Book Review of “Solar Energetic Particles: A Modern Primer on Understanding Sources, Acceleration, and Propagation” by Donald V. Reames (Springer, 2017). Reviewed by Stephen Kahler.

In 1946 Scott Forbush published the records of ground-based ionization chambers showing three transient increases of space radiation in the GeV energy range that were associated with observed solar flares. Subsequent observations in the 1950s with ground-based neutron monitors revealed more such events (termed GLEs for ground-level events), and the pattern of a large solar flare closely followed by a GLE implied that solar energetic particles (SEPs) were produced in and escaped from the strong magnetic fields of the active region flare site. With the opening of the space age and satellite measurements of space radiation near Earth, the same scenario played out at lower (down to few MeV) energies. The detection of hard X-ray and gamma-ray bursts confirmed the production of energetic electrons and ions, respectively, in solar flares. Besides the basic question of how the particles were accelerated, there was the problem of understanding how those charged particles could propagate through the relatively strong magnetic fields of the solar corona to reach spatial regions many tens of degrees removed in longitude from the flare sites. One popular model of the time, called the bird-cage, envisioned episodic particle releases across spatially separated sets of closed coronal magnetic loops until the particles reached field lines open to the solar wind, along which they escaped the Sun.

There had been indications that the flare-source model had problems. In 1963 a comprehensive survey of solar metric wavelength radio bursts was published, in which one of the five basic types, the type II bursts, was ascribed to shock waves propagating through the corona. The authors suggested that particle acceleration could occur in those shocks, and indeed, good associations between SEP events (confusingly, sometimes SPEs, for solar particle events) and the type II bursts were found. However, the spatial and temporal relationship between the type II bursts and SEP production was not clear, so the concept of SEP production in magnetic loops of solar active regions persisted. This paradigm was challenged only when white light images of the solar corona were returned from the coronagraph instrument on the Skylab spacecraft in 1974. They showed enormous eruptions extending over widths of many tens of degrees from Sun center and with speeds often greatly exceeding that of the ambient solar wind. These coronal mass ejections (CMEs), unobservable from ground-based instruments, made clear what only a few investigators had previously suspected.

So what did CMEs have to do with SEP events? Were they only an interesting side show to the real SEP action in solar flares? Not only was there a good association between type II bursts, CMEs, and SEP events, but fast CMEs driving coronal and interplanetary shocks provided an explanation for the observed organization of the SPE intensity-time profiles, generally rapid from western hemisphere flares and more gradual from sources in the eastern hemisphere. They furthermore accounted for the “energetic storm particle” events seen one to three days later in the decay phases of SPEs. Nevertheless, a significant portion of the solar and space community continued to count the solar flares, covering a few tens of square degrees of the solar surface, as the drivers of all of space weather, including the SEP events.

In 1993, two decades after Skylab, Jack Gosling, a prominent member of the coronagraph team, had finally had enough. He published a provocative article entitled “The Solar Flare Myth” in which he castigated prominent groups and members of the space community for their continued reliance on the solar flare model. The subsequent backlash and rebuttals brought out the basic issues and ultimately resulted in a general acceptance that CMEs were at least the primary drivers of SPEs as well as of geomagnetic storms. This did not end the role of solar flares as players in the production of SPEs, however, as a separate class of SPEs emerged, defined by large abundance enhancements of 3He/4He and of heavy (hi-Z) elements when compared with coronal abundances. These "impulsive" SPEs were generally associated with small solar flares, sometimes accompanied by small CMEs, but not by shocks. Their smaller longitudinal extents and peak intensities further distinguished them from the larger and longer "gradual" SPEs resulting from acceleration in CME-driven shocks.

Work on the properties and solar associations of the two classes of SPEs continued through the 1980s and 1990s and was summarized in a comprehensive 1999 review article by Don Reames, then at NASA/GSFC, which he updated in 2013. Reames has done extensive work on SPEs, largely based on the SEP elemental composition measurements from the GSFC Low Energy Matrix Telescope instrument on the Wind satellite, launched in 1986 and still returning data. He has collaborated with theorists, modelers, and other investigators (including this reviewer) to maximize the scientific return of the SEP data. His efforts were recognized by the Solar Physics Division of the American Astronomical Society with their award of the 2012 George Ellery Hale Prize.

The present book is a concise (127 pages in paperback) and inexpensive ($27 at Amazon) summary of SEP events, which well satisfies the stated goal of the Springer Lecture Notes in Physics series "to be a compact and modern up-to-date source on a well-defined topic". It consists of seven self-contained chapters, each beginning with an abstract and a short introduction, enhanced with well reproduced figures, and ending with a reference list. The first three chapters set the stage with (1) descriptions of the sun and solar activity, (2) a historical exposition on SPEs, and (3) the basic observational distinction between impulsive and gradual SPEs. Chapters 4 and 5 review the impulsive and gradual SPEs and end with lists of open questions for future research. Chapters 6 and 7 cover topics of more immediate interest to the NASA THREE community, radiation effects and methods and limitations of measuring SEPs. Chapter 8 concludes with a two-page summary of nine basic take-aways on SPEs.

The author provides an account of SEPs from their appearance as thermal ions in the solar corona to their effects on humans and instruments at 1 AU. The fundamental scientific limitation in this field is that SEPs are produced in shocks and propagate through interplanetary magnetic fields in collisionless processes that leave no radiative signals for remote observations. The challenge of deducing the nature of the SEP seed particles and the basic processes of acceleration and transport of SEPs has been addressed by a broad range of inferential studies. These necessarily include remote observations and models of the structures of the coronal and interplanetary magnetic fields, models and theory of shock acceleration, solar observations of flares and CMEs with a wide range of wavelengths, and in situ observations of SPE onset timings, energy spectra, and elemental compositions of SEPs.

As charged particles, protons and alphas are the same things for radiation effects and for SEP physics, but high-Z particles are a different story. When treating the radiation effects of high-Z

SEPs with matter, the approximation of charge state Q = atomic number Z is good because the SEP ions will be stripped of their electrons. But for SEP physics the Q is important because the ion acceleration and propagation is determined by the rigidity R = pc/Qe ~ A/Q, where A is the atomic mass. Higher R values mean larger gyroradii in the magnetic wave fields at shocks and subsequently earlier escape from the shock acceleration process and longer mean free paths in propagating through the interplanetary fields. For this reason, the Fe/O ratio in SPEs (measured at the same energy per nucleon) often rises early in SEP events and then decreases because the higher rigidity of Fe favors earlier escape from the shock and more direct propagation through space than for O, with a lower rigidity. This effect in turn implies lower maximum energies in SPEs for Fe than for O, with different resulting radiation effects from the two ions.

SEP charge states are not directly measured, but they are important not only for their propagation effects but also as diagnostics of the shock seed particle populations. The physics of shock acceleration of SEPs depends critically on the charge states and energies of the ambient particles processed by the shocks. Since the acceleration process is collisionless, the initial charge states are retained. If the ambient particles are part of a thermal population, then the charge states define a temperature, which in turn might tell us something about the source population. Reames has recently pioneered a technique to determine the ion source temperatures from the SPE fluences. Basically, the ion event fluences relative to coronal abundances are plotted as functions of A/Q at a given energy/nucleon. As one varies the assumed equilibrium temperature, the A/Q for each ion changes. The optimum temperature is determined when the log-log plot of relative ion fluences versus A/Q attains the best linear fit. The author describes his technique, which results in a significant result that impulsive SPEs are drawn from a population of T = 2.5 to 3.2 MK, which absolutely excludes the T > 10 MK temperature of flare plasmas. Most of the gradual SPEs have T < 2 MK, which excludes the higher temperatures of active regions, but seems about right for ambient solar wind. Relating the SEP source regions to known solar wind sources becomes the next challenge in understanding the basics of SPEs.

There are at least three other recent reviews that include SEPs. “Large gradual solar energetic particle events” by Mihir Desai and Joe Giacalone is a 2016 publication in the Living Reviews in Solar Physics series. That work complements the Reames review with more discussion of energetic storm particle events, multi-spacecraft observations of SPEs, and the theory of shock acceleration. “Energetic Particles in the Heliosphere” by George Simnett (Springer, 2017) also extends beyond SPEs to include solar energetic electrons, energetic particles from interplanetary corotating interaction regions and planetary atmospheres, observations at high heliographic latitudes, and solar anomalous cosmic rays. “Solar Cosmic Rays” by Leonty Miroshnichenko (Springer, 2015) covers particle acceleration at the Sun and interactions of those SEPs with the solar atmosphere. It also has chapters on effects of SEPs in the geosphere, radiation hazards in space, and predictions of SPEs.