Distinguishing the Sources

3

Abstract

Our discussion of history has covered many of the observations that have led to the ideas of acceleration by shock waves or by magnetic reconnection in gradual and impulsive solar energetic particle (SEP) events, respectively. We now present other compelling observations, including onset timing, SEP-shock correlations, injection time profiles, high-energy spectral knees, e/p ratios, and intensity dropouts caused by a compact source, that have helped clarify these acceleration mechanisms and sources. However, some of the newest evidence now comes from source-plasma temperatures. In this and the next two chapters, we will find that impulsive events come from solar active regions at ≈ 3 MK, controlling ionization states Q , hence A/Q , and, in most gradual events, shocks accelerate ambient coronal material from ≤ 1.6 MK. When SEPs are trapped on closed loops they supply the energy for flares. In addition to helping to define their own origin, SEPs also probe the structure of the interplanetary magnetic field.

The history in Chap. 2 suggested how the flow of observations and ideas eventually led to credible evidence of two sites of SEP acceleration and the related physical mechanisms. While some observations have been described, some of the clearest evidence of origin has not yet been presented. In this chapter we continue the story of particle origin, showing where and when SEPs are accelerated, and measurements that allow us to compare impulsive and gradual events. There are many different lines of evidence that fit together to determine the most probable origins, and that evidence continues to grow.

3.1 SEP Onset Times

Even in relatively intense SEP events, it is likely that the earliest detectable particles at each energy will be those that were originally focused in the diverging magnetic field in the inner heliosphere and have scattered least, simply traversing along the magnetic field line from the source with an average pitch-angle cosine, $\langle\mu\rangle \approx 1$, so that they arrive first. An example of the observed arrival times of particles of different energies is shown in Fig. 3.1. The rise of the intensities is clear and sharp and intensities rise by two or three orders of magnitude. If 1% or more of the ions in each energy interval have traveled with $\langle\mu\rangle \approx 1$, we will be able to determine the scatter-free onset time with reasonable accuracy. The accuracy of this scatter-free approximation has been well studied and will be discussed below. As discussed in Sect. 2.3.4, impulsive events are all almost entirely scatter-free. The particle transit time $t = L/v$ where L is the path length along the field line and v is the particle velocity. By fitting the measurements we can determine both the path length and the time that the particles left the Sun, the so-called solar particle release (SPR) time.

Note that the SPR time is the release time *at the Sun*; to compare with photon observation times at Earth one should add 8.3 min to the SPR time. The path length of 1.11 ± 0.02 AU allows for some curvature of the Parker spiral, typically 1.1–1.2 AU. For large gradual events, including the ground level events (GLEs), generally the SPR times occur quite late in the event. Timing in impulsive (left) and gradual (right) events is compared in Fig. 3.2.

For the impulsive SEP events in Fig. 3.2, the SPR times fall rather precisely on the hard-X-ray peak times (there are no measurable γ -rays in these events). For the

Fig. 3.1 The *left panel* shows the arrival of ^4He ions of the indicated MeV amu^{-1} intervals at the *Wind* spacecraft near Earth. The *right panel* shows the onset time of these and other intervals vs. v^{-1} . For the fitted line, the slope is the pathlength and the intercept is the solar particle release (SPR) time at the Sun for this large gradual GLE event (Reames 2009a, © AAS)

Fig. 3.2 A comparison is shown of timing in two impulsive (*left*) and two gradual (*right*) SEP events. Solar particle release (SPR) times of the particles (*red with dashed errors*) are compared with hard X-ray (*dark blue, left*), γ -ray (*dark blue, right*) and GOES soft X-ray (*violet*) time profiles. Onset times of metric (m) and decametric-hectometric (DH; 1–14 MHz) type II and III radio bursts (*light blue*) and CME locations (*green*) are shown (adapted from Tylka et al. 2003)

Fig. 3.3 The *right panel* shows the height of the CME at SPR time vs. longitude for numbered GLEs. The cartoon on the *left* shows the CME and SPR location widening on the flanks (Reames 2009a, b © AAS). The height distribution is fit to a symmetric parabola for comparison; actually a height of 2–3 R_S is fairly constant over $\sim 70^\circ$. This could be the width of the source shock surface above closed loops that was once incorrectly called the “fast propagation region”. SPR may differ on each local SEP field line, while type II onset occurs near the source longitude

GLEs, the SPR times often fall well after the γ -rays are over (by up to 30 min), but always after the metric type II onset indicates the formation of a shock wave. Rouillard et al. (2016) relate the SPR delay to the time required for the shock to become supercritical, i.e. $\text{Mach} > 3$.

It is interesting to plot the height of the CME leading edge at SPR time as a function of longitude of the observer relative to that of the CME source as shown in the right panel of Fig. 3.3 for the GLEs. For a multi-spacecraft study of a single event see Reames and Lal (2010).

Clearly a correct estimate of the SPR time depends upon the intensities being sufficiently high that a small number of un-scattered ions are detectable. Gopalswamy et al. (2012) have simply assumed a path length of 1.2 AU in order to avoid the velocity-dispersion analysis. However, Rouillard et al. (2012, see Appendix) have calculated that the error in the SPR time from scattering should be less than 1–2 min., comparable with errors from the 5 min-averaged data used. If scattering delayed low energies more, the apparent SPR would be too *early*. Note also that the *impulsive* events on the left in Fig. 3.2 show *no* evidence of onset errors. Tan et al. (2013) have found that the SPR times and path lengths of the non-relativistic electrons agree with those of the ions, and Rouillard et al. (2012) have also shown lateral spreading of the shock wave as imaged by the coronagraphs.

High-energy (GeV) protons are often strongly beamed along the interplanetary magnetic-field $\mathbf{B}$, so a particular neutron monitor on Earth sees a peak when its asymptotic look direction is aligned with $\mathbf{B}$. As $\mathbf{B}$ varies, neutron monitors often see spiky increases or multiple peaks and valleys of intensity.

Surely there are a few GLEs where the SPR timing alone would permit some kind of (unspecified) acceleration at the time of the associated flare. However, these events may just have faster CMEs or a faster decrease in V_A with radius that would permit earlier ion acceleration by the shock, or earlier arrival of the shock above closed magnetic loops. If the GLEs with late SPR times are clearly shock accelerated, why would we seek a new mechanism for those events with earlier SPR times which have equally strong shocks? Shock acceleration is able to account for SEP acceleration in all gradual events, including GLEs, especially in GLEs. No other mechanism is required, no other seems capable.

3.2 Realistic Shock-SEP Timing and Correlations

With recent measurements on the STEREO spacecraft, it has been possible to construct three-dimensional distributions of CMEs and shocks and compare them with SEPs, i.e. to compare the SEPs and the shock along the same single field line (Rouillard et al. 2011, 2012, 2016). Figure 3.4 shows aspects of this comparison.

The left-hand simulation in Fig. 3.4 reconstructs the way the CME and shock spread. The actual SPR time depends upon the time an active shock actually strikes the (dashed) field line to an observer. It would be a great improvement on the comparison in Fig. 3.3 if we could see the *local* shock as we can here. Some images of the shock are shown in the upper right panels of Fig. 3.4.

The lower-right panels in Fig. 3.4 show correlations of peak proton intensities at 2 and 20 MeV with CME speed from the earlier study by Kahler (2001) shown in Fig. 2.12. However, no single speed exists for any CME or shock, and there is no single peak proton intensity, since both vary strongly with longitude. The red points in the lower right panel of Fig. 3.4 compare intensity and CME speed on single magnetic flux tubes, apparently improving the correlation. Kouloumvakos et al. (2019) have extended the CME-SEP correlations by modeling the 3D geometry of

Fig. 3.4 Left-hand panels show a STEREO simulation of the evolution and lateral spread of the CME and shock. Upper-right panels show actual images of the shock. Lower right panels show possible improvement in the intensity—CME-speed correlation (red points) when observed on single field lines at two different longitudes in an event (Rouillard et al. 2011, 2012 © AAS)

shock waves using the three coronagraph images from SOHO/LASCO and STEREO A and B, as noted in Sect. 2.10.

More recently, Gopalswamy et al. (2013) studied the first GLE of Solar Cycle 24, GLE 71 on 17 May 2012, together with 6 other large, well-connected events with fast CMEs. The evolution of two of the CMEs is compared in Fig. 3.5.

In the GLE, the shock formation height (type II radio burst onset) is at $1.38 R_S$ and the observed CME height at the time of particle release was directly measured as $2.32 R_S$. This is consistent with the findings from extrapolations of GLEs in Cycle 23. The authors concluded that the event of May 2012 was a GLE simply because it was better connected to Earth than the other large SEP events with similar or even faster CMEs. Note that the SPR time is the SEP onset on the local field-line longitude of the SEP observer, while the type II onset is at a longitude nearest the source; hence, the type II onsets do not show the quasi-parabolic behavior of the SPR height in Fig. 3.2.

Thakur et al. (2016, see also Tylka and Dietrich 2009) compared the >700 MeV proton channel on GOES as an alternate indicator of GLEs. They found two events

Fig. 3.5 The time evolution of two CMEs, 9 August 2011 and the GLE on 17 May 2012, are shown from their first appearance on SOHO/LASCO. In panels (a) and (e), the SDO/AIA solar image at 195 Å shows the solar sources while the remaining difference images show evolution of the CMEs and shocks. *Red arrows* point to the CME nose. The shock remains closer to the CME in (h) than in (d), indicating a stronger shock (Gopalswamy et al. 2013 © AAS)

that differed, one GLE with no increase at >700 MeV and one >700 -MeV increase that was not a GLE. They ascribed the difference to the level of the background. They also found that GLEs were generally observed when the shocks form at 1.2 – $1.93 R_S$ and when solar particle release (SPR) occurs between 2 – $6 R_S$. Note that the electron acceleration that produces the type II burst could occur while the shock is still propagating within closed magnetic loops, but SPR time must occur where the shock is on open field lines, and at a local longitude.

Clinger et al. (2004) found a strong ($\sim 90\%$) association of decametric-hectometric (DH; 1 – 14 MHz) type II radio emission produced at $\sim 3 R_S$ by SEP events with 20 MeV protons (see Fig. 2.1). The correlation was only 25% for lower-altitude metric type II's without DH, suggesting that shock acceleration is strongest at or above $\sim 3 R_S$.

3.3 Injection Profiles

Relating to SEP increases early in events, Kahler (1994) plotted the intensity of SEPs, not as a function of time, but as a function of the height of the CME, using the height-time plot for the CME, as shown in Fig. 3.6. Not only are the protons injected

Fig. 3.6 Injection profiles of high-energy protons are shown as a function of CME height for three GLEs in 1989: August 16, September 29, and October 24. The CME speeds for these events are 1377, 1828, and 1453 km s⁻¹, respectively (Kahler 1994, © AAS)

late, but their intensities continue to rise until $R > 6 R_S$, even at 21 GeV. A final peak in the Alfvén speed vs. height occurs at $\sim 4 R_S$ and V_A has probably declined to about 600 km s⁻¹ at $6 R_S$ (Mann et al. 2003; see also Sect. 1.4). The Alfvén-Mach number of the shock, V_S/V_A remains at ~ 2 or greater above $\sim 1.2 R_S$ for these shock waves.

3.4 High-Energy Spectra and Spectral Knees

Are GLEs fundamentally different from other gradual SEP events? Is it likely that there is some new source of particles that can only be seen at energies above ~ 0.5 GeV? Much of the evidence connecting gradual SEPs to shock acceleration, especially element abundances and source-plasma temperatures, comes from energies below 100 MeV. Do the high-energy spectra come from the same source? Some spectra are shown in Fig. 3.7.

Mewaldt et al. (2012) studied spectra and element abundances of 16 GLEs. They found that the empirical double power-law spectral forms give a better fit than the

Fig. 3.7 The *left panel* shows H and He in the large GLE of September 29, 1989 (Lovell et al. 1998). The *shaded region* is the spectrum deduced from neutron monitors and the spectra are fit to the shock-spectral shape of Ellison and Ramaty (1985). The four *right-hand panels* show GLE fluence spectra that are typical of the 16 GLE spectra assembled by Mewaldt et al. (2012 © Springer) fit to double power-law spectra

power-law-times-exponential spectrum of Ellison and Ramaty (1985, see also Lee 2005) that models escape of high-energy particles from the shock. In any case, *none* of the 16 GLEs showed evidence of high-energy spectral *hardening* that might suggest the existence of a new source that could dominate higher energies.

Tylka and Dietrich (2009) have used the geomagnetic cutoff rigidities at neutron-monitor stations to develop integral rigidity spectra, using data from the world-wide neutron monitor network for 53 GLEs. The proton spectra are fit to double power laws in rigidity, decreasing with a power above 1 GV (430 MeV) in the range of 5–7 in 70% of the GLEs (see Sect. 6.1). None show hardening.

3.5 Intensity Dropouts and Compact Sources

When Mazur et al. (2000) plotted the energy of individual ions as a function of their arrival time, as seen in Fig. 3.8, they found that the pattern of velocity dispersion that we described in Fig. 3.1 was sharply interrupted for time intervals when the spacecraft was simply not magnetically connected to the particle source. This was seen for impulsive SEP events and would be expected if magnetic flux tubes that were connected to a compact source were interspersed with others that were not, as confirmed by theory (Giacalone et al. 2000). Gaps were not often seen in gradual events where a spatially extensive shock wave would be expected to populate all field lines with SEPs.

Fig. 3.8 Panels (a) show the energy vs. the arrival time of individual ions from an impulsive (*left*) and a gradual (*right*) SEP event. Panels (b) show the corresponding ion count rates while (c) and (d) show the magnetic field direction. Particles or gaps occur because some flux tubes connect to the compact source of impulsive SEPs and others do not (Mazur et al. 2000, © AAS)

Subsequent observations (Chollet and Giacalone 2011) found the boundaries between flux tubes with and without SEPs were extremely sharp. This indicated that there was little or no cross-field transport. The mixing of magnetic flux tubes that do and do not connect to any specific location on the Sun is expected from the random walk of their footpoints prior to the particle event (see Sect. 2.3.5).

More-recent observations (Tan and Reames 2016; Tan 2017) have shown that there are occasional dropouts during gradual SEP events as well. Differences in the scattering in some magnetic flux tubes can have an especially strong affect on the intensities and angular distributions of non-relativistic electrons. These profound sudden changes in particle intensities mostly occur when differently-connected flux tubes are sampled inside a passing CME, as measured by multiple spacecraft in the SEP event of 14 December 2006 (von Rosenvinge et al. 2009).

3.6 Abundances

Abundances of elements and isotopes were one of the earliest indications of the two different sources of SEPs:

1. The average abundances of the elements in gradual events, relative to those in the

photosphere, measured a FIP pattern related to the abundances in the corona and solar wind (see Sects. 1.5.2 and 2.5.1). Since they were associated with fast, wide CMEs driving shock waves, this fit well with the idea of a shock wave sampling ambient coronal abundances.

2. The strong 1000-fold enhancements of $^3\text{He}/^4\text{He}$, and the associations with streaming electrons, and with the type III radio bursts they produce, were clearly related to an impulsive source at the Sun and soon connected with narrow CMEs and solar jets (see Kahler et al. 2001; Reames et al. 2014a; Bučík et al. 2018; see also Sects. 2.5.2 and 4.7).

In the next chapters (Sects. 4.6 and 5.6) we will see that the pattern of the power-law dependence of abundance enhancements on A/Q of the ions leads to a determination of Q values and of the associated source-plasma temperature T . The results are:

1. Gradual events: ~69% of events $0.8 < T < 1.6$ MK, 24% of events $T = 2\text{--}4$ MK from re-accelerated impulsive SEP seed ions (Reames 2016).
2. Impulsive SEP events: $T = 2\text{--}4$ MK (Reames et al. 2014a, b).

Thus in 69% of gradual events, shocks sweep up material at ambient coronal temperatures. In 24%, shocks traverse active regions and re-accelerate some residual impulsive suprathermal ions diluted by some ambient active-region plasma, especially protons. We will develop the techniques for determining source temperatures in Sects. 4.6 and 5.6. The temperatures are strong evidence for shock acceleration of large gradual SEP events. Ambient coronal temperatures of SEPs would seem to be hard to explain for those who would like to accelerate gradual SEPs in hot flares, or even to *store* SEPs in hot flare loops. Furthermore, GLEs show a similar distribution of source-plasma temperatures and abundances as non-GLEs. We find nothing unique about the physics of GLEs; they just happen to have harder spectra and direct a few more high-energy particles toward Earth.

3.7 Electrons

In a review article, Ramaty et al. (1980) studied peak intensities of 0.5–1.1 MeV electrons vs. those of 10 MeV protons. For sufficiently intense protons they found a correlation between the electrons and protons that they ascribed to common acceleration by a shock wave. Cliver and Ling (2007) revisited this study from the perspective of impulsive and gradual SEP events. Their interesting findings are shown in Fig. 3.9.

This clever study makes use of the fact that impulsive events are nearly all magnetically well-connected. The known impulsive events show no evidence of electron-proton intensity correlation. The shock-accelerated events span a much larger region of solar longitude and show electron-proton correlation where the

Fig. 3.9 The panels each show peak 0.5-MeV electron intensity vs. peak 10-MeV proton intensity. Events in the *upper panel* are well connected (20–90 W) while those in the *lower panel* are poorly connected. The events in blue are impulsive events that are ^3He -rich with enhanced heavy elements. A proton-intense subset of well-connected events shows a strong correlation while essentially all of the poorly-connected events are correlated (Cliver and Ling 2007 © AAS)

impulsive events are absent, i.e. events that are poorly connected or those that have high proton intensities.

Are the 0.5-MeV electrons accelerated at the same shock as the 10-MeV protons? Apparently so. In general, it is difficult to know how to compare protons and electrons. Unfortunately, low-energy electrons do not resonate with Alfvén waves as low-energy protons do. Should they be compared at the same energy, rigidity, or velocity? Usually the available intervals are used that are neither; yet, despite the lack of an ideal variable for comparison, it is still usually possible to conclude that

impulsive SEPs are electron rich, and that shocks in gradual events accelerate both protons and relativistic electrons.

Recently, an extensive list of over 1000 electron events spanning a solar cycle was prepared by Wang et al. (2012). The list includes radio, CME, X-ray, flare, $^3\text{He}/^4\text{He}$, and 10-MeV proton data.

Electron acceleration at shock waves is a historical problem. There is even lore that shocks cannot accelerate electrons While ions can scatter back and forth against Alfvén waves at the quasi-parallel nose, where the shock is fastest, non-relativistic electrons cannot resonate with Alfvén waves and are not similarly accelerated. However, electrons can be accelerated in the $\mathbf{V}_S \times \mathbf{B}$ electric fields on the oblique flanks of the shock.

Are type-II radio bursts only emitted from the flanks of shocks? No. They come from the nose as well. Type-II emission from the shock nose and flanks can be distinguished because the nose is farther out from the Sun, at lower n_e , and therefore lower frequency; the frequencies can be correlated with the coronagraph image. Actually, type-II emission from the flanks of a shock goes by the special name: diffuse interplanetary radio emission (DIRE; e.g. Gopalswamy 2020).

Electron acceleration at the quasi-parallel nose of a shock probably occurs because real shocks are not planar but are very complex structures, varying in space and time. This complexity was even noted in Jones and Ellison (1991) and has been observed directly in interplanetary shocks with the *Cluster* spacecraft by Kajdič et al. (2019). The fluctuations can even involve θ_{Bn} so $\mathbf{V}_S \times \mathbf{B}$ electric fields may be available everywhere to accelerate electrons. Electrons are certainly accelerated at shocks, they produce type-II emission and they even manage to reach relativistic energies as seen in Fig. 3.9.

3.8 Why Not Flares?

Impulsive SEP events in space are produced by solar jets, not flares. Solar flares exist *precisely* because the SEPs in them are magnetically trapped. Sites of electron acceleration in magnetic reconnection occur above the newly-forming closed magnetic loops at heights of >20 Mm and at densities of a few times 10^9 cm^{-3} (Krucker et al. 2010; Krucker and Battaglia 2014). Ion acceleration is likely to occur at the same location (e.g. Drake et al. 2009). These SEPs eventually scatter into the dense regions of the loop footpoints where they dump all their energy, causing heating and expansion of hot, bright plasma back up into the loops. Observations of γ -ray lines have shown that the energetic ions in flares are ^3He -rich (Mandzhavidze et al. 1999; Murphy et al. 2016) and Fe-rich (Murphy et al. 1991), just like the impulsive SEP events we see in space. However, these γ -rays arise from nuclear reactions that also produce secondary ions of ^2H , ^3H , and isotopes of Li, Be, and B. These reaction products are *not* seen in space. Serlemitsos and Balasubrahmanyam (1975) found $^3\text{He}/^4\text{He} = 1.52 \pm 0.10$, compared with $(4.08 \pm 0.25) \times 10^{-4}$ in the solar wind

(Gloeckler and Geiss 1998), but they also found ${}^3\text{He}/{}^2\text{H} > 300$. Limits on Be/O or B/O in large SEP events are $< 2 \times 10^{-4}$ (e.g. McGuire et al. 1979; Cook et al. 1984). Neutral γ -rays and neutrons (Chupp et al. 1982; Evenson et al. 1983, 1990) from nuclear reactions escape, but SEPs that actually caused the flare never escape the closed magnetic loops. One cannot exclude a stray leak from a flare, but that must be swamped by SEPs from the shock source.

In Carrington’s (1860) first observation of a flare, he was “surprised . . . at finding myself unable to recognize any change whatever as having taken place.” The fields maintain their shape. Modern instruments allow measurement of the reconnection magnetic flux and a recent data base contains reconnection flux for 3137 solar-flare ribbon events (Kazachenko et al. 2017). Large reconnection events that lacked fast shock waves produce beautiful flares, but *no* SEPs (Kahler et al. 2017). Flares *require* containment by closed magnetic fields and disrupt the general field topology very little; the field energy transmitted to particles accelerated in flares is dissipated as heat in the footpoints and loops and we do not see these energetic particles in space.

Historically, it has been the neutron monitors that have been used most often to try to associate a flare source with GLEs. These are the *biggest* events, where *everything* happens, and are the most prone to the errors of causal association that result from “big flare syndrome” (Kahler 1982). Worse yet, neutron monitors do not measure particle abundances, their energy measurements are limited, and anisotropic intensities of streaming GeV protons are often modulated by variations in the direction of the interplanetary magnetic field relative to the asymptotic look direction of a site. At best, neutron monitors mainly measure timing, and many physical processes, including shock acceleration, can be fast.

We prefer to study SEPs measured in the *smallest* events, to identify sources. Jets (Sect. 4.7) *without* fast shocks give us impulsive SEP events, and disappearing-filament events (Sect. 2.7) drive fast shocks with no flares or jets, yet they give us gradual SEP events that depend upon the shock properties. These smaller, simpler single-source events better define SEP origins.

Flares are bright because they are *hot*, reaching temperatures of 10–40 MK. When we measure the source plasma temperatures of SEPs (see Sects. 2.6, 4.6 and 5.6), we find temperatures of 1–4 MK, i.e. ambient temperatures of coronal plasma. At 10–40 MK, even the elements Ne, Mg, and Si become fully ionized so they all have $A/Q = 2$, just like He, C, N, and O. This hot plasma would not support the observed enhancements seen in Ne/O or even Si/O (Chap. 4). SEPs from hot flare plasma are not seen. The observed properties of SEPs in space are not compatible with such hot flare plasma and closed-field regions do not just open to release them. The SEP sources we once attributed to specific flares most likely come from nearby jets where the SEPs escape rapidly with minimal heating.

To the extent that SEPs in flares are similar to those in jets, flare observations, especially γ -ray lines, could be a benefit in understanding the physics of impulsive

acceleration mechanisms. It would be helpful to have more-extensive measurements of γ -ray lines (Sect. 4.9).

3.9 SEPs as Probes

As SEPs stream out along the interplanetary field they can map its structure. This was shown early by the radio mapping of the electron population in type III radio bursts. Knowing the direction to the center of the radio signal and its distance from the Sun determined by the frequency and models of the electron density vs. radius, the electrons could be followed, as seen in Fig. 3.10. Occasionally, trajectories of this kind can be made using triangulation from two or more spacecraft (Reiner et al. 1998; see also Li et al. 2016). While such electron trajectories generally follow the Parker spiral, it is important to realize that field lines are often distorted by variations in the solar-wind speed and by the passage of CMEs.

Fig. 3.10 The trajectory of the electron population in the type III radio burst accompanying a ^3He -rich SEP event is shown in three dimensions (a) and as a projection on the ecliptic (b) (Reames and Stone 1986 © AAS)

Fig. 3.11 The pitch-angle spectrogram of 40 keV electrons from the 2 May 1998 SEP event is shown in the *upper panel*. Electrons first appear from the Sun at $\mu \approx -1$ near 1400 UT and reflected electrons appear at $\mu \approx +1$ around 1500 UT. The *lower panels* show the field direction (Tan et al. 2013, © AAS)

Low-energy (<100 keV) electrons are often seen passing Earth outbound then returning sunward from a magnetic reflection site beyond Earth (Kahler and Reames 1991; Tan et al. 2012, 2013) as shown in the example in Fig. 3.11. These electrons have highly scatter-free transport (Tan et al. 2011) and are thus excellent probes of the magnetic topology.

Figure 3.12 uses separate incident and reflected electron onset times to determine the release times and pathlengths for each, and also shows He ions, with no reflected beam (Tan et al. 2012). Pathlengths for the incident ions and electrons are quite similar and near the length of the Parker spiral. Electrons depart about 13 min earlier. Reflected electrons travel ≈ 1 AU farther in this event.

However, electrons are not the only particles affected by their journey, Reames and Ng (2002) found that in some SEP events Fe/O was higher for sunward bound ions than for those that were outward bound. Since Fe scatters less than O, the Fe more rapidly passed Earth to be reflected sunward than O, so the returning particles were more Fe-rich, i.e. they had simply traveled farther from the source.

There should be no surprise that the magnetic fields depart from the simple Parker spiral and become quite complex. Not only is there the random walk of field lines

Fig. 3.12 The *upper panel* shows the onset times of both incident and reflected electrons vs. v^{-1} with the fitted release time and pathlength for each. The *lower panel* shows omni-directional data for He (Tan et al. 2012, © AAS). The He SEPs are actually highly collimated for a day after onset; they show no reflection at the same time as the reflected electrons

discussed in Sect. 2.3.5, but there is a constant progression of CMEs that disturb the field as suggested by Fig. 3.13.

The Sun can eject 2.5 CMEs day⁻¹ at solar maximum (Webb and Howard 1994). If each CME occupies one steradian and its typical speed is ~ 400 km s⁻¹, CMEs will be randomly spaced at radial distances of typically ~ 1 AU apart, one after the other, out into the heliosphere in any direction. While most of them would be too slow to

Fig. 3.13 The Sun can emit a progression of CMEs as suggested here. Particles accelerated at a shock preceding the smaller, newer CME can easily be reflected by converging field lines of the outer CME or by turbulence at the shock that precedes it

generate shocks, they would have low β_p and would carry magnetic flux ropes that contribute to magnetic distortions capable of reflecting particles.

Bidirectional flows of protons or electrons are commonly seen within CMEs near 1 AU (e.g. Kahler and Reames 1991; Richardson and Reames 1993). These flows are often used as probes to study the topology of the magnetic fields, and even to identify CMEs. Their common occurrence also shows that pitch-angle scattering is minimal within CMEs.

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