Element Abundances and FIP: SEPs, Corona, and Solar Wind

8

Abstract

We have used abundance measurements to identify the sources and the physical processes of acceleration and transport of SEPs. Here we study energetic particles themselves as samples of the solar corona that is their origin, distinguishing the corona from the photosphere and the SEPs from the solar wind. Theoretically, differences in the first ionization potential “FIP effect” may distinguish closed- and open-field regions at the base of the corona, which may also distinguish SEPs from the solar wind. There is not a single coronal FIP effect, but two patterns, maybe three. Are there variations? What about He?

There are many different opportunities to sample solar and coronal material. Meteorites are a sample of the non-volatile material left over from the time when the solar system was forming, and can be compared with abundances from spectral line intensities from the photosphere (e.g. Lodders et al. 2009). The fast and slow solar wind (Bochsler 2009) and gradual SEP events (Reames 2018a, b, 2020) each provide unique samples of the solar corona, which all seem to differ. Separately, the shock-accelerated solar wind provides a comparison with the direct measurements (Sect. 8.3; Reames 2018c). Spectroscopic extreme-ultraviolet, X-ray (Feldman and Widing 2007; Sylwester et al. 2014), and γ -ray line (Ramaty et al. 1996) measurements provide localized measurements in the corona and in the heated plasma of solar flares.

In a modern theory of the FIP effect (Laming 2015, Laming et al. 2019), the ponderomotive force of Alfvén waves can preferentially drive ions, but not neutral atoms, across the chromosphere and into the corona. The Alfvén waves can resonate with the loop length of magnetic loops that are closed in this region but not with open field lines, producing two fundamentally different FIP patterns.

8.1 Element Abundances in the Sun

Element abundances in the Sun are presumed to have changed little, apart from some gravitational settling, from their values in the pre-solar molecular cloud from which the Sun was formed by gravitational collapse. Material left over from that time period was left as meteorites or eventually collapsed further to form the planets. As the collapsing Sun began to heat and radiate, the surrounding material was heated then condensed into pea-sized molten drops called chondrules (after Greek *chondros* for sphere) which would later clump to form chondritic meteorites. With the onset of the solar wind, the volatile elements tended to be blown out of the inner heliosphere, denuding it of volatiles and leading to the inner rocky planets. Most of the H and He was swept out to Jupiter and beyond.

Thus the chondritic meteorites provide a measure of the abundances of the non-volatile elements in the pre-solar and early-solar nebula and hence of the Sun. In particular, the carbonaceous chondrites or CI chondrites (Carbonaceous of the Ivuna type), of which there are actually few examples, show the least depletion of volatiles, giving the most complete set of abundances. When these meteoritic abundances are compared with those from spectral line measurements of the photosphere, nearly 40 elements now show agreement within about 10% (Lodders et al. 2009).

For the spectral-line measurements, recent years have seen a change from assumed local thermal equilibrium to three-dimensional modeling of the emitting plasma (Grevesse et al. 2013; see also Schmelz et al. 2012). This has led to the abundances of Asplund et al. (2009) shown in Table 1.1, who have concentrated on well-resolved and isolated spectral lines, but also led to the abundance measurements of the dominant volatile elements, especially C, N, O, S, and Fe, by Caffau et al. (2011), who have resolved elements from blended spectral lines and provided the photospheric abundances listed in Table 8.1. However, the new abundances do conflict with helioseismic determinations of the sound speed, the He abundance, and depth of the convection zone (Grevesse et al. 2013).

8.2 The Solar Wind

Unlike the conceptually simple dE/dx vs. E measurement of SEPs (Chap. 7), measurements of the solar wind abundances must resolve the charge state, mass, and energy of each ion. Instruments use stages of collimation, electrostatic deflection, post acceleration, time of flight, and energy deposit (e.g. Gloeckler et al. 1992). The need to measure all of the individual ionization states of each element leads to some cases of overlap, which are difficult to resolve, e.g. C^{+6} and O^{+8} , or some charge states of Ne or S. However, abundance measurements have now been made of solar wind abundances emitted spatially over three dimensions around the Sun (von Steiger et al. 2000) and abundance measurements have been collected and summarized for us by Bochsler (2009). An alternative technique that has contributed

Table 8.1 Photospheric, reference SEP, CIR, and SSW abundances

	Z	FIP [eV]	Photosphere ^a	SEPs ^b	CIRs ^c	SSW ^d
H	1	13.6	$(1.74 \pm 0.04) \times 10^{6e}$	$(1.6 \pm 0.2) \times 10^6$	$(1.81 \pm 0.24) \times 10^6$	–
He	2	24.6	$1.46 \pm 0.07 \times 10^5$	$91,000 \pm 5000$	$159,000 \pm 10,000$	$90,000 \pm 30,000$
C	6	11.3	550 ± 76^e	420 ± 10	890 ± 36	680 ± 70
N	7	14.5	126 ± 35^e	128 ± 8	140 ± 14	78 ± 5
O	8	13.6	1000 ± 161^e	1000 ± 10	1000 ± 37	1000
Ne	10	21.6	195 ± 45	157 ± 10	170 ± 16	140 ± 30
Na	11	5.1	3.47 ± 0.24	10.4 ± 1.1	–	9.0 ± 1.5
Mg	12	7.6	60.3 ± 8.3	178 ± 4	140 ± 14	147 ± 50
Al	13	6.0	5.13 ± 0.83	15.7 ± 1.6	–	11.9 ± 3
Si	14	8.2	57.5 ± 8.0	151 ± 4	100 ± 12	140 ± 50
P	15	10.5	0.501 ± 0.046^e	0.65 ± 0.17	–	1.4 ± 0.4
S	16	10.4	25.1 ± 2.9^e	25 ± 2	50 ± 8	50 ± 15
Cl	17	13.0	0.55 ± 0.38	0.24 ± 0.1	–	–
Ar	18	15.8	5.5 ± 1.3	4.3 ± 0.4	–	3.1 ± 0.8
K	19	4.3	0.224 ± 0.046^e	0.55 ± 0.15	–	–
Ca	20	6.1	3.72 ± 0.60	11 ± 1	–	8.1 ± 1.5
Ti	22	6.8	0.138 ± 0.019	0.34 ± 0.1	–	–
Cr	24	6.8	0.759 ± 0.017	2.1 ± 0.3	–	2.0 ± 0.3
Fe	26	7.9	57.6 ± 8.0^e	131 ± 6	97 ± 11	122 ± 50
Ni	28	7.6	2.95 ± 0.27	6.4 ± 0.6	–	6.5 ± 2.5
Zn	30	9.4	0.072 ± 0.025	0.11 ± 0.04	–	–
Se–Zr	34–40	–	≈ 0.0118	0.04 ± 0.01	–	–
Sn–Ba	50–56	–	≈ 0.00121	0.0066 ± 0.001	–	–
Os–Pb	76–82	–	≈ 0.00045	0.0007 ± 0.0003	–	–

^aLodders et al. (2009). Ratios to O of elements from Lodders et al. (2009) are taken before correction of O by Caffau et al. (2011)

^bReames (1995, 2014, 2020)

^cReames, et al. (1991); Reames (1995)

^dBochsler (2009)

^eCaffau et al. (2011)

to the results is the return and analysis of foils that have been exposed to collect solar wind ions.

The solar wind consists of fast ($500 > V_S > 800 \text{ km s}^{-1}$) solar wind or high-speed streams emerging from coronal holes and slow ($200 > V_S > 500 \text{ km s}^{-1}$) wind or interstream wind diverging (Wang and Sheeley 1990) around closed structures such as streamers which contain magnetic field reversals and pseudo-streamers which do not. Much of the solar wind also consists of solar ejecta and magnetic clouds. The fast wind contains cooler plasma with $O^{+7}/O^{+6} < 0.1$ while the slow wind and magnetic clouds tend to contain hotter plasma with $O^{+7}/O^{+6} > 0.1$. A more complete scheme for distinguishing different regions of the solar wind has been developed by

Xu and Borovsky (2015). We will see that the amplitude of the FIP-level difference, i.e. the FIP *bias*, for the slow solar wind is similar to that for the SEPs, yet the location of the crossover from high to low FIP differs. The fast solar wind has a smaller FIP bias ($\approx 70\%$), but not for all elements (Bochsler 2009). Abundances for the slow solar wind are shown in Table 8.1.

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) and large variations are seen in H/He with phase in the solar cycle (Kasper et al. 2007). This makes it difficult to include H and He in FIP studies of the solar wind, as is also the case for SEPs (see Sect. 5.9 and Chap. 9). However, variations of H and He in SEPs seem to be unrelated to those in the solar wind.

8.3 Corotating Interaction Regions: Accelerated Solar Wind

Corotating interaction regions (CIRs) occur when high-speed solar-wind streams, emerging from coronal holes, overtake and collide with slow solar wind emitted earlier in the solar rotation. Two shock waves can form from this collision, a forward shock propagates outward into the slow solar wind and a stronger, reverse shock propagates sunward into the fast wind (Belcher and Davis 1971; Richardson 2004). Near the Sun, the fast wind flows nearly parallel to the slow wind, but as the distance increases, the fast wind begins to “bite” into the slow wind, often beyond 1 AU, and the shock waves strengthen. *Pioneer* spacecraft observations have shown that the maximum particle acceleration by the shock waves occurs at about 5 AU (McDonald et al. 1976; Van Hollebeke et al. 1978). The energetic particle intensity seen at 1 AU is usually a combination of acceleration from the solar wind at the reverse shock and of transport, streaming sunward, in the solar-wind frame, along the field lines to the observers (Marshall and Stone 1978) and displaying unique abundances (e.g. Reames et al. 1991; Richardson et al. 1993; Mason et al. 1997, 2008). CIRs allow us to measure element abundances of shock-accelerated solar wind with the same instruments that measure element abundances of shock-accelerated SEPs.

As we found for SEP events, scattering mean free paths of particles can often be expressed as a power law in particle rigidity so that high-rigidity particles propagate more easily. This can be seen in Fig. 8.1 where scattering has confined low-energy He from a CIR much more closely to the source, when it is near 1 AU, than high-energy He which is seen relatively undiminished a week later when the spacecraft is magnetically connected to a point on the shock that is far out from the Sun. Whereas SEP events show velocity dispersion with the fastest particles arriving first, for CIRs, the low energies dominate early but decrease in importance rapidly. Of course, this rigidity dependence affects element abundances as well. If we can accommodate the corresponding A/Q dependence, as we did with SEPs, the energetic ions at CIRs give us an alternate way to measure the FIP dependence when the source is the solar wind. The two sources of fast and slow wind are poorly resolved by the energetic ion abundances.

Fig. 8.1 The lower panel shows intensities of He at various energies given in MeV amu^{-1} observed near Earth by the *Wind* spacecraft in a CIR event produced by the high-speed solar-wind stream shown in the upper panel. Increased scattering causes low-rigidity ions to be confined near the shock while high-rigidity ions spread widely from the distant shock even as it moves far out in the heliosphere

CIRs form a steady spiral spatial pattern that rotates with the Sun and can persist for several rotations, on each pass accelerating ions that have been seen to last 17 days and span 225° of solar longitude at MeV energies (Reames et al. 1997). The lagging intensities of higher-energy particles are fed by the much higher intensities from the shock wave that is stronger in the outer heliosphere at ~ 5 AU, not by the weaker shock near us that produced the low-energy peak.

Figure 8.2 shows time variations of element abundances during passage of a CIR and during three impulsive SEP events. Like any other shock wave, a CIR shock

Fig. 8.2 The lower panel shows intensities of ^4He , C, O, and Fe at $2.5\text{--}3.2\text{ MeV amu}^{-1}$ vs. time early in the year 2000. A CIR event and three impulsive SEP events are indicated. The SEP events have $\text{C/O} < 0.5$ and $\text{Fe/O} \approx 1$, while the CIR event has $\text{C/O} \approx 1$ but very low Fe/O . The upper panel shows the solar-wind speed (Reames 2018c, © Springer)

wave can accelerate a seed population from any source, including pre-accelerated ions from impulsive and gradual SEP events. Even a very small impulsive SEP event, which could occur near coincidence with a CIR passage, would contaminate the otherwise small Fe abundances of the CIR, but would appear to affect little else.

Energy spectra of ions are shown for a sample of four CIR events in Fig. 8.3. The intensity spectra of ^4He , C, and O are well matched to the form

$$j(v) = j_{0i}(A/Q)^a v^b \exp(-v/v_0) \quad (8.1)$$

Fig. 8.3 Energy spectra of four CIR events compare C and O with He in the lower panel and Fe with He in the upper panel. Spectral shapes for He, C, and O (and other species) generally agree well, but Fe in event 3 shows either (i) steepening at Fe because of its higher rigidity, or (ii) Fe background injected by impulsive SEPs at low energies (Reames 2018c, © Springer)

where v is the ion speed and j_{0i} , a , b , and v_0 are adjustable constants, j_{0i} varying with species as injected at the shock. This is the form derived by Fisk and Lee (1980) with the addition of the explicit A/Q dependence. In general, $a \neq b$, and both values vary from event to event. In principle, simple shock acceleration should yield $b = a - 4$ since shocks have a correlated affect on both spectra and abundances, but transport can complicate and disrupt this simple relationship as discussed in detail in Sect. 9.9. Also, the observed spectra flatten with time (see Reames et al. 1997) because the distant shock strengthens with time but low rigidity ions are increasingly suppressed during transport.

The spectra of ^4He , C, and O show similar shapes for all elements in the events in the lower panel of Fig. 8.3 and for the normalized Fe and ^4He spectra for most events in the upper panel. However, the event numbered 3 shows either possible low-energy contamination of Fe or steepening of high-rigidity Fe relative to lower-rigidity He and O. Fe spectra in the same range of E have much higher rigidity P and transport depends upon P .

We can now use the same analysis technique for these CIR events that we used for gradual SEP events in Sect. 5.6. Figure 8.4 shows best-fit power-law lines for the relative abundances, i.e. the normalization factors for the spectra relative to O divided by the corresponding fast solar wind (FSW) abundances relative to O (Bochsler 2009), vs. A/Q . The A/Q values correspond to plasma temperatures of 1.0–1.3 MK which are appropriate for the FSW and are determined from the best-fit power law.

All of the 12 recent CIR events studied by Reames (2018c) showed negative power-law dependence of abundance enhancements on A/Q ; for these events the shock waves began outside 1 AU. However, in an earlier event in May 1982 (Reames et al. 1991) the shock began locally and the relative abundances seemed to be independent of A/Q , directly providing an alternative measure of element abundances of the solar wind are shown as CIR in Table 8.1.

It seems that when the shock forms near 1 AU, we see a direct sample of the source ions locally (both slow and fast), as accelerated, but when the shocks form far outside 1 AU, ions (from the FSW) with high A/Q are suppressed as they spread widely by transport. These energetic CIR ions give us another measure of the FIP effect in the solar corona, presumably similar to the combined solar wind.

8.4 Comparing FIP Patterns of SEPs and the Solar Wind

Assuming the higher value of 91 for source He/O for SEPs (Sects. 5.8 and 5.9), we compare the FIP plot for SEPs with that for the slow solar wind (SSW; Bochslers 2009) in Fig. 8.5. The upper panel compares these abundances relative to those in the photosphere from Caffau et al. (2011) and Lodders et al. (2009). Here we renormalized the solar wind values by a factor of 1.2 to improve the agreement at both high and low FIP. The lower panel compares SEP and slow-solar-wind abundances directly, showing the alternate normalization as a dashed line. The

Fig. 8.4 Best-fit power laws (blue) and element abundance enhancements (black) relative to O, divided by corresponding abundances in the FSW (Bochsler 2009), are plotted vs. A/Q for each of our four CIR events. The atomic number Z is shown at the position of each element and successive measured elements are joined. The reference FSW abundance of S ($Z = 16$) seems to be consistently too large in all of the events and Fe may be too small

Fig. 8.5 The upper panel shows the SEP/photospheric and 1.2 times the slow solar wind (SSW)/photospheric abundance ratios as a function of FIP. The curves are empirical curves used to show the trend of the data. The lower panel shows the direct ratio of the coronal abundances from SEPs to those of the SSW (Bochsler 2009), as a function of FIP. The dashed line suggests the alternate normalization factor of 1.2 (Reames 2018a, © Springer)

alternative normalization means that O is not the best choice for a reference, i.e. O is more enhanced in the SSW than in SEPs.

The FIP bias, i.e. the ratio of the levels at low and high FIP, is quite similar for SEPs and the slow solar wind. The FIP bias of the fast solar wind is smaller (Bochsler 2009). However, the difference in Fig. 8.5 is in the FIP value of the crossover between low- and high-FIP regions, ~ 10 eV for SEPs and ~ 14 eV for the slow solar wind. Thus, the elements C, S, and P, seem to behave more like neutral atoms for the SEPs and like ions for the slow solar wind, as if the SEPs are derived from regions of cooler plasma where C, S, and P are not sufficiently ionized. Theory suggests that it may be more likely that SEPs are accelerated from closed field lines while the solar wind must come from open field lines near the base of the corona (Reames 2018a; Laming 2015; Laming et al. 2019). Spectral line measurements of the corona also show suppressed values of S/O (Schmelz et al. 2012) presumably on closed field lines.

In any case, the differences in FIP behavior seen in Fig. 8.5 strongly suggest that SEPs provide a unique sample of coronal material. FIP patterns are determined near and below the base of the corona, *not* at the height or time of SEP acceleration. Thus, at energies above a few MeV amu⁻¹, SEPs *cannot* be merely reaccelerated solar wind; they are an *independent* sample of coronal material (Reames 2018a). This irreconcilable difference in FIP patterns was first noted by Mewaldt et al. (2002) and Desai et al. (2003) also noted that SEPs were not merely reaccelerated solar wind. This is why SEPs exhibit the same abundances whether they are found in fast or in the slow wind (Kahler and Reames 2003; Kahler et al. 2009).

8.5 FIP Theory: The Sources of SEPs and the Solar Wind

Recent theory of FIP fractionation (Laming 2015; Laming et al. 2019) involves extensive numerical calculations of ionization states of the elements as a function of altitude across the chromosphere where ions are guided along magnetic fields in the presence Alfvén waves, which neutral atoms cannot feel. Comparing with the results of that theory, it is shown in the lower panel of Fig. 8.6 that the SEPs best fit the theoretical FIP pattern derived for closed field lines with adiabatic invariant conservation (Laming et al. 2019), where the elements C, P, and S are suppressed like high-FIP elements, while, in the middle and upper panel of Fig. 8.6, the CIRs and solar wind fits the open-field pattern (Laming et al. 2019), where C, P, and S are elevated like low-FIP ions. The pattern of CIR abundances vs. FIP in Fig. 8.6 clearly resembles the SSW in that C, P, and S are elevated. Here the principal photospheric abundances are those of Caffau et al. (2011) supplemented by those of Lodders et al. (2009). The differences between the panels in the abundances of C, P, and S in the crossover region are highlighted in the light blue band.

As atoms cross the chromosphere, densities and ionized fractions change, as do the collision frequencies of ions and neutrals with the background H plasma. Low in the chromosphere, the plasma $\beta_P > 1$, and turbulence prevents fractionation. Higher, when $\beta_P < 1$, ions flow along $\mathbf{B}$ under the ponderomotive force of Alfvén waves; increased ionization of the background H tends to reduce that flow. On closed loops, where Alfvén waves resonate with the loop length, fractionation is concentrated near the top of the chromosphere where ionization of H limits fractionation to ions with FIP < 10 eV. On open field lines, lack of resonance allows fractionation to take place more broadly throughout the loop where H is not ionized, leading to additional enhancements of C, S, and P. These conclusions are the result of extensive calculations of the wave patterns and the ionization states of the elements as a function of altitude (Laming 2015; Laming et al. 2019). The pattern of waves required for the observed abundances suggest (Laming 2017) that the Alfvén waves actually descend from the corona where they may be created by nanoflares.

While there have been some small changes in CIR abundances (Reames 2018c) since publication of the comparisons in Fig. 8.6, the apparent difference based upon open- and closed-field geometry persists. Recently, this theory has been updated and

Fig. 8.6 Average abundances of (a) SEPs, (b) CIR ions and (c) slow solar wind (SSW; Bochsler 2009), relative to solar photospheric abundances, (solid blue) are shown as a function of the FIP of each element and compared with theoretical calculations (open red) by Laming et al. (2019) for loop structures (a), and for the open field SSW (b and c). All abundances are normalized at O. The light blue band compares elements C, P, and S that are suppressed like high-FIP elements in SEPs, but are elevated like low-FIP elements in the solar wind. However, decreasing the photospheric C/O ratio by 20% would greatly improve the agreement of observation and theory for all three samples: SEPs, CIRs, and SSW (Reames 2020)

Table 8.2 Various C/O values

Photosphere	C/O = 0.550 ± 0.076 C/O = 0.550 ± 0.063	Caffau et al. (2011) Asplund et al. (2009)
Closed fields	SEPS C/O = 0.430 ± 0.010 γ -rays $0.35 < \text{C/O} < 0.44$ FIP Theory C/O ≈ 0.671 ($1.22 \times \text{phot}$)	Reames (2014) Ramaty et al. (1996) Laming et al. (2019)
Open fields	FSW C/O = 0.68 ± 0.07 SSW C/O = 0.68 ± 0.07 CIRs C/O = 0.860 ± 0.054 FIP Theory C/O ≈ 1.232 ($2.24 \times \text{phot}$)	Bochsler (2009) Bochsler (2009) Reames (2018c) Laming et al. (2019)

has been compared with the SEP, SW, and CIR abundance measurements by Laming et al. (2019).

The most significant difference between all of the observed open- and closed-field patterns is in C/O as shown in Table 8.2. Actually the closed-field measurements are significantly *below* the recent photospheric values, contrary to any expectations. Agreement with theory for all three samples, SEPs, CIRs, and slow solar wind, would improve greatly if the photospheric C/O ratio were decreased 20%.

8.6 A Full-Sun Map of FIP

Since it now is possible to make full-disk images the Sun in the light of a single spectral line, it has become possible to compare spectral lines of high-FIP and low-FIP elements. Thus, Brooks et al. (2016) have constructed a map of FIP derived from the Si/S ratio, specifically $\text{Si} \times 258.37 \text{ \AA}/\text{S} \times 264.22 \text{ \AA}$ that is shown on the right in Fig. 8.7. From the evidence above, it is not certain that this is a map of FIP for the slow solar wind, as the authors suggest, since both Si and S seem to behave as low-FIP elements for the solar wind. However, this may be an excellent map of distribution of FIP for the source of the SEPs, where Si is low-FIP and S is definitely high-FIP (Fig. 8.6a).

The image on the left in Fig. 8.7 shows the Sun in the Fe XIII 202.044 $\text{\AA}$ line formed at 2 MK which highlights active regions. The locations of the active regions on the left can be compared with the regions of high FIP bias on the right, suggesting that these regions have the appropriate FIP bias to be the sources of the SEPs.

The technique in Fig. 8.7 is an extremely powerful way of exploring the distribution of element abundances in the solar corona when the ionization-state distributions of the ions are understood. However, it is important to insure that differences measure FIP and not density or ionization state (temperature).

If we measure the corresponding FIP bias using Si/S from the 8-h averages in gradual SEP events, we find a mean of 2.44 ± 0.04 with a $\pm 20\%$ spread in the individual measurements. We limited to SEPs to measurements with $0.8 \leq T \leq 1.5$ MK to avoid possible bias from the steep positive power-law increase vs. A/Q for the events with $T \geq 2$ MK from impulsive suprathermal seeds. Perhaps the FIP bias of

Fig. 8.7 The solar image on the left in the 2 MK Fe XIII 202.044 Å line shows the location of active regions, while that on the right shows the ratio of $\text{Si} \times 258.37 \text{ Å} / \text{S} \times 264.22 \text{ Å}$ that is a measure of FIP bias for SEPs (Brooks et al. 2016, CC BY 4.0)

~3 MK near active regions shown in Fig. 8.7 is diluted somewhat by acceleration of surrounding material to produce the average bias of 2.4 in SEPs.

8.7 A Possible SW-SEP Model

The foregoing observations suggest a model that distinguishes the origins of the SEPs and the solar wind sketched in Fig. 8.8. The *solar wind speed varies inversely with the divergence of the magnetic field lines from the corona* (Wang and Sheeley 1990) so high wind speeds come from slowly diverging fields (blue) and the slow wind (green, yellow) comes from highly divergent regions as shown in Fig. 8.8. Both fast and slow solar winds come from field lines that were never closed to the currently emerging plasma, but always open from the chromosphere, where FIP fractionation occurs, outward. Solar jets (brown) can occur at magnetic reconnection sites involving open and closed loops of active regions (red), and producing impulsive SEP events and narrow CMEs.

As the slow solar wind diverges past closed field lines above active regions there is the possibility of some exchange in their abundances through magnetic reconnection. Abundances produced on closed field lines are not forever trapped or only limited to ejection in a CME.

How can SEPs come from closed-field regions?

Fig. 8.8 The lower panel shows a possible configuration of the solar magnetic field where the fast solar wind flows from coronal holes (blue), the slow wind from highly divergent open fields (green, yellow) and jets (brown) emerge from active regions (red). In the upper panel, a CME-driven shock (gray) accelerates SEPs from weakly closed loops and from suprathermal ions and plasma residue from jets, when it is present (Reames 2018b)

1. The gradual SEP events with source temperatures of $T > 2$ MK are probably accelerated by shock waves that sample both the residual suprathermal impulsive SEPs from pools formed by numerous small jets from an active region and some recently ejected local plasma. Gradual SEP events with ions from $T < 2$ MK plasma may simply fail to encounter any regions with impulsive suprathermal ions.
2. When plasma, which is contained near loop tops with $\beta_p \approx 1$, is suddenly shock accelerated, ion rigidities are boosted by an order of magnitude or more, so the ions are no longer trapped; thus, shock waves can also accelerate SEPs from ambient plasma on cooler less-active loops where $T < 2$ MK.

Therefore, a single CME-driven shock, shown in the upper panel of Fig. 8.8 can reaccelerate material from the impulsive SEPs and jet ejecta above an active region and can also accelerate cooler plasma from the closed loops on its flanks. SEP source composition and temperature can change across the shock face.

8.8 FIP-Dependent Variations in He

The abundances of many elements vary from event to event in SEP events, but He is the only example where we believe those variations may depend upon FIP, i.e. they occur as material transitions from the chromosphere to the corona, not later during acceleration or transport. Source abundance variations in He were discussed in Sect. 5.9. In principle, these variations could occur because He, with the highest FIP value of 24.6 eV, is slow to ionize as it is transported across the chromosphere as calculated by Laming (2009).

However, the order-of-magnitude suppression of He in some small impulsive SEP events shown in Fig. 4.12 presents a greater challenge to the theory, but the jet model for these events shown in Fig. 4.16 may involve emerging flux which may suddenly project only the ionized chromospheric material up into the corona. Calculation of the He ionization in such a dynamic situation has not yet been performed, but it is possible that assumed slow ionization of He may conflict with the fast transport of material that is an important factor in this case.

Nevertheless, it is the impulsive SEP events with shock reacceleration (see Fig. 9.6) and the gradual events that reaccelerate residual impulsive suprathermal material (see Sect. 5.9; Reames 2017, 2018b) that have the highest ratios of $\text{He/O} \approx 90$. Most of the larger gradual SEP events that sample ambient coronal material have $\text{He/O} \approx 40\text{--}60$. However, photospheric models have $\text{He/O} \approx 150\text{--}170$.

8.9 Open Questions

1. What do differences in the FIP-effect for SEPs and for slow solar wind say about the specific coronal locations of origins of the two populations?
2. Why is C/O so low in SEPs, even lower than in the photosphere?
3. What is the level of FIP processing for the chromospheric filament ejected within a CME?
4. What does He/O tell about the locations of SEP acceleration and the physical processes?

References

- Asplund, M., Grevesse, N., Sauval, A.J., Scott, P.: The chemical composition of the sun. *Ann. Rev. Astron. Astrophys.* **47**, 481 (2009). <https://doi.org/10.1146/annurev.astro.46.060407.145222>
- Belcher, J.W., Davis Jr., L.: Large-amplitude Alfvén waves in the interplanetary medium, 2. *J. Geophys. Res.* **76**, 3534 (1971). <https://doi.org/10.1029/JA076i016p03534>
- Bochsler, P.: Solar abundances of oxygen and neon derived from solar wind observations. *Astron. Astrophys.* **471**, 315 (2007). <https://doi.org/10.1051/0004-6361:20077772>
- Bochsler, P.: Composition of matter in the heliosphere. *Proc. IAU Sympos.* **257**, 17 (2009). <https://doi.org/10.1017/S1743921309029044>
- Brooks, D.H., Ugarte-Urra, I., Warren, H.P.: Full-sun observations for identifying the source of the slow solar wind. *Nat. Comms.* **6**, 5947 (2016). <https://doi.org/10.1038/ncomms6947>
- Caffau, E., Ludwig, H.-G., Steffen, M., Freytag, B., Bonofacio, P.: Solar chemical abundances determined with a CO5BOLD 3D model atmosphere. *Sol. Phys.* **268**, 255 (2011). <https://doi.org/10.1007/s11207-010-9541-4>
- Collier, M.R., Hamilton, D.C., Gloeckler, G., Bochsler, P., Sheldon, R.B.: Neon-20, oxygen-16, and helium-4 densities, temperatures, and suprathermal tails in the solar wind determined with WIND/MASS. *Geophys. Res. Lett.* **23**, 1191 (1996). <https://doi.org/10.1029/96GL00621>
- Desai, M.I., Mason, G.M., Dwyer, J.R., Mazur, J.E., Gold, R.E., Krimigis, S.M., Smith, C.W., Skoug, R.M.: Evidence for a suprathermal seed population of heavy ions accelerated by interplanetary shocks near 1 AU. *Astrophys. J.* **588**, 1149 (2003). <https://doi.org/10.1086/374310>
- Feldman, U., Widing, K.G.: Spectroscopic measurement of coronal compositions. *Space Sci. Rev.* **130**, 115 (2007). <https://doi.org/10.1007/s11214-007-9157-7>
- Fisk, L.A., Lee, M.A.: Shock acceleration of energetic particles in corotating interaction regions in the solar wind. *Astrophys. J.* **237**, 601 (1980). <https://doi.org/10.1086/157907>
- Gloeckler, G., Geiss, J., Balsiger, H., Bedini, P., Cain, J.C., Fischer, J., Fisk, L.A., Galvin, A.B., Gliem, F., Hamilton, D.C., et al.: The solar wind ion composition spectrometer. *Astron. Astrophys.* **92**, 267 (1992)
- Grevesse, N., Asplund, M., Sauval, A.J., Scott, P.: “Old” versus “new” solar chemical composition. In: *ASP Conference Proceedings*, vol. 479. San Francisco: Astronomical Society of the Pacific, p. 481 (2013)
- Kahler, S.W., Reames, D.V.: Solar energetic particle production by coronal mass ejection-driven shocks in solar fast-wind regions. *Astrophys. J.* **584**, 1063 (2003). <https://doi.org/10.1086/345780>
- Kahler, S.W., Tylka, A.J., Reames, D.V.: A comparison of elemental abundance ratios in SEP events in fast and slow solar wind regions. *Astrophys. J.* **701**, 561 (2009). <https://doi.org/10.1088/0004-637X/701/1/561>
- Kasper, J.C., Stevens, M.L., Lazarus, A.J., Steinberg, J.T., Ogilvie, K.W.: Solar wind helium abundance as a function of speed and heliographic latitude: variation through a solar cycle. *Astrophys. J.* **660**, 901 (2007). <https://doi.org/10.1086/510842>
- Laming, J.M.: 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 (2009). <https://doi.org/10.1088/0004-637X/695/2/954>
- Laming, J.M.: The FIP and inverse FIP effects in solar and stellar coronae. *Living Rev. Sol. Phys.* **12**, 2 (2015). <https://doi.org/10.1007/lrsp-2015-2>
- Laming, J.M.: The first ionization potential effect from the ponderomotive force: On the polarization and coronal origin of Alfvén waves. *Astrophys. J. Lett.* **844**, L153 (2017). <https://doi.org/10.3847/1538-4357/aa7cfl>
- Laming, J.M., Vourlidas, A., Korendyke, C., et al.: Element abundances: a new diagnostic for the solar wind. *Astrophys. J.* **879**, 124 (2019). <https://doi.org/10.3847/1538-4357/ab23f1>. arXiv: 19005.09319

- Lodders, K., Palme, H., Gail, H.-P.: Abundances of the elements in the solar system, In: Trümper, J.E. (ed.) *Landolt-Börnstein, New Series VI/4B*, Chap. 4.4, p. 560. Springer, Berlin (2009). https://doi.org/10.1007/978-3-540-88055-4_34
- Marshall, F., Stone, E.C.: Characteristics of sunward flowing protons and alpha particle fluxes of moderate intensity. *J. Geophys. Res.* **83**, 3289 (1978). <https://doi.org/10.1029/JA083iA07p03289>
- Mason, G.M., Mazur, J.E., Dwyer, J.R., Reames, D.V., von Rosenvinge, T.T.: New spectral and abundance features of interplanetary heavy ions in corotating interaction regions. *Astrophys. J.* **486**, 149 (1997). <https://doi.org/10.1086/310845>
- Mason, G.M., Leske, R.A., Desai, M.I., Cohen, C.M.S., Dwyer, J.R., Mazur, J.E., Mewaldt, R.A., Gold, R.E., Krimigis, S.M.: Abundances and energy spectra of corotating interaction region heavy ions observed during solar cycle 23. *Astrophys. J.* **678**, 1458 (2008). <https://doi.org/10.1086/533524>
- McDonald, F.B., Teegarden, B.J., Trainor, J.H., von Rosenvinge, T.T., Webber, W.R.: The interplanetary acceleration of energetic nucleons. *Astrophys. J. Lett.* **203**, L149 (1976). <https://doi.org/10.1086/182040>
- 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.: Fractionation of solar energetic particles and solar wind according to first ionization potential. *Adv. Space Res.* **30**, 79 (2002). [https://doi.org/10.1016/S0273-1177\(02\)00263-6](https://doi.org/10.1016/S0273-1177(02)00263-6)
- Rakowsky, C.E., Laming, J.M.: On the origin of the slow speed solar wind: helium abundance variations. *Astrophys. J.* **754**, 65 (2012). <https://doi.org/10.1088/0004-637X/754/1/65>
- Ramaty, R., Mandzhavidze, N., Kozlovsky, B.: Solar atmospheric abundances from gamma ray spectroscopy. In: Ramaty, R., Mandzhavidze, N., Hua, X.-M. (eds.) *AIP Conference Proceedings of 374, High Energy Solar Physics*, p. 172. AIP, New York (1996). <https://doi.org/10.1063/1.50953>
- Reames, D.V.: Coronal abundances determined from energetic particles. *Adv. Space Res.* **15**(7), 41 (1995)
- Reames, D.V.: Element abundances in solar energetic particles and the solar corona. *Sol. Phys.* **289**, 977 (2014). <https://doi.org/10.1007/s11207-013-0350-4>
- Reames, D.V.: The abundance of helium in the source plasma of solar energetic particles. *Sol. Phys.* **292**, 156 (2017). <https://doi.org/10.1007/s11207-017-1173-5>. arXiv: 1708.05034
- Reames, D.V.: The “FIP effect” and the origins of solar energetic particles and of the solar wind. *Sol. Phys.* **293**, 47 (2018a). <https://doi.org/10.1007/s11207-018-1267-8>. arXiv 1801.05840
- Reames, D.V.: Abundances, ionization states, temperatures, and FIP in solar energetic particles. *Space Sci. Rev.* **214**, 61 (2018b). <https://doi.org/10.1007/s11214-018-0495-4>. arXiv 1709.00741
- Reames, D.V.: Corotating shock waves and the solar-wind source of energetic ion abundances: power laws in A/Q . *Sol. Phys.* **293**, 144 (2018c). <https://doi.org/10.1007/s11207-018-1369-3>. arXiv 1808.06132
- Reames, D.V.: Four distinct pathways to the element abundances in solar energetic particles. *Space Sci. Rev.* **216**, 20 (2020). <https://doi.org/10.1007/s11214-020-0643-5>. (arXiv 1912.06691)
- Reames, D.V., Richardson, I.G., Barbier, L.M.: On the differences in element abundances of energetic ions from corotating events and from large solar events. *Astrophys. J. Lett.* **382**, L43 (1991). <https://doi.org/10.1086/186209>
- Reames, D.V., Ng, C.K., Mason, G.M., Dwyer, J.R., Mazur, J.E., von Rosenvinge, T.T.: Late-phase acceleration of energetic ions in corotating interaction regions. *Geophys. Res. Lett.* **24**, 2917 (1997). <https://doi.org/10.1029/97GL02841>
- Richardson, I.G.: Energetic particles and corotating interaction regions in the solar wind. *Space Sci. Rev.* **111**, 267 (2004). <https://doi.org/10.1023/B:SPAC.0000032689.52830.3e>
- Richardson, I.G., Barbier, L.M., Reames, D.V., von Rosenvinge, T.T.: Corotating MeV/amu ion enhancements at ≤ 1 AU from 1978 to 1986. *J. Geophys. Res.* **98**, 13 (1993). <https://doi.org/10.1029/92JA01837>

- Schmelz, J.T., Reames, D.V., von Steiger, R., Basu, S.: Composition of the solar corona, solar wind, and solar energetic particles. *Astrophys. J.* **755**, 33 (2012). <https://doi.org/10.1088/0004-637X/755/1/33>
- Sylwester, B., Sylwester, J., Phillips, K.J.H., Kepa, A., Mrozek, T.: Solar flare composition and thermodynamics from RESIK X-ray spectra. *Astrophys. J.* **787**, 122 (2014). <https://doi.org/10.1088/0004-637X/787/2/122>
- Van Hollebeke, M.A.I., McDonald, F.B., von Rosenvinge, T.T.: The radial variation of corotating energetic particle streams in the inner and outer solar system. *J. Geophys. Res.* **83**, 4723 (1978). <https://doi.org/10.1029/JA083iA10p04723>
- von Steiger, R., Schwadron, N.A., Fisk, L.A., Geiss, J., Gloeckler, G., Hefti, S., Wilken, B., Wimmer-Schweingruber, R.F., Zurbuchen, T.H.: Composition of quasi-stationary solar wind flows from Ulysses/solar wind ion composition spectrometer. *J. Geophys. Res.* **105**, 27217 (2000). <https://doi.org/10.1029/1999JA000358>
- Wang, Y.-M., Sheeley: Solar wind speed and coronal flux-tube expansion. *Astrophys. J.* **355**, 726 (1990). <https://doi.org/10.1086/168805>
- Xu, F., Borovsky, J.E.: A new four-plasma categorization scheme for the solar wind. *J. Geophys. Res. Space Phys.* **120**, 70 (2015). <https://doi.org/10.1002/2014JA020412>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.