Energetic Particle Propagation in Three Dimensions
A White Paper Submitted to the Solar Physics Panel of the 2024 Solar & Space Physics Decadal Survey

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1. Abstract

Ulysses observations during its rapid transit over the polar regions of the Sun challenged our understanding of SEP transport in 3 dimensions. This white paper provides the scientific justification for obtaining new measurements out-of-the-ecliptic plane so that we can fully understand particle transport in the inner heliosphere.

2. Introduction

Solar energetic particles (SEPs) are accelerated at many different locations such as flare loops, sites where magnetic reconnection takes place, and shocks driven by coronal mass ejections (CMEs) as they move through the lower corona into the inner heliosphere. The largest SEP events, which can increase radiation levels near Earth, may be accelerated at more than one location. SEPs can often reach Earth within minutes of the solar explosion, but in other cases could arrive hours later. Our basic understanding of the arrival time differences between two seemingly similar events is that occasionally SEPs can be trapped in closed magnetic loops or scattered by turbulence near the CME shock which, in turn, could delay their escape into interplanetary space. In some cases, the SEPs may only have access to poorly connected interplanetary magnetic field (IMF) lines between the observer and the acceleration region. Eventually when these SEPs do reach an observer, the distinct effects of acceleration, escape, and propagation through a turbulent medium are washed out to such an extent that the source characteristics remain obscured.

Currently, Parker Solar Probe and Solar Orbiter are making ground-breaking measurements close to the Sun, so that we can untangle some of these effects and understand the fundamental processes responsible for the production of SEPs. Understanding the transport of SEPs from acceleration sites at the Sun through interplanetary space is important for forecasting space weather. The propagation of energetic particles through the heliosphere is the affected by [1] the large-scale IMF which has two distinct polarities separated by the global, complex, wavy structure known as heliospheric current sheet (HCS), [2] transient and recurrent structures formed in the solar wind such as shocks and stream interaction regions, and [3] small-scale properties of the IMF characterized by its turbulence (Battarbee et al., 2019). With the notable exception of Ulysses, our current understanding of SEP transport is essentially confined to observations near the ecliptic plane, and is hence inherently 2-dimensional. However, Ulysses data obtained during its rapid transit over the polar regions of the Sun showed several key differences with respect to the near-ecliptic measurements (e.g., Lario et al. 2003; Dalla, 2004).

In particular, significant delays in the arrival of the ions and in reaching their peak intensity was inconsistent with standard models of SEP acceleration and propagation, and was instead attributed to efficient cross-field diffusion of energetic particles across helio-latitudes. Clearly, SEP observations from an out-of-the-ecliptic plane mission during a large sample of events are needed to fully characterize particle transport in the inner heliosphere and understand the physical causes of the differences with respect to the near-ecliptic measurements (e.g., Dalla, 2003; 2004).

3. Solar Energetic Particle Propagation in 3D and Heliospheric Particle Reservoirs

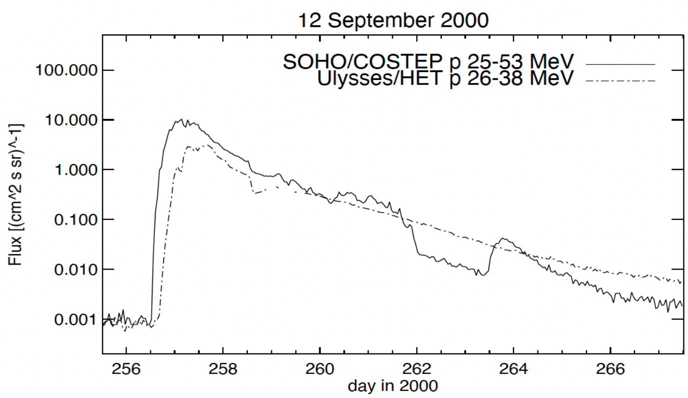

Figure 1. Time-intensity profiles of an SEP event observed simultaneously by Ulysses at a heliolatitude of 71° and by the Solar and Heliospheric Observatory (SoHO) near the ecliptic plane at 1 au, taken from Dalla (2004).

The radiation dose produced mainly by high-energy particles in a given SEP event appears to be more closely linked to the duration of the event instead of the peak intensity. It is currently believed that the peak intensity is controlled by mechanisms that are responsible for the acceleration and release of SEPs into the interplanetary medium. In contrast, the event durations appear to be influenced by properties of the interplanetary medium where transport effects such as scattering, convection by the solar wind, and energy loss or adiabatic cooling of the particles in the expanding solar wind, all of which play important roles. This situation is exacerbated further because of the following: 1) effects of transport processes smear out the source SEP properties further away from the Sun; 2) high rate of energy loss closer to the Sun; and 3) SEPs undergo significant propagation across the average magnetic field due to transport along the HCS. Thus, to make accurate predictions of SEP event decays and durations, and thus of the impending radiation hazards at Earth and in deep space, we must understand these effects in the inner heliosphere in three dimensions.

Early studies of SEP transport in 3D showed that particle transport across the mean IMF may occur on timescales that are significantly shorter compared with corresponding timescales associated with the random walk of field lines due to supergranulation (e.g., Zhang et al., 2003). To account for these puzzling high-latitude observations, many of the state-of-the-art SEP acceleration and transport models now include all essential ingredients that govern particle transport, namely, 1) streaming along magnetic field lines, 2) convection with the solar wind, 3) pitch-angle diffusion, 4) focusing by the IMF, 5) cross-field diffusion, and 6) pitch-angle scattering, and 7) adiabatic cooling in the expanding solar wind (e.g., Qin et al., 2004a,b; Zhang et al., 2009). Although Solar Orbiter will provide valuable SEP measurements up to ~33° latitude and advance our current understanding of particle transport out of the ecliptic plane, complete validation of existing transport models will require a comprehensive database of SEP observations throughout the higher latitude heliosphere.

Ion and electron intensities observed during the decay phases of large SEP events at spatially separated spacecraft (in radius, longitude, and latitude) have often shown remarkable similarity not only in their temporal behavior but also in the intensity levels (e.g., Lario, 2010). This is seen as evidence that SEPs have easy access to a broad range of longitudes and latitudes, and that the 3D heliosphere acts as a global reservoir that is filled uniformly regardless of the location of the observer. These results also showed that the intensity decays at different spacecraft are not organized by solar wind speed or the SEP energy spectra, thus implying that effects other than local solar wind convection and adiabatic cooling are playing a major role during SEP decay phases. One possibility is that SEPs at different locations are mixed rapidly so they experience the rate of dissipation due to efficient particle propagation along and across magnetic field lines. Other plausible effects include reflection and re-distribution of particles from structures such as CMEs or compression regions that have transited or exist beyond the spacecraft location.

While the existence of particle reservoirs is easily identifiable during isolated SEP events, the occurrence of multiple SEP events within a few days, as is often the case during major solar storms, can create and sustain elevated radiation levels for extended periods, i.e., up to several days. The observation of ICMEs at high heliolatitudes (Lario et al., 2004) and the Forbush decreases that they might produce to the GCRs (Lario, 2006) may provide clues to our understanding of the energetic particle propagation in three dimensions and the factors that play a role in the latitudinal extent of SEP events. Without fully understanding the physics of how such 3D global particle reservoir are produced and incorporating it in predictive models, such a scenario could severely impact NASA's plans for deep space human and robotic exploration.

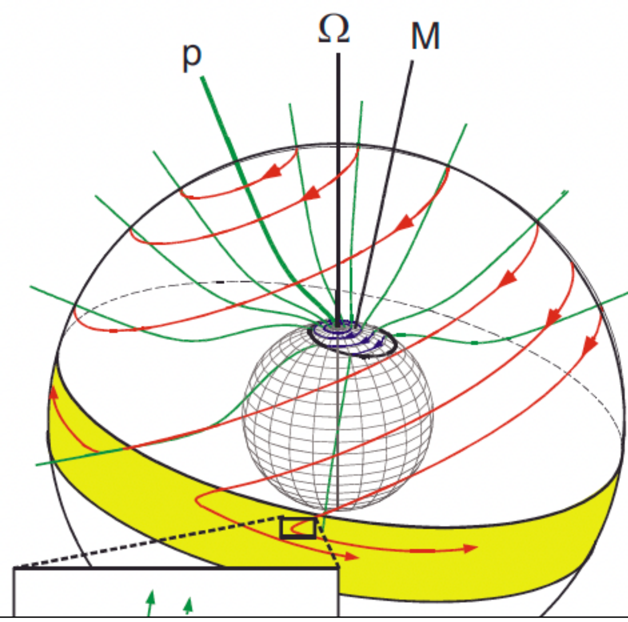

Figure 2. Schematic of the motions (in red) of open magnetic field lines (in green) from the polar coronal hole resulting from a combination of: 1) the offset of the rigidly rotating polar coronal hole; 2) differential rotation of the Sun; and 3) the nonradial expansion of the magnetic field from the polar coronal hole. The insert shows the diffusive motions of open field lines that can result from reconnection with coronal loops, taken from Fisk (1996).

4. CIRs, Energetic Particles, and GCRs: Implications for Transport and IMF configuration

Corotating interaction regions or CIRs form when fast solar wind interacts with the slower solar wind that was ejected from similar latitudes at an earlier time. During the period when Ulysses first left the ecliptic plane and started exploring the southern hemisphere, the solar wind plasma and magnetic field signatures associated with these CIRs were confined within ~40° of the equatorial plane – the angle driven essentially by the tilt angle between the solar magnetic and rotation axes during the solar minimum period of 1992-1994. Even though these local recurrent signatures were not observed beyond this latitudinal range, the very low-energy electrons (~50 keV) and sub-MeV protons, which are most likely accelerated at the shock waves that bind the CIRs at low latitudes, were observed up to ~80° by Ulysses (e.g., Lanzerotti et al., 1997). Furthermore, both the low-energy ions and electrons as well as the galactic cosmic rays (GCRs) showed recurrent variations matching those seen in association with the CIRs observed at lower latitudes (Simpson et al., 1996). These Ulysses observations suggest that energetic particles over a wide range of energies can propagate relatively easily in heliographic latitude, carrying signatures of recurrent variations from low latitudes.

These observations are difficult to understand in the context of the Archimedes spiral pattern of the heliospheric magnetic field proposed by Parker (1958). In this model, the field is attached to the rotating Sun is frozen-in and carried radially outward by the solar wind, and lies on cones of constant latitude. One way to account for the highest-latitude observations of energetic particles and GCRs in this model is to assume particle diffusion across magnetic field, which may be difficult to achieve, especially for the low energy particles in e.g., Jokipii and Parker (1969), Kóta and Jokipii (1995). Extensive random walk of magnetic field lines is needed to achieve efficient cross-field diffusion. Supergranulation may be enough. Magnetic reconnection in the chromosphere may amplify the field line random walk in the corona. Alternatively, Fisk (1996) proposed a modification of the heliospheric magnetic field model of Parker (1958), which combines the differential rotation of the Sun at the poles and the equator with nonradial expansion of the magnetic field from the polar coronal hole that rigidly rotates at the equatorial rotation rate of the Sun creates a distinct field configuration from the standard Parker model.

In this configuration, the location from where the heliospheric magnetic field is convected radially outward with the solar wind moves dramatically in latitude and the field in the heliosphere provides a direct magnetic connection from low to high heliographic latitudes. However, magnetic field and SEP observations during the Ulysses solar maximum orbit challenged this direct magnetic connection between low and high latitudes (Lario et al., 2003). Both, the Fisk's heliospheric magnetic field model and the cross-field transport of particles facilitate the 3D spreading of SEPs in the heliosphere, but which process plays a major role in the latitudinal properties of the SEP events has not been resolved. Systematic observations of CIRs, ICMEs, and associated energetic particles, as well as GCRs are now required over a wide range of heliographic latitudes to make further progress in understanding the roles played by cross-filed diffusion across latitudes and the IMF configuration out-of-the ecliptic plane.

5. Summary

Ground-breaking measurements from the Parker Solar Probe and Solar Orbiter close to the Sun will enable us to untangle the effects of acceleration and transport on SEPs. A complete understanding of how coronal and interplanetary transport change SEP properties between the Sun and Earth is important for forecasting SEP radiation levels and their hazards to astronauts and technology. The limited Ulysses observations obtained during its rapid transit over the polar regions of the Sun revolutionized our understanding of SEP transport in 3 dimensions. Explanation of the transport behaviors is still challenging. There clearly is a need for a mission to make measurements out-of-the-ecliptic plane during a large sample of SEP events to fully characterize particle transport in the inner heliosphere and understand the physical causes of key differences (e.g., significant delays in the arrival of the ions and in reaching peak intensities) with respect to the near-ecliptic measurements (e.g., Dalla, 2003; 2004).

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