting the abundances right for GLEs is a powerful test of the quality of the underlying physics.

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