Abstract

Gradual solar energetic-particle (SEP) events are “big proton events” and are usually much more “gradual” in their decay than in their onset. As their intensities increase, particles streaming away from the shock amplify Alfvén waves that scatter subsequent particles, increasing their acceleration, eventually limiting ion flow at the “streaming limit.” Waves generated by higher-speed protons running ahead can also throttle the flow of lower-energy ions, flattening spectra and altering abundances in the biggest SEP events. Thus, we find that the A/Q -dependence of scattering causes element-abundance patterns varying in space and time, which define source-plasma temperatures T , since the pattern of Q values of the ions depends upon temperature. Differences in T explain much of the variation of element abundances in gradual SEP events. In nearly 70% of gradual events, SEPs are shock-accelerated from ambient coronal plasma of ~ 0.8 – 1.6 MK, while 24% of the events involve material with $T \approx 2$ – 4 MK re-accelerated from residual impulsive-suprathermal ions with pre-enhanced abundances. This source-plasma temperature can occasionally vary with solar longitude across the face of a shock. Non-thermal variations in ion abundances in gradual SEP events reaccelerated from the 2–4 MK impulsive source plasma are reduced, relative to those in the original impulsive SEPs, probably because the accelerating shock waves sample a pool of ions from multiple jet sources. Late in gradual events, SEPs become magnetically trapped in a *reservoir* behind the CME where spectra are uniform in space and decrease adiabatically in time as the magnetic bottle containing them slowly expands. Finally, we find variations of the He/O abundance ratio in the source plasma of different events.

We begin by showing proton intensities in the classic large gradual SEP event of 4 November 2001 in Fig. 5.1. This event, from a source longitude of W17 on the Sun, has the typical time profile of a centrally located event (see Sect. 2.3.3). The

Fig. 5.1 Proton intensities vs. time from the NOAA/GOES satellite are shown for the large gradual SEP event of 4 November 2001 at solar longitude W19 (compare Fig. 2.2). Distinctive event phases are listed along the *abscissa* (Reames 2013 © Springer)

figure lists phases of the event along the abscissa, which we will study in approximate time order, although onsets were discussed previously in Sect. 3.1.

In impulsive SEP events, most particles traveled to us scatter free so we had little need to discuss transport. With increased intensities, protons from gradual SEP events generate or amplify their own spectrum of resonant Alfvén waves for pitch-angle scattering, which complicates their transport more and more as intensities increase. In fact, it is the resonant waves, generated by the out-flowing particles, which scatter subsequent particles back and forth across the shock, incrementally increasing ion velocity, driving particles to higher and higher energy.

For recent reviews of gradual SEP events see Desai and Giacalone (2016), and Lee et al. (2012). For theoretical background see Parker (1963) and Jones and Ellison (1991).

5.1 Parallel Transport

5.1.1 Diffusive Transport

The diffusion of particles of type X and velocity v by pitch-angle scattering with scattering mean free path λ_X with a power-law dependence on radial position r as $\lambda_0 r^\beta$ varies as (Parker 1963; see Eq. C1 in Ng et al. (2003))

$$n_x(r, t) = \frac{1}{4\pi\Gamma(\varepsilon)} \left(\frac{\varepsilon}{3}\right)^{2\varepsilon-1} \left(\frac{3}{\lambda_0 v t}\right)^\varepsilon \exp \left[\frac{-3r^{(2-\beta)}}{(2-\beta)^2 \lambda_0 v t} \right] \quad (5.1)$$

where $\varepsilon = 3/(2 - \beta)$ and β must be less than 2.

If we examine the ratio of species X and Y , where λ is a power of rigidity P and where $L = \lambda_X/\lambda_Y = R^\alpha = ((A_X/Q_X)/(A_Y/Q_Y))^\alpha$, as a result of the rigidity dependence of λ , and $\tau = 3r^{2-\beta}/[\lambda_Y(2-\beta)^2 v]$, remembering that $\log x \approx 1-1/x$, it can easily be shown (e.g. Reames 2016a, b) that

$$X/Y = L^{-\varepsilon} \exp[(1 - 1/L)\tau/t] \approx L^{\tau/t-\varepsilon} \quad (5.2)$$

The ratio in Eq. (5.2) is the enhancement or suppression relative to that ratio at the SEP source and does not include any pre-enhanced impulsive suprathermal ions, although those are also power-law in form. Thus, relative abundances vary approximately as a *power of* A/Q . This will prove to be important in determining source-plasma temperatures (Sect. 5.6). If the ratio $R > 1$, as for Fe/O, the abundance ratio, X/Y begins at infinity and falls asymptotically to $R^{-\alpha\varepsilon}$. Ratios begin at infinity because diffusion does not account for the particle transit time at the onset. Breneman and Stone (1985) observed that element abundance enhancements were power laws in A/Q , rising with A/Q in some SEP events and falling in others as we saw in Fig. 2.5 in Sect. 2.5.1. In standard diffusion theory, scattering does *not* change with time; thus, the waves affect the particles, but the particles have no effect on the waves (defying energy conservation).

5.1.2 Wave Growth

The amplification of Alfvén waves by streaming protons has been discussed in textbooks on plasma physics for many years (e.g. Stix 1962, 1992; Melrose 1980; see also Ng et al. 2003; Rice et al. 2003; Li et al. 2005). In quasi-linear theory, ions, streaming along the magnetic field $\mathbf{B}$, resonate with Alfvén waves of wave number k :

$$k \approx \frac{B}{\mu P} \quad (5.3)$$

in the rest frame of the waves. Here $P = pc/Qe$ is the rigidity of a particle of charge Qe , and momentum p , and μ is the cosine of its pitch angle relative to $\mathbf{B}$.

Equation (5.3) results from quasi-linear theory (QLT) where particles are assumed to orbit the unperturbed field and the electric field vector of the resonant circularly-polarized Alfvén wave rotates so as to maintain its phase relative to the direction of rotation of the gyrating particle. This resonance maximizes the transfer of energy between the wave and the particle, seen as pitch-angle scattering in the rest frame of the wave, or wave frame, approximately the plasma rest frame.

The growth rate of the σ polarization mode of Alfvén waves (see Ng et al. 2003; Stix 1992; Melrose 1980) produced by protons is clearest and simplest in the wave frame, where it is given by

$$\gamma_{\sigma}(k) = 2\pi^2 g_{\sigma} e^3 c V_A \iint d\mu dP \frac{P^3}{W^2} R_{\mu\mu}^{\sigma} \frac{\partial f_H^{\pm}}{\partial \mu} \quad (5.4)$$

where $g_{\sigma} = \pm 1$ for outward (inward) wave direction and $f_H^{\pm}$ is the proton phase-space density in each corresponding wave frame. Here W is the total proton energy, and $R_{\mu\mu}^{\sigma}$ is the resonance function (see Ng and Reames 1995; Ng et al. 2003) that imposes the resonance condition (Eq. 5.3) while allowing for resonance broadening near $\mu \approx 0$. Resonance broadening overcomes the limitation of QLT that prevents scattering across $\mu = 0$ (Ng and Reames 1995). If we can ignore the effects of slow propagation of the waves, then the wave intensity of the σ mode, $I_{\sigma}(k, r, t)$ obeys the simple equation

$$\frac{\partial I_{\sigma}(k, r, t)}{\partial t} = \gamma_{\sigma}(k, r, t) I_{\sigma}(k, r, t) \quad (5.5)$$

also in the wave frame, where we have explicitly shown the dependence upon space r and time t , which may be quite significant. We will see that the pitch-angle diffusion coefficient for protons depends linearly upon the intensity of resonant waves (Sect. 5.1.3). Equation (5.5) was used by Ng and Reames (1994) to study time-dependent wave growth during proton transport that was quantitatively consistent with the streaming limit as we will see in Sect. 5.1.5.

Thus, streaming protons grow the waves, and those waves scatter the subsequent protons to reduce the streaming and the wave growth. This causes the scattering mean free paths to vary in both time and space (Ng et al. 1999, 2003). While the wave growth caused by heavier ions is negligible, they respond to the waves in ways that are not always obvious, a priori. Waves, grown by protons at a particular value of μP , resonate with other energies and other species with the same value of μP , as shown in Eq. (5.3).

Wave growth is commonly combined with quasi-parallel shock acceleration, where scattering is especially important. However, wave growth is entirely a transport phenomenon, its dependence upon the particles is only through $\partial f_H^{\pm} / \partial \mu$; it is otherwise completely independent of the nature of the proton source. Wave growth will also be important near quasi-perpendicular shocks when streaming intensities of protons become large. This point is sometimes overlooked by students.

Working in the wave frame is illustrative but inconvenient when both inward and outward waves are present and when the Alfvén speed V_A decreases as r^{-1} with distance. Transforming to the plasma frame introduces terms of order $(V_{SW} + g_\sigma V_A)/v$ (see e.g. Ng et al. 2003).

5.1.3 Particle Transport

The equation of particle transport may be simplified in the fixed inertial frame where f is the phase-space density of a given particle species averaged over gyrophase (Roelof 1969; Ng and Reames 1994; Ng et al. 1999).

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial r} + \frac{1 - \mu^2}{r} v \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu} \left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right) = G \quad (5.6)$$

The third term in Eq. (5.6) represents focusing of the particles in the diverging magnetic field while the fourth term represents pitch-angle scattering with the diffusion coefficient $D_{\mu\mu}$. Here v is the particle speed, μ is its pitch angle cosine, and the term G on the right-hand side of the equation represents particle sources, for example, it might be a power-law energy spectrum times a delta-function at the radial location of a shock wave.

The diffusion coefficient $D_{\mu\mu}$ is given by

$$D_{\mu\mu} = \frac{v^2}{4P^2} \sum_\sigma \int dk I_\sigma R_{\mu\mu}^\sigma \quad (5.7)$$

where P is the particle rigidity and σ runs over wave modes. The wave intensity I_σ and the resonance function $R_{\mu\mu}^\sigma$ were discussed in the previous section.

The set of Eqs. (5.4–5.7) completely describe the evolution of both particles and waves and their coupling. Equation (5.4) shows that the growth of waves is controlled by the streaming particles and Eq. (5.7) relates the particle scattering to the intensity of waves. *Scattering causes wave growth as a direct consequence of energy conservation* (Ng et al. 2003, Appendix B).

5.1.4 Initial Abundance Ratios

We noted above that in diffusion theory, when λ has a power-law dependence on rigidity, hence upon A/Q , ratios like Fe/O or He/H begin with large enhancements that decrease with time. While this occurs for small gradual SEP events, Fig. 5.2 shows that He/H can reverse in large SEP events where wave growth becomes important. This is an example of a case where waves that control the arrival of protons depend upon the proton's velocity, but those that affect He, for example, depends upon protons of a much higher velocity, at their common value of μP ; those protons already arrived and generated their waves much earlier.

Fig. 5.2 Particle intensities and abundance ratios are shown for small (*left*) and large (*center*) gradual SEP events (Reames et al. 2000 © AAS). Initially He/H ratios fall in the small event but rise in the large one. Proton spectra at times A, B, C, and D, (shown in the *right panel*) are much more intense (*gray circle*) in the large October event (*red*), their greater wave generation causing initial suppression of He/H (*gray arrow*) since He in the ratio resonates with waves produced by copious higher-energy protons that arrived much earlier than the H in the ratio

Why does the initial behavior reverse for He/H in the large event? The early ions stream out into space from the event with $\mu \approx 1$ with few resonant Alfvén waves and little scattering. The H at 2 MeV, for example, has suffered little scattering and is only beginning to make its own resonant waves. He at 2 MeV amu^{-1} , however, is scattered by waves that were amplified by 8-MeV protons (same rigidity) that came out much earlier. If the intensity of 8-MeV protons is high (i.e. a big event), they arrive earlier and generate waves so the newly arriving 2-MeV amu^{-1} He will be trapped near the shock since it is scattered much more than the 2-MeV H. Similar logic applies to He/H at higher energies. This effect does not occur for Fe/O since both species are scattered by earlier proton-generated waves. Waves that scatter Fe are coupled to protons of quite high energy, which are less intense, so they actually increase Fe/O initially. The progression of enhancements is modeled by Ng et al. (2003).

5.1.5 The Streaming Limit

In a study of large SEP events observed at the *Helios* spacecraft in solar orbit, Reames (1990) noticed that there was an early plateau period (see Fig. 5.1) during large SEP events near 1 AU, where the proton intensities seemed to have an upper limit of intensity as shown in Fig. 5.3.

Fig. 5.3 Initial intensities of 3–6 MeV protons are shown overlapped for six large SEP events, all near 1 AU. Intensities do not seem to exceed $\sim 200 \text{ (cm}^2 \text{ sr s MeV)}^{-1}$ early in the events, but can become much higher later when shock peaks arrive (Reames 1990 © AAS)

The intensities can rise much higher at the shock peaks, which are at the particle source, because particles at the shock have no net streaming. The streaming limit is a transport phenomenon.

Imagine an experiment that slowly increases the SEP injection intensity at a source near the Sun. At first, the intensity at 1 AU would increase proportionally. Then, at higher source intensities, wave growth would begin to scatter and trap the particles, with most wave growth near the source where intensities are highest. Eventually, further increasing flow from the source would increase the wave growth and scattering so much that the intensity at 1 AU would no longer increase. This is the “streaming limit” that also emerges from theoretical transport models that include wave growth (e.g. Lee 1983, 2005; Ng and Reames 1994; Ng et al. 1999, 2003, 2012). The intensity behavior at 1 AU vs. that at the source near the Sun is shown in the left panel of Fig. 5.4 while the right panel shows the spatial dependence caused by increasing injection levels at the source.

Note that the wave growth depends upon the *absolute* value of the streaming intensity and the parameters shown in Eq. (5.4); there are *no arbitrarily adjustable*

Fig. 5.4 The *left panel* shows intensity at 1 AU vs. that at 0.1 AU. The *right panel* shows the spatial variation as the source intensity level is increased with linear behavior at low intensities (see Ng and Reames 1994; Ng et al. 2003, 2012)

parameters. The peak intensity in the left panel of Fig. 5.4 is just over $200 \text{ (cm}^2 \text{ sr s MeV)}^{-1}$, similar to the value observed in Fig. 5.3.

However, the plateau intensities in the largest gradual SEP events can involve more than just waves that are self-generated by particles of a single energy. They can involve waves generated by higher-energy protons that contribute to the scattering of lower-energy ions by coupling through the μ dependence of Eq. (5.3). These waves preferentially retard the lower-energy particles and flatten the power-law source spectra on the plateau as seen in the left panel of Fig. 5.5. Intense protons of 10–100 MeV stream out early, generating waves as they scatter toward smaller μ . Waves generated at high P and low μ resonate with ions of low P and $\mu \approx 1$ which are coming behind more slowly. Thus, waves amplified by protons of 10 MeV at $\mu \approx 0.5$ will scatter protons at 2.5 MeV and $\mu \approx 1$, retarding their flow and thus flattening their spectrum at 1 AU.

Some proof of this mechanism is given by its absence in the 2 May 1998 SEP event; its plateau proton spectrum is shown in the right panel of Fig. 5.5. The spectrum in this event remains a power law since the intensity of 10 MeV protons is two orders of magnitude smaller than that in 28 October 2003. The low intensities of 10–100 MeV protons do not generate enough waves to suppress the low-energy spectrum in the May event. The theoretical fits to these spectra, shown in Fig. 5.5, support this explanation. Wave growth can control spectral shape.

Fig. 5.5 The *left panel* shows energy spectra of H and O in five large gradual SEP events (all GLEs) that are flattened at low energies (Reames and Ng 2010 © AAS). The *right panel* shows that the small event of 2 May 1998, with greatly reduced H intensities at 10–100 MeV (gray arrows), cannot generate enough waves to suppress lower energies. Model fits to the spectra are shown in gray and purple curves (see Ng et al. 2012)

5.1.6 Electron Transport

Non-relativistic electrons cannot resonate with Alfvén waves, so they do not participate in much of the physics we have just described. Low-energy electrons usually propagate scatter free with highly-anisotropic angular distributions mainly because of absorption by the solar wind of 0.1–1 Hz frequencies that would resonate with these electrons. Electron spectra often show a break in the ~100-keV energy region. Above the break the spectrum steepens and the width of the angular distribution broadens as scattering becomes much more important (see Tan et al. 2011). It is sometimes erroneously concluded that 1 MeV electrons are accelerated much later than those at 20–50 keV in SEP events; this apparent delay could result from transport rather than acceleration (Strauss and le Roux 2019).

5.2 Angular Distributions

Not surprisingly, angular distributions also show the effects of increased scattering when high proton intensities amplify waves. This is seen in the angular distributions of H and He ions in large and small SEP events as shown in Fig. 5.6. The particle intensities remain clustered along the field direction around 180° for more than a day

Fig. 5.6 Intensities (*top*) and angular distributions, relative to B , for H (*middle*) and ^4He (*bottom*) are shown for small (*left*) and large (*right*) gradual SEP events. Note the much higher intensity of the (red) 19–22 MeV protons in the *upper right panel*

in the angular distributions of the small event on the left in Fig. 5.6 but, in the more intense event on the right, the angular distributions begin to spread in only a few hours.

Of course, the scattering and the wave growth depend upon the initial wave intensity. However, small impulsive and gradual events usually remain scatter-free and angular distributions rapidly isotropize in more-intense gradual events and especially in GLEs (see Reames et al. 2001). Most SEP events begin nearly scatter free at energies above a few MeV amu^{-1} , but not at low energies where μ -coupling shown in Fig. 5.5 applies and traps ions with energies below a few MeV amu^{-1} near their source.

5.3 Models and Shock Acceleration

General information about shock formation and acceleration may be found in comprehensive review articles (Jones and Ellison 1991; Lee et al. 2012; Desai and Giacalone 2016). However, there is such compelling experimental evidence of wave growth in the larger gradual SEP events that we focus on models that include it.

The earliest time-equilibrium model of shock acceleration with self-consistent treatment of particles and waves was the work of Bell (1978a, b) on GCRs, which was subsequently adapted to interplanetary shocks by Lee (1983). Shock models were applied to acceleration of GeV protons in the corona by Zank et al. (2000, see

Fig. 5.7 The *left panel* shows the time evolution of the proton energy spectrum at the shock for the first ~10 min. The *right panel* shows the time evolution of the spatial distribution of 12.3 MeV protons upstream of the shock. Once accelerated at ~3 min, 12.3 MeV proton intensities form a streaming limit within 0.1 R_S of the shock at ~4.2 min (Ng and Reames 2008 © AAS)

also Lee 2005, Sandroos and Vainio 2007, Zank et al. 2007, Afanasiev et al. 2016, 2018).

The time-dependent self-consistent model of particle transport with wave amplification (Ng et al. 2003) was applied to shock acceleration by Ng and Reames (2008) resulting in modeling of the time-evolution of the proton spectra at the shock shown in Fig. 5.7 along with the evolution of the radial dependence of the intensity upstream of the shock for a given energy proton. A streaming limit soon forms within 0.1 R_S of the shock as seen in the right panel.

An interesting feature of the time-dependent numerical acceleration calculations is the growth of waves as the proton spectrum grows to higher energy. With the growth of waves that resonate with particles of the highest energy E_1 and rigidity P_1 , some protons will begin to be accelerated to still-higher energy E_2 and rigidity P_2 . Initially, the only waves that can trap ions at E_2 are those that resonate with protons with $\mu_2 < P_1/P_2$, i.e. only at small μ_2 can ions at the new energy find resonant waves generated by lower-energy protons. Thus at each new energy the particles begin with a pancake distribution at small μ (Ng and Reames 2008).

The Ng and Reames (2008) model prevents the scattering from approaching the Bohm limit by requiring that the scattering mean free path be more than three times the particle gyroradius, so that the quasi-linear approximation remains valid. This makes the maximum energy lower and the acceleration rate slower than that in the calculation of Zank et al. (2000), who assumed the more-likely Bohm limit where scattering mean free path equals the particle gyroradius, i.e. $\delta B/B \approx 1$, as has been observed in strong shocks (Lario and Decker 2002; Terasawa et al. 2006). It is also true that an oblique shock, where ions gain energy in the $\mathbf{V}_S \times \mathbf{B}$ electric field, can affect the acceleration time and maximum energy by increasing the particle energy gained on each traversal of the shock. We would speculate that a fast shock

traversing a sufficiently dense seed population should have no trouble accelerating GeV protons in a minute or so.

Ng and Reames (2008) solved the self-consistent time-dependent wave-particle interaction while Zank et al. (2000) used a series of instantaneous steady-state solutions in their PATH (Particle Acceleration and Transport in the Heliosphere) model. The latter simplicity gave a better determination of maximum particle energies of GeV and allowed the inclusion of more-realistic two-dimensional versions of the CME and shock in the PATH models, including oblique shocks (Li et al. 2012) and perpendicular diffusion of the particles caused by random walk of the magnetic fields (Hu et al. 2017, 2018).

It can not escape our attention that it is much easier for theoreticians to work in a universe where particle scattering is constant in time, and waves never grow. Quasi-perpendicular shocks need no change in scattering to increase acceleration, only a small change in θ_{Bn} . Such approximations are often useful in making tractable solutions to explore specific functional dependences. However, observations show that wave growth dominates the largest SEP events. Further realistic studies that include it could help advance our understanding of these important events.

5.4 Shock Acceleration In Situ

Traveling interplanetary shock waves near Earth are the local continuation of the CME-driven shock waves that produce gradual SEP events. These shocks provide an opportunity to directly measure, in situ, the properties of accelerated particles together with the characteristics of the shock and its driver under an extremely wide variety of shock conditions (see e.g. Berdichevsky et al. 2000). Desai et al. (2003) showed that low-energy ion abundances near the shock peak were much more closely related to ambient abundances of those ions upstream of the shock than to the abundances of the corresponding elements in the solar wind, as might be expected from our discussion of the seed population in Sect. 2.5.3. Desai et al. (2004) found that energy spectra at the shocks were better correlated with the spectra upstream than with those expected from the shock compression ratio. Especially for low-energy ions, shock acceleration persists far out from the Sun and tends to reaccelerate ions from the same population that was accelerated earlier.

The choice of a location to measure the ambient, background, or reference abundances and spectra upstream of the shock is difficult. If it is chosen prior to the time that shock leaves the Sun, perhaps $\sim 2\text{--}3$ days before the shock arrival, then solar rotation insures that background is sampled at a longitude of $26\text{--}40$ degrees to the west of the longitude sampled at the shock peak. If it is chosen hours prior to the shock arrival, background will be dominated by particles accelerated earlier by the same shock. Neither choice is ideal.

In effect, the re-acceleration of ions from the seed population found in the reservoir of an earlier event evokes the classical two-shock problem considered, for example, in the review by Axford (1981) and subsequently by Melrose and Pope

(1993). Here, the integral equilibrium distribution function $f(p)$ of momentum p of accelerated particles from a shock with compression ratio s is

$$f_a(p) = ap^{-a} \int_0^p dq q^{a-1} \phi(q) \quad (5.8)$$

where $a = 3s/(s-1)$ and $\phi(p)$ is the injected distribution. If we take $\phi(p)$ as a delta function at p_0 we find a power-law spectrum $f_a(p) \sim (p/p_0)^{-a}$ after the first shock. If we reapply Eq. (5.8), injecting $f_a(p)$ into a shock with compression ratio s' and let $b = 3s'/(s'-1)$, we find that integrating the power law gives.

$$f_{a,b}(p) = \frac{kab}{p_0(b-a)} \left[\left(\frac{p}{p_0} \right)^{-a} - \left(\frac{p}{p_0} \right)^{-b} \right] \text{ for } a \neq b. \quad (5.9)$$

The corresponding intensity is $j(E) = p^2 f(p)$.

Note that Eq. (5.9) is symmetric in the powers a and b , and will be dominated by the shape of the hardest, flattest spectrum, either the background (i.e. a) or the new shock, b . Thus, it is no surprise that one finds local-shock spectra that are dominated by the shape of the upstream background spectrum (Desai et al. 2004; Reames 2012) produced earlier when the shock was stronger. It is quite often that ions with properties from an earlier epoch seem to be only “trapped” at a shock when their intensities are actually being increased by that shock. A further complication occurs when we include a spectral knee with a factor like $\exp.(-E/E_0)$ (e.g. Ellison and Ramaty 1985; see also Mewaldt et al. 2012) to allow for the finite acceleration time. At energies above the knee, observers will find spectra that are much steeper than either the background or the expected equilibrium spectra.

These possibilities for spectral shapes were considered in the observations of Reames (2012), who studied ^4He spectra of $\sim 1\text{--}10$ MeV amu^{-1} in 258 in situ interplanetary shocks observed near Earth by the *Wind* spacecraft (<https://www.cfa.harvard.edu/shocks/>). The purpose of this study was to determine which shock parameters were important to produce measurable particle acceleration and which were not. Figure 5.8 shows well-defined shock event No. 83.

Particle intensities in Fig. 5.8 are shown in the upper left panel, the plasma parameters: solar-wind speed V_{sw} , magnetic field intensity B , and density N , in the lower left panel, and the shock and background spectra in the upper right panel. The times over which the two spectra are taken are shown in the upper left panel (Bk and Sh). This is a quasi-perpendicular shock with the angle between B and the shock normal, $\theta_{\text{Bn}} = 80^\circ \pm 3^\circ$.

Figure 5.9 compares properties of the shocks in this study. The left panel shows a histogram of the shock speed distribution for all of the shocks and for the subset that showed measurable particle acceleration. High shock speed was the strongest determinant for measurable acceleration, followed by high shock compression ratio, and large θ_{Bn} . High background intensity was also important: more input produced more output. Measurable acceleration was more than twice as likely for shocks with $\theta_{\text{Bn}} > 60^\circ$ as for those with $\theta_{\text{Bn}} < 60^\circ$. Quasi-parallel shocks, i.e. small θ_{Bn} , may

Fig. 5.8 Particle intensities are shown vs. time in the *upper left panel* with plasma parameters *below* for shock number 83. Spectra of the shock and background are shown to the *right* with spectral slopes indicated (Reames 2012 © AAS)

have been more likely to have knee energies below the energy of observation. Recently, Zank et al. (2006) have suggested that “higher proton energies are achieved at quasi-parallel rather than highly perpendicular interplanetary shocks within 1 AU.” The in situ observations (Reames 2012) show the opposite; quasi-perpendicular shocks are favored; this difference likely occurs because ample pre-accelerated seed populations were available for these real shocks.

The right panel in Fig. 5.9 shows the background-corrected peak shock intensity of 1.6–2.0 MeV amu⁻¹ ⁴He as a function of shock speed. The shock speed has a

Fig. 5.9 The *left panel* shows the distribution of shock waves at 1 AU with measurable acceleration of $>1 \text{ MeV amu}^{-1} {}^4\text{He}$ vs. shock speed (*green*) within the distribution of all 258 shock waves vs. shock speed (*yellow and green*) observed by the *Wind* spacecraft. The *right panel* shows the background-corrected peak intensity of $1.6\text{--}2.0 \text{ MeV amu}^{-1} {}^4\text{He}$ versus shock speed for the shocks in situ. Shock speed is the strongest determinant of accelerated intensity for local shocks; this mirrors the correlated behavior of peak intensity versus CME speed in Fig. 2.12 (adapted from Reames 2012 © AAS, Reames 2013)

correlation coefficient of 0.80 with intensity. This correlation for in situ shocks mirrors the correlation of peak proton intensity with CME speed in Fig. 2.12 as modified by Rouillard et al. (2012) and shown in the lower right-hand panel of Fig. 3.4.

Particle intensities peak at the time of shock passage in nearly all of the events in the Reames (2012) study. However, sometimes intensities peak before or after shock passage when a spacecraft encounters magnetic flux tubes that connect it to a stronger part of the shock nearby, perhaps even one with a different value of θ_{Bn} .

Absolute intensities of accelerated particles are not directly predicted by acceleration theories that omit wave growth. The rate of injection of seed particles is treated as an adjustable parameter—more input results in more output, and this is the case for in situ events. However, streaming protons and increasing wave intensities can trap particles near the source. At a few powerful shock waves, such as 20 October 1989, it has been observed that the energy in energetic particles exceeds that in the plasma and magnetic field (Lario and Decker 2002). Those authors suggested that the peak intensities of particles up to 500 MeV are simply trapped in a region of low density and low magnetic field near a shock. Maybe, but, how did they get there? Surely they were accelerated there near the peak intensity even though their spectrum may reflect shock properties from an earlier time (see Eq. 5.9). Perhaps the wave-trapped particles are in the process of destroying (i.e. pushing apart B at) the shock that accelerated them. Another shock where the particle energy exceeds the magnetic energy is that of 6 November 2001, in Fig. 5.1 (C. K. Ng, private communication), where the sharp proton peak up to 700 MeV shows a shock that

is still clearly intact. This is the issue of “cosmic-ray-mediated” shocks discussed by Terasawa et al. (2006) for two additional interplanetary shocks. This is a fascinating process that can be observed, in situ, at some interplanetary shocks.

5.5 Averaging SEP Abundances

We began by discussing the reference abundances in Chap. 1 and comparing them with the solar photospheric abundances as a function of first ionization potential (FIP) in Fig. 1.6 (see also Chap. 8). The reference abundances are obtained by averaging over many gradual SEP events. Since the transport of particles varies as a power of A/Q (see Eq. 5.2), different species such as Fe and O will be distributed differently in space and time, but these particles are likely to be conserved. If we can successfully average over time or space we will recover the source abundances. If this assumption is correct and our averaging is representative, the reference abundances will approach the coronal abundances. Evidence for the space-time distribution is shown in Fig. 5.10.

The SEP event on the East flank of the CME (W85 source, on the left in Fig. 5.10), shows enhancement of Fe/O early then suppression later, since Fe, with higher A/Q , scatters less than O. Ne/O, involving similar values of A/Q , varies little. Solar rotation and the Parker spiral translates this time variation into a spatial one and the events toward the West flank of the CME show mainly depleted Fe/O.

5.6 Source-Plasma Temperatures

Since particle transport of gradual SEPs varies as a power of A/Q , and Q varies with T , we can use this power law to find the source-plasma temperature T that gives the best-fit pattern vs. A/Q , just as we did for impulsive events. Figure 5.11 (similar to Fig. 4.8) shows A/Q vs. T with Q derived from the atomic physics.

The red shaded region in Fig. 5.11 is 2.5–3.2 MK, corresponding to active region temperatures that we found for the impulsive SEP events that reflect the temperature of active-region jets where the SEPs originate (see Sect. 4.6). As we decrease T below this region, O, then N, then C move from the 0-electron to the 2-electron closed shells. Meanwhile, Ca, then Ar, then S, then Si, then Mg move from the 2-electron to the 8-electron shells. Thus, we can tell the temperature by the pattern of abundance enhancements. We need only notice which elements are in which group; which elements have no enhancement like He; which elements are in the group with Ne; which are in the group with Ar.

Figure 5.12 compares the observed pattern of enhancements early in a large gradual SEP event (on the left) scaled to the pattern of A/Q (on the right). The patterns match best near $T \approx 0.6$ MK, an unusually low temperature for an SEP event. Note that C, N, and O have moved well above He to the 2-electron shell with Ne, while Mg, Si, and S have moved up to the 8-electron shell close to Ar and Ca. Patterns of enhancement in other SEP events are shown in Reames (2016a).

Fig. 5.10 Intensities of C, Ne, and Fe are shown for three gradual SEP events at different solar longitudes in the *lower panels*, relative abundances in the *middle panels*, and the location and evolution of a CME *above* (after Reames 2014 © Springer)

For the LEMT telescope on the *Wind* spacecraft, 8-h intervals during a large SEP event will provide adequate statistics for the rarer elements to determine enhancement patterns. For each 8-h period we can calculate least-squares fits of enhancement vs. $A/Q(T)$ for all values of T in the range of interest and plot χ^2 of the fit vs. T (upper-right panel in Fig. 5.13). The minimum value of χ^2 gives the best-fit temperature and power of A/Q for that time interval. This process gives the

Fig. 5.11 A/Q is plotted as a function of the theoretical equilibrium temperature for the elements named along each curve. Points are spaced 0.1 units of $\log_{10} T$ from 5.7 to 6.8. Bands produced by closed electron shells with 0, 2, and 8 orbital electrons are indicated, He having no electrons at this T . Elements tend to move from one closed-shell group to another as the temperature changes. (Data for $Z \leq 28$ from Mazzotta et al. 1998, for $Z > 28$ from Post et al. 1977)

source-plasma temperature as a function of time during an event, as shown in the upper-left panel of Fig. 5.13 for the event of 8 November 2000. For this event we find temperatures near 1 MK for all time periods with either abundance enhancements or suppressions. For two of the time periods, the best fits to enhancement vs. A/Q are shown in the lower-right panel of Fig. 5.13. However, for time periods when enhancements in the abundances are flat, neither enhanced nor suppressed relative to the coronal reference abundances, we cannot measure T , since any A/Q values will fit and χ^2 has no minimum. Larger enhancement or suppression of the abundances produces clearer minima in χ^2 and smaller errors in T .

Fig. 5.12 The *left panel* shows the abundance enhancements at $\sim 3\text{--}5$ MeV amu^{-1} observed early in the 22 May 2013 SEP event. The *right panel* compares a section of the A/Q vs. T plot from Fig. 5.11. The patterns match best at about 0.6 MK (Reames 2016a © Springer)

For 45 gradual SEP events that had reasonably well-defined temperatures, Reames (2016a) found:

- 69% (31 events) showed ambient coronal temperatures $T \leq 1.6$ MK
- 24% (11 events) had $2.5 \leq T \leq 3.2$ MK active region temperatures, like impulsive SEP events where $T \approx 3$ MK is the typical temperature in solar jets associated with active regions (see Fig. 14 in Raouafi et al. 2016).

Some (11) of the events with ambient coronal temperatures showed a second minimum at the upper limit of T in χ^2 vs. T . These were originally attributed to the possible presence of stripped ions, but have been subsequently found to be artificially induced by variations in the source abundances of He (Reames 2017b; see Sect. 5.9). Subsequent studies omit H and He from fits (see Chap. 9).

While the gradual-event temperatures and fit parameters are not strongly correlated with any particular properties of the accelerating CME or shock,

Fig. 5.13 Clockwise from the *lower-left panel* are the intensities of H, C, and Fe during the 8 November 2000 SEP event, the enhancements in Fe and Ne during the event, the best-fit temperatures in *color-coded* 8-hr intervals, values of χ^2/m vs. T for each time interval (where m is the number of degrees of freedom), and fits of enhancements from samples (*blue filled square* and *red filled circle*), early and late in the event, relative to O, vs. A/Q (Reames 2016a © Springer)

Fig. 5.14 shows T vs. CME speed. The un-weighted correlation coefficient is -0.49 for these events. Events that happen to be GLEs are identified in the figure; their temperature distribution and other properties are similar to those of the other gradual SEP events.

We now realize that attempts to study abundance cross-correlations in gradual SEP events were often ineffective because most variations were caused by temperature differences that previously were not known. For example, the average value of Fe/O is a factor of ~ 10 higher in gradual events with $T = 3.2$ MK than in those with $T = 1.5$ MK. This is shown in Fig. 5.15 which plots normalized Fe/O vs. C/He, for intervals during the gradual SEP events, in both panels, with T as symbols in the lower panel and power of A/Q as symbols in the upper.

Fig. 5.14 Source-plasma temperature is shown as a function of associated CME speed for gradual SEP events with GLE events identified (data from Reames 2016a)

The region of abundances showing active-region temperatures $T \geq 2$ MK is immediately distinguishable, clustering in the upper left of the lower panel of Fig. 5.15. These events, which get their enhanced Fe/O from their impulsive seed population which also has enhanced He (see Sects. 5.8 and 5.9), are distinguished as open circles in the upper panel as well. Points during large events accelerated from specific temperatures of ambient coronal plasma stretch from upper right, with steep positive A/Q enhancements early in the events, toward the lower center, where the A/Q slopes are reduced or negative, late in the same events.

The events beginning in the large gray circle in the upper right corners of the panels in Fig. 5.15 are all high-fluence, $T < 2$ MK events with >30 MeV proton fluences above 10^7 protons $\text{cm}^{-2} \text{sr}^{-1}$. The intense streaming protons early in these events are likely to generate waves that increase particle scattering and steepen the positive A/Q dependence early in the events (e.g. Fig. 9.18), enhancing both Fe/O and C/He. Smaller events with $T < 2$ MK lack large enhancements of Fe/O. The events with $T > 2$ MK are also smaller but they get their Fe/O enhancement from their impulsive seed population. Thus, gradual SEP events can become Fe-rich either by reaccelerating Fe-rich impulsive suprathermal ions or by having protons intense enough that self-generated waves preferentially transmit Fe and retard O.

One might well ask: why do we use theoretical values of Q vs. T when there are actually direct measurements of Q in some events (see Sect. 2.6)? Direct measurements can determine distributions of Q which may not be isothermal and may differ somewhat from element to element. Primarily, direct measurements are rare, especially above 1 MeV, where deflection in the Earth's field is usually required (e.g. Leske et al. 1995). Also, in impulsive events, for example, Q_{Fe} measured at 1 AU, is observed to increase with energy at low energies (e.g. DiFabio et al. 2008),

Fig. 5.15 Normalized abundance ratios Fe/O vs. He/C is plotted in both panels with *symbol size* and *color* representing T (lower panel) and power of A/Q (upper panel). (Reames 2016b © Springer). The large circle surrounds “big events” with high fluences of >30 MeV protons

suggesting that the ions have traversed enough material after acceleration to strip them to equilibrium charges that depend only upon their velocity, i.e. they are stripped to high Q . The theoretical charges, obtained from abundance measurements, are more likely to be appropriate earlier, i.e. at the time of acceleration. In addition, the theoretical charges from atomic physics are available for essentially all elements we measure and abundance measurements are often available at places and times where direct measurements are not. Thus we can measure the average source plasma temperatures wherever abundance measurements are available, but, unfortunately, these measurements do not determine charge distributions, distinguish multiple sources, or assess small temperature variations among elements, as direct measurements can.

An alternative method suggested for measuring ionization states in large SEP events involves fitting the Q/A -dependent shapes of the intensity-time profiles using diffusion theory (Sollitt et al. 2008). The comparison of this diffusive method with the power-law techniques is presently somewhat limited, and, unfortunately, we will see in the next section that the time decay profile of SEP events is actually controlled much less by diffusion than by the expansion of a magnetic trapping volume called the *reservoir*.

5.7 Spatial Distributions and the Reservoir

As spacecraft began to probe more-distant areas of the heliosphere, it became possible to view spatial distributions of SEPs, and their time variations, within a single SEP event. While spatial gradients were expected, it was rather surprising when equal intensities of ~ 20 MeV protons were found over long distances of solar longitude of $\sim 180^\circ$ on the *Pioneer* spacecraft by McKibben (1972). Twenty years later equal intensities were found in radius late in large events between *Ulysses* at 2.5 AU and IMP 8 near Earth by Roelof et al. (1992) who named the regions “reservoirs.” Reservoirs extend to *Ulysses* at heliolatitudes up to $>70^\circ$, N and S (Lario 2010), and they are also seen in other electron observations (Daibog et al. 2003).

The two spacecraft of the *Helios* mission provided another opportunity to measure the evolution of SEP events at different longitudes confirming that the longitude distribution of Fig. 2.2 was appropriate for each individual event. Figure 5.16 shows that, at widely separated spacecraft, the intensities merge with that at *Helios 1* as each of the other spacecraft, *Helios 2* and IMP 8, joins it in the reservoir. Spectra are identical throughout the reservoir but intensities decrease adiabatically with time as the volume of this “magnetic bottle” expands. (The drawing in the lower panel of Fig. 5.16 shows the spacecraft penetrating the CME; in reality, of course, the spacecraft are nearly stationary as the CME expands past them, but that version would be much more difficult to draw.)

If there were significant leakage from the reservoir, one would expect the highest-energy protons to leak first, since they are faster, scatter less, and encounter the

Fig. 5.16 The *upper left* panel shows the intensities of 3–6 MeV protons at three spacecraft vs. time. The paths of the spacecraft into the expanding CME are shown *below* as they penetrate into the reservoir region (*red hashing*) behind the shock and CME where all intensities and spectra (*upper right*) are equal spatially, though they decrease with time as the trapping volume expands (Reames 2013; after Reames et al. 1997b © AAS)

boundary most often, but this would steepen the spectrum with time and is *not* observed. Thus the leakage must be minimal.

One common, but rather poor, way of comparing spatial variations is to plot peak intensity at each of three spacecraft vs. longitude and fit the three points with a parabola. Does this measure particle spread in longitude? Suppose we made such a plot with the data shown in Fig. 5.16. The intensity at *Helios 1* peaks at the time of local shock passage. The intensity at *Helios 2* peaks when it enters the reservoir, where it has the same intensity as *Helios 1*. The intensity at IMP 8 peaks when it enters the reservoir later, where *all three intensities are equal*. What does the parabola defined by these three peak intensities measure? Is it the spread of the particles or the spread in the trapping volume behind the CME with time? The peaks all occur at different times and that *essential* timing information is lost when plotting

Fig. 5.17 In invariant spectral regions, particle intensities at different energies maintain the same relative normalization as a function of time, as shown for different species in two different events (Reames 2013; after Reames et al. 1997a, b © AAS)

only peak intensities vs. longitude. Isn't it more important to note that all intensities are equal when the intensity at IMP 8 peaks? It seems more productive to try to *distinguish* spatial and temporal effects rather than combining them.

For a single spacecraft, one way to show that spectra do not change their shape in time is to normalize the intensity-vs.-time plots at one point in time. If they stay normalized subsequently, then the spectral shapes are invariant. This is shown for two gradual SEP events in Fig. 5.17. This technique demonstrates invariance even when the spectra do not have power-law form. Multiple spacecraft at different locations can be included or abundance variations can be compared similarly.

Note that a reservoir can sometimes extend upstream of the CME and shock on the East flank, as seen in the left panel of Fig. 5.17; here the particles may be partly contained by self-amplified waves from earlier streaming or by other preexisting magnetic boundaries.

The realization that the slow decline in a gradual SEP event results from expansion of a reservoir is most important because it displaces the previous idea that slow particle spatial diffusion detained the ions to explain the decay phase of events. Actually, reservoirs are scatter free, as shown by the striking example of the little scatter-free ^3He -rich event from Mason et al. (1989) shown as Fig. 2.3 in Sect. 2.3.4. A whole literature of fitting SEP events to diffusion theory had emerged, leading to the “Palmer (1982) consensus” that “ $\lambda_{\parallel} = 0.08 - 0.3$ AU over a wide range of rigidity.” This is yet another example of the misapplication of diffusion theory; the intensity decline comes from the expansion of a magnetic bottle in time, not inefficient transport through space. There are no significant spatial gradients within reservoirs.

In some events we may use abundances to map variations of source plasma temperatures across the face of the shock and back into the reservoir. Figure 5.18 shows a temperature analysis that compares conditions at the STEREO B and the *Wind* spacecraft during an SEP event on 31 August 2012.

Fig. 5.18 Time variations of (a) intensities, (b) Fe/O, and (c) derived source plasma temperatures are compared at STEREO B (*closed symbols*) and Wind (*open symbols*) for the SEP event of 31 August 2012 where spacecraft locations are shown above. Probable entry of the spacecraft into a reservoir occurs sometime on 3 September as noted in (c). Curves of χ^2/m vs. T used to select the best-fit temperatures are shown in (d) and (e) and fits to enhancements vs. A/Q are shown at STEREO (f) before (September 1) and after (September 3) reservoir entry (Reames 2017a © Springer)

The event in Fig. 5.18 shows the presence of hot ($\sim 3\text{--}4$ MK) source plasma at the well-connected spacecraft (STEREO B), but not an enhancement from impulsive seed particles, and ambient coronal plasma (~ 1.6 MK) on the flanks of the CME (at *Wind*). This condition persists until both spacecraft seem to have entered a reservoir, where similar intensities (Fig. 5.18a) and lower-temperature plasma (Fig. 5.18c) prevails.

Similar temperature variations across the face of the shock are possible, but less dramatic, in other events that have been measured (Reames 2017a). In one event, 23 January 2012, a spectral break disrupts the abundances, but we successfully revisit this event in Sect. 9.7. Spectral breaks are likely to make it difficult to derive temperatures from abundances; breaks are more likely above ~ 10 MeV amu^{-1} . At low energy (< 1 MeV amu^{-1}), shock waves accelerate ions far out into the heliosphere, sampling a widely varying seed population that may blur temperatures. In addition, strong suppression of low-energy spectra by the streaming limit (see Fig. 5.5) may disrupt temperature measurements at energies below 1 MeV amu^{-1} . Thus, ion temperatures for gradual SEP events are best measured in the range of 1–10 MeV amu^{-1} .

5.7.1 Reservoirs, Loops, and Long-Duration γ Rays

It is important to recognize that reservoirs trap energetic ions in an expanding volume above the solar surface for a long period of time. While this population of particles tends to be mirrored by the converging magnetic fields above the corona, some undoubtedly scatter into the loss cone and plunge into the corona to produce γ -rays (just as the particles in flaring loops must do on a much faster time scale). Vestrand and Forrest (1993) observed γ -ray production spanning over $\approx 30^\circ$ of the Sun's surface in the large GLE of 29 September 1989. More recently, Plotnikov et al. (2017) found three events for which CMEs from *behind the solar limb* drove quasi-perpendicular shock waves around to the footpoints of field lines on the visible disk, producing long-duration emission of > 100 MeV γ -rays.

Ryan (2000) discussed long-duration γ -ray events lasting an hour or more while the flare-associated X-rays died away rapidly. See, also, the long-duration γ -ray observations by Ackermann et al. (2014) and Ajello et al. (2014). Share et al. (2018) studied 29 long-duration events with > 100 MeV γ -rays. They concluded that the γ -rays resulted from the decay of neutral π mesons produced by shock-accelerated > 300 MeV SEP protons trapped in the reservoirs behind these events. Reservoirs provide an invariant spectrum of shock-accelerated ions that can bombard a large area of the solar corona with energetic SEP proton intensities that slowly decrease over many hours or days. The SEPs trapped in a reservoir may have difficulty directly penetrating the magnetic fields above active regions, and the higher-energy SEPs may begin to reach the lower solar corona only as the trapping volume widens laterally beyond the active region. In some cases studied by Share et al. (2018), the > 100 MeV γ -ray intensity rises slowly for several hours before it eventually begins

to decrease, suggesting a slow increase in the area of the reservoir footprint on the Sun.

Gopalswamy et al. (2019) found a strong correlation of the duration of events with sustained γ -ray emission with the frequency and duration of associated type II radio emission. They found that the tail of the γ -ray event “seems to last until the end of the associated type II burst.” Evidently both types of emission were associated with shock acceleration, as would not be too surprising if CMEs drive shocks and trap reservoirs. However, Gopalswamy et al. (2020) found an unusual geometry in the 1 September 2014 SEP event, where a shock wave was driven along an east-west flux rope, accelerating protons that plunged into the corona at the end of the flux rope, producing π^0 mesons and their energetic γ -ray decays. Thus, some γ -ray events are produced directly by shock-driven proton events.

Those few events where the γ -rays seem to exceed estimated production by the observed proton spectra can be explained by poor magnetic connection. For example, a case where the nose of the shock is seen to be driven toward high latitude above the ecliptic so the Earth only samples an inadequate soft proton spectrum from the flank of the shock. All of the γ -ray events can be reasonably explained by shock-accelerated protons (Gopalswamy et al. 2019, 2020).

5.8 Non-thermal Variations: Impulsive vs. Gradual SEPs

Knowing the source-plasma temperatures allows us to compare impulsive and gradual SEP events from the same temperature source—i.e. impulsive SEP ions and impulsive seed particles. Figure 5.19 compares the normalized abundances of O/C vs. C/He for impulsive and gradual SEP events plotted at the same scale. The impulsive events have been limited to those with modest $<20\%$ statistical errors in the ratios and the gradual events at $T \geq 2$ MK come from impulsive seed ions.

Especially at a temperature of 3.2 MK (red symbols in Fig. 5.19) the elements He and C are likely to be fully ionized with $A/Q = 2$ and O is nearly so (as seen in Fig. 5.11). Thus the ratios should be unaltered source abundances for both populations. However the dashed line also shows that the normalization is wrong for C/He since the central mean should be at 1.0 if properly normalized. This suggests that the reference abundance He/O should be 91 rather than 57. This would bring He in somewhat better alignment with other high-FIP elements on a FIP plot (Fig. 1.6) and is shown as a red open circle on that figure.

More significantly, the spread in the distribution of gradual events is much smaller than that of impulsive events in Fig. 5.19. The spread in the impulsive events must come from non-thermal abundance variations in the local plasma of jets where the magnetic reconnection is occurring. However, neither wave-particle interactions nor magnetic reconnection can alter C/He when both elements have $A/Q = 2.0$. If the shock wave of a gradual SEP event were accelerating only suprathermal ions from a single impulsive source, we would expect the same non-thermal distribution for gradual events that we see for impulsive events. This is *not* the case.

Fig. 5.19 Enhancements of O/C vs. C/He are compared, for gradual events with $T \geq 2.0$ MK (*upper panel*) and impulsive events with $< 20\%$ errors so that the spread is not from statistical errors (*lower panel*). Both panels are plotted at the same scale and T is indicated by the size and color of the symbols. (1) The distribution is much smaller for the gradual events. (2) The median of the distribution of C/He for the gradual events, shown as a dashed line, implies a reference value for He/O of 91 rather than 57 (Reames 2016b © Springer)

As the shock in a gradual event passes over an active region, it must average contributions (1) from impulsive suprathermal ions, which have enhancements in Fe/O and $^3He/^4He$, for example, and perhaps (2) from ions in the ambient ~ 3 MK plasma, which have no such enhancements. Ko et al. (2013) found that Fe-rich gradual SEP events were commonly connected to active regions. The result of the

two contributions is to reduce the enhancements, as observed, and somewhat reduced distributions in the spread of abundance ratios, more like those in the upper panel of Fig. 5.19.

However, if we really expect to reduce the spread of the distributions as seen in the gradual events, we need to average over *several* small jets producing impulsive SEP events rather than only one; n events will reduce the spread by a factor of $\sqrt{n}$. Thus a pool of 10 contributing events with 30% abundance variations would reduce the average variation of the seed population below 10%. It is likely that the number of small impulsive SEP events in an active region increases as the event size decreases, contributing a fairly steady flow of impulsive suprathermal ions; each temporarily contributes to the potential seed population before it diminishes. Based on the increasing number of flares with decreasing size, Parker (1988) proposed that a large number of small nanoflares could actually heat the corona. We need only a small increase in the number of jets producing impulsive SEP events that are too small to resolve as separate events, yet adequate to contribute to the seed population in the pool of impulsive suprathermal ions above a solar active region which may be subsequently sampled and averaged by a shock wave. Thus, no single impulsive event determines the seed population for acceleration by the shock wave in a subsequent gradual SEP event.

Many small jets (i.e. microjets or nanojets?) probably also contribute to the periods of persistent ^3He seen by Wiedenbeck et al. (2008), of long-lived and recurrent sources (Bučík et al. 2014, 2015; Chen et al. 2015), often generated by “geysers” that produce multiple jets (e.g. Paraschiv and Donea 2019), and, of course, to the substantial persistent ^3He abundances below 1 MeV amu^{-1} in the seed population directly observed at 1 AU “upstream” region (labeled period A) in Fig. 2.8 where ^3He -rich, Fe-rich periods in the seed population are seen on 20 and 21 June 2000 and Fe-rich periods (labeled B) again on 24 and 25 June after the shock wave of interest (e.g. Desai et al. 2003).

Source-plasma temperatures provide a powerful new tool for the comparative study of SEP events.

5.9 The Abundance of He and the FIP Effect

The preceding section suggests that He/O, in both impulsive SEP events and in gradual events that re-accelerated impulsive ~ 3 MK plasma, may be similar to the average value of He/O in the solar wind, while He/O can be much lower in gradual events involving cooler (< 2 MK) ambient source plasma. He variations should not come as a complete surprise since variations of He/O are also seen in the solar wind as functions of time and of solar-wind speed (Collier et al. 1996; Bochsler 2007; Rakowsky and Laming 2012). The study of the source-plasma temperatures of gradual SEP events (Reames 2016a) originally assumed the source had He/O = 57

Fig. 5.20 Best fits to enhancement vs. A/Q assuming the source $\text{He}/\text{O} = 57$ at times during three gradual SEP events (Reames 2017b). For (a) the He enhancement is too low, for (c) it is too high, and for (b) it is approximately correct (i.e. in agreement with the fit of other ions) for both enhanced and suppressed periods of Fe/O

as derived from the SEP average. For some events, however, He fell far from the least-squares fits of enhancements vs. A/Q for all the other elements, as seen in Fig. 5.20a, c.

For the SEP event of 23 August 2005 in (a), for which $T = 1.0 \pm 0.2$ MK, a lower value of source $\text{He}/\text{O} \approx 45$ would lift the enhancement of He to the fit lines. For the 6 November event (c), with $T = 2.5 \pm 0.2$ MK, a value of source $\text{He}/\text{O} \approx 100$ would drive He down to the fit lines. However, for the event of 14 July 2000, with $T = 1.2 \pm 0.2$, the average value of source $\text{He}/\text{O} \approx 57$, or slightly less, seems quite reasonable for both ascending and descending enhancement periods (Reames 2017b). He, the element with the highest FIP (24.6 eV), is the slowest element to ionize during its transit of the chromosphere into the corona, so its abundance is most likely to lag that of the other elements (Laming 2009, 2015); thus, low values of He/O may indicate newly arriving coronal ions while high values suggest established abundances.

The distribution vs. T of the values of the source He/O that would be required for the observed He/O to fit the power-law defined by the $Z > 2$ elements in each 8-h interval is shown in Fig. 5.21. The reaccelerated impulsive-event material at ≈ 3 MK supplies the higher reference He/O material.

Understanding the possible slow ionization of He helps resolve differences in He/O between SEPs and the solar wind, although the remaining differences, especially in C/O , show us that SEPs and the solar wind have different FIP patterns, hence different origins at the base of the solar corona, as we will find in Chap. 8. This will show that SEPs are *not* merely accelerated solar wind. They are a particle population with unique coronal origin.

Fig. 5.21 A histogram for 8-h intervals in gradual SEP events of the source value of He/O required for the He/O abundance enhancement to fit the power-law distribution defined by the elements with $Z > 2$, as a function of the best-fit source-plasma temperature (Reames 2017b © Springer)

5.10 Open Questions

This section suggests open questions that might be addressed in future research.

1. What can cause the large non-thermal spread of abundances such as C/He in impulsive SEP events in Fig. 5.19 when both He and C should be fully ionized? Does source depth in the corona matter?
2. How well do SEP-derived temperatures correlate with differently-determined coronal temperatures near the observer's magnetic footpoint early in a gradual SEP event?
3. How can reservoirs contain particles of all energies with such apparently equal efficiency? How do they attain uniformity of intensities across longitudes when the particles upstream of the shock do not? Is diffusion along the turbulent shock front a factor?

4. In principle, a shock could accelerate 1-MK plasma at one longitude and 3-MK plasma at another longitude. Only one clear case is seen. Is there enough lateral transport in and behind the shock to mix SEPs from these sources in the reservoir late in events?
5. Which events have reservoirs and which do not? What is the difference?
6. What happens when the energy in SEPs exceeds the energy in B at a shock, especially a quasi-perpendicular shock? Can it do so? Does acceleration cease?
7. Measurements on a spacecraft nearer the Sun can improve SEP onset timing by removing the blurring effect of scattering during transport. How does the SEP onset SPR time at 10-second resolution compare with X-ray and γ -ray-line onsets, type II burst timing, and shock observations? Note that intensities may vary as $\sim r^{-3}$, causing extremely high rates in instruments. To what extent does electron and ion source timing differ in gradual SEP events? In impulsive events?
8. Discrete ionization states affect the assignment of source-plasma temperatures. $^{12}\text{C}^{+5}$ is enhanced but $^{12}\text{C}^{+6}$ is not; treating Q as 5.5 is approximate. $A/\langle Q \rangle$ is not the same as $\langle A/Q \rangle$. Then there is ^{13}C which always has high A/Q . Can we improve the estimates of T ?

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