ABSTRACT

In situ observations in the innermost part of the heliosphere will provide us with decisive clues regarding the outstanding problems of solar energetic particle origin, acceleration and transport. In order to have successful missions approaching the Sun as close as ~0.22 AU, it is indispensable to have an estimation of the energetic particle environment that these missions will encounter. Observations from prior spacecraft that traveled within 1 AU of the Sun allow us to describe the energetic particle populations that missions such as Solar Orbiter (SoI0) and Inner Heliospheric Sentinels (IHS) most likely will observe. In this paper, I describe the radial gradients of these particle populations as inferred from particle observations at 1 AU and inner heliocentric distances. I also discuss open questions regarding the processes of particle acceleration and transport throughout the heliosphere that SoI0 and IHS observations may help to answer.

1. INTRODUCTION

The Solar Orbiter (SoI0) and the Inner Heliospheric Sentinels (IHS) spacecraft, specifically designed to approach the Sun as close as ~0.22 AU and ~0.25 AU, respectively, will provide an excellent opportunity for studying long-standing problems regarding the origin, acceleration and propagation of solar energetic particles (SEPs). The opportunity of going closer to the Sun and into the innermost part of the heliosphere cannot ignore the extraordinary advance that in-situ observations will represent for our understanding of the processes involved in the generation of SEPs. Unlike the two Helios spacecraft, these new missions will carry on powerful state-of-the-art instruments. Combination of remote-sensing with in-situ observations will allow us to identify the sources of SEPs. In addition, the unique orbit of SoI0, with phases of near-corotation with the Sun and several degrees out of the ecliptic, will provide us with a new perspective on the study of SEP physics allowing us to analyze repetitive particle injections from the same active region and thus analyze SEP events under similar conditions.

Spacecraft missions that have already traveled into the innermost part of the heliosphere (such as the two Helios spacecraft with perihelion at ~0.3 AU and aphelion at 0.98 AU; or the Mariner-10 spacecraft traveling to Venus and Mercury) have allowed us to picture the charged energetic particle environment within 1 AU. Energetic particle populations observed at these inner distances include (1) low-energy ions associated with corotating interaction regions (CIRs), (2) solar energetic particles (SEPs) originated in association with active processes at the Sun such as coronal mass ejections (CMEs) and solar flares, (3) energetic particles associated with the passage of transient interplanetary shocks, also known as Energetic Storm Particle (ESP) events, (4) high-energy cosmic rays of interstellar origin, and (5) Jovian electrons accelerated within the Jupiter’s magnetosphere and able to escape from the planet. Helios observations of these particle populations were described in [1]. Here, I discuss the radial gradients of these particle populations. Estimation of these gradients will allow us to evaluate the particle radiation environment that SoI0 and IHS will most likely encounter.

2. PARTICLE POPULATIONS WITHIN 1 AU: RADIAL GRADIENTS

2.1. CIR events

During periods of minimum solar activity, the low-energy (<20 MeV/nucleon) ion population in the inner heliosphere is dominated by intensity enhancements associated with recurrent high-speed solar wind streams [2]. Intensity enhancements at heliocentric distances ≤1 AU last typically for 4 to 10 days [1] and, in contrast to observations taken in the ecliptic plane and further out in the heliosphere, maximum intensities occur within the high-speed solar wind streams and not in association with the passage of the recurrent forward and reverse shocks formed at the CIRs [3]. The interaction between the solar wind streams of different speeds evolve into corotating shocks, but these shocks usually form beyond ~2 AU. Since the acceleration of CIR particles is related to the interaction region and associated shocks, particle intensities are expected to peak around 2-5 AU.

Van Hollebeke et al. [4] studied the radial gradient of CIR associated energetic particle streams measured by instruments on Helios -1 and -2, IMP-7 at 1 AU, and Pioneer -10 and -11 beyond 1 AU. Fig. 1 shows the maximum intensity of 0.96-2.2 MeV protons measured in association with CIR-events during the 1973-1976
solar minimum period and normalized to the intensity measured at 1 AU by IMP-7. Since different CIR events have different intensities, it was necessary to identify individual events at each of the spacecraft locations, and compare them with the same CIR at 1 AU. Between 0.3 and 1 AU, a positive gradient of 350±150% per AU was found, while between 1 and 3-5 AU the gradient was variable with an average value of 100% per AU. The CIR fluxes declined significantly beyond 4-5 AU, indicating that acceleration and/or transport processes change in this region [4].

2.2. SEP events

The determination of the radial dependence of SEP intensities and fluences is not an easy task because both radial and longitudinal effects are interrelated [6]. Lario et al. [7] used energetic particle data from the IMP-8 (at ~1 AU) and the two Helios spacecraft to analyze the 4-13 MeV and 27-37 MeV proton peak intensities and fluences of large SEP events observed simultaneously by at least two of these spacecraft at different radial distances. Fig. 2 shows (a) the radial and (b) the longitudinal distribution of 4-13 MeV proton peak intensities for those events analyzed in [7]. Red symbols indicate events observed by IMP-8, whereas black and blue symbols are events observed by Helios-1 and Helios-2, respectively. Green lines connect events simultaneously observed by two or three spacecraft, whereas the thin blue lines connect those events observed by two or three spacecraft but one of the spacecraft did not detect any particle intensity increase. The horizontal axis in Fig. 2b indicates the angular distance $\Phi$ between the parent solar flare site and the estimated footpoint of the interplanetary magnetic field (IMF) line connecting each spacecraft with the Sun (well-connected events have $\Phi$ close to 0 degrees).

Figure 1. Relative intensity of the 0.96-2.2 MeV protons as a function of radial distance from the Sun. The observations have been normalized to the intensity at 1 AU. Adapted from [4].

Ulysses observations have shown that CIRs may also accelerate near-relativistic (~50 keV) electrons [5]. Helios observations within 1 AU and close to the ecliptic plane did not show 0.3-0.8 MeV electron intensity enhancements in association with CIRs [1]. However, several observations at 1 AU have noted that ~40 keV electron intensities are enhanced above background during recurrent low-energy ion events, though the electron and ion temporal profiles are usually different [3]. Depending on the phase of the solar cycle, SoI and IHS will most probably observe CIR events from close to the Sun. In the phases of near-corotation with the Sun, SoI may continually observe enhanced intensities due to uninterrupted connection to CIRs.

Fig. 2b shows that the maximum values of the peak intensities occur at $\Phi$ close to about 0 degrees or slightly negative (i.e. east of the footpoint). From Fig. 2, it is clear that, on average, the azimuthal distance to the flare site has a stronger influence than the radial distance. Whereas for some events the Helios spacecraft at distances <1 AU observed higher intensities than IMP-8 at 1 AU, other events showed the opposite trend. The longitudinal distance between the observer’s magnetic footprint and the site of the parent active region seems to be the dominant factor that determines the peak intensity of the SEP event [7].

Lario et al. [7] approximated the radial and longitudinal distributions of 4-13 MeV and 27-37 MeV proton peak intensity and fluences of large SEP events by a...
functional form \( j = j_0 r^{-\alpha} \exp[-k(\Phi - \Phi_0)^2] \), where \( r \) is the heliocentric radial distance of the spacecraft, \( \Phi_0 \) is the centroid of the distributions, and \( j \) is either the peak intensity or the event fluence. It was found that, over the ensemble of events, \( \alpha \) ranges from 2.7 to 1.9 for 4-13 MeV and 27-37 MeV proton peak intensities, and from 2.1 to 1.0 for 4-13 MeV and 27-37 MeV proton event fluences (see details in [7]).

These radial dependences contrast with those deduced from diffusive transport models that assume isotropic energetic particle populations, particle propagation within flux tubes whose cross-sectional area increases as \( r^2 \), and neglect focusing effects. Hamilton et al. [8] deduced power-law radial dependences for the 10-20 MeV proton peak intensities (\( r^{-2.1} \)) and event fluences (\( r^{-2.1} \)). Observations in the innermost part of the heliosphere, where the focusing effect is a dominant factor in the SEP transport, show large and long-lasting SEP anisotropies [9, 10]. These observations indicate that particle distributions within 1 AU of the Sun are not isotropic and that the SEP transport in the innermost part of the heliosphere is far from being dominated by diffusion.

The use of more appropriate focused-diffusion transport equations to describe particle propagation along Parker spiral magnetic field lines [6] shows that the radial dependence of peak intensities and event fluences varies with the energy of the particles, the conditions for particle transport (i.e. the mean free path along the magnetic field \( \lambda \)), and the duration of the particle injection [11]. By assuming particle injections at the base of a flux tube, Lario et al. [11] deduced power-law indices \( \alpha \) that range from 3.2 to 1.4 for 8.3 MeV proton peak intensities and from 1.4 to 0.8 for 8.3 MeV proton event fluences for heliocentric radial distances ranging from 0.3 to 1.0 AU. The dependence of \( \alpha \) with the energy of the particles and the adopted values of \( \lambda \) shows that (i) the smaller the mean free path of the particles, the larger the decrease of both peak intensities and fluences with radial distance, and (ii) the smaller the energy of the particles, the larger the decrease of both peak intensities and fluences with radial distance. When particle injection at the base of the flux tube extends over a long time interval, peak intensities do not decrease so fast with radial distance as when particle injections are of short duration. The radial dependence of the total event fluence does not vary substantially with the duration of the particle injection (if the rest of transport parameters are kept constant). When including mobile sources of particles (i.e. traveling interplanetary shocks), different factors (such as shock speed, shock width, shock efficiency in particle acceleration, observer’s longitude with respect to the nose of the traveling shock) determine the radial dependence of peak intensities and fluences [12, 13, 14].

These studies allow us to realize that transport conditions determine the radial gradient of particle intensities. Recommended guidelines to extrapolate particle fluxes measured at 1 AU to radial distances within 1 AU (i.e., \( \alpha=3 \) for peak intensities, and \( \alpha=2.5 \) for event fluences, see report edited by Feynman and Gabriel [15]) can be used as worst-case limits to estimate the particle radiation within 1 AU, and allow engineers to be on the safe side when designing space instrumentation traveling within 1 AU. Observational studies, however, indicate that these limiting restrictions may be relaxed [7].

![Figure 3](image)

**Figure 3.** (a) Hourly averages of the 4-13 MeV proton intensities as measured by Helios-1 (black traces) and IMP-8 (red traces) during a SEP event in 1978 when the nominal connections of both spacecraft to the Sun were less than 7 degrees apart in longitude. Dot symbols indicate the maximum peak intensity. Square symbols indicate the time interval over which event fluences are computed. The vertical lines indicate the passage of interplanetary shocks by both spacecraft. (b) Location of Helios-1 (black dot) and IMP-8 (red dot) on the day of the onset of the event. Black and red lines show the nominal magnetic connection of Helios-1 and IMP-8 with the Sun.

Owing to the dominant influence of the longitudinal distance on the particle intensities (Fig.2), it is essential to find SEP events observed by at least two spacecraft at different radial distances for which the longitudinal factor can be eliminated (i.e. spacecraft whose magnetic footpoints on the Sun are relatively close). Fig. 3 shows 4-13 MeV proton intensities from Helios-1 at 0.31 AU and IMP-8 at 1 AU for one event when the nominal IMF connection sites on the Sun of both spacecraft were less than 7 degrees apart. For this specific event, the absolute 4-13 MeV proton peak intensity scales as \( r^{-2.25} \) and the event fluence as \( r^{-1.57} \) [7]. The fortuitous location of Helios-1 and IMP-8 during this event allows us to see that there were striking differences in the rise phases of the SEP event at the two spacecraft, but the decay phases of the event (after the passage of the interplanetary shock waves (indicated by vertical lines in Fig. 3a) and before day 123) showed similar intensities that decayed at the same rate. Therefore, energetic particle reservoirs are observed not only at
different heliolongitudes and heliolatitudes [16], but also at different radial distances and, in principle, by spacecraft with good magnetic connection.

Transport models [e.g., 6] allow us to infer the characteristic of the SEP events (both the intensity and the anisotropy time profiles) at several radial distances along a given flux tube. The top panel of Fig. 4 shows the 8.3 MeV proton omni-directional intensity as a function of time as observed at several radial distances. Particle injection is assumed at the base of the flux tube and follows a Reid-Axford profile with $\beta=1.5$ h and $r=1.5$ h. A constant mean free path along the magnetic field $\lambda||=1.0$ AU is assumed to describe the pitch-angle scattering processes. The bottom panel of Fig. 4 shows the anisotropy-time profile as defined in [17]. According to this definition, the maximum value of the anisotropy (=3) corresponds to the observation of particles arriving only along the magnetic field direction and no particles in other directions, whereas the value 0 corresponds to isotropic flows. From Fig. 4, it is clear that for observers close to the Sun, anisotropies remain high throughout the rising phase of the event and even at the maximum of the event (indicated by solid dots). Therefore, in order to detect the early phase of the SEP events, it is essential to mount particle sensors with fields of view that are as close as possible to the magnetic field direction. Only with this orientation will we assure the observation of the first arriving particles and then the possibility to associate these particles with the acceleration processes occurring at the Sun.

The field direction close to the Sun has been determined using Helios measurements. Mariani et al. [18] analyzed the large-scale structure of the IMF as observed by Helios-1 between 0.3 to 1.0 AU. Fig. 5 shows the distribution of the azimuthal orientation in four different ranges of radial distances. The progressive tendency of the field to become more radial as the Sun is approached is clearly apparent as expected from a Parker spiral magnetic field. Therefore, particle detectors should be pointed as close along the nominal (average) Parker spiral as possible. In approaching the Sun, the presence of transversal fluctuations may help to scan a broad range of pitch-angles and thus the possibility to catch the rising phase of the SEP events. However, that does not change the general wish to point the detectors along the field direction.

Figure 4. Top panel. Time profiles of the 8.3 MeV proton omni-directional intensities observed at several radial distances. Bottom panel. Anisotropy profiles for the intensities shown in the top panel. The dots indicate the time of the maximum intensity.

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Transport processes (including pitch-angle scattering by turbulent field fluctuations, magnetic focusing by the radial diverging IMF, solar wind convection, adiabatic cooling, and field-line wandering) affect the time-intensity profiles of the SEP events as observed at

Figure 5. Distribution of the azimuthal IMF orientation in four different ranges of the heliocentric radial distances as observed by Helios-1 from 0.3 to 1.0 AU. Adapted from [18].
different radial distances. Fig. 6 shows 0.3-0.8 MeV electron and 2-4 MeV/n He intensities as measured by Helios-1 at 0.31 AU and IMP-8 at 1 AU. Helios-1 observed four separate particle injections; however IMP-8 observed only a broad increase with no separable injections. Presumably, transport processes between 0.31 AU and 1.0 AU significantly modified the aspect of this specific SEP event with radial distance [19]. SEP events observed at 1 AU that have been usually interpreted as a result of a single particle injection may be actually associated with multiple particle injections. The proximity of SolO and IHS missions to the particle sources will help us to reduce considerably the uncertainty introduced by particle propagation through the inner heliosphere, and thus identify individual particle injections. Therefore, the number of small events to observe close to the Sun is expected to be larger than at 1 AU.

2.3. ESP events

The efficiency of CME-driven shocks as particle accelerators varies with time (as the shock travels away from the Sun) and with longitude (as the observer establishes magnetic connection to different regions of the shock front) [6]. Whereas shocks are believed to be able to accelerate protons to GeV energies when they are close to the Sun (at 3-5 solar radii) [20], when they reach 1 AU they hardly accelerate ions above 20 MeV/n [21]. CME-driven shocks have also been proposed as near-relativistic (>30 keV) electron accelerators when they start propagating close to the Sun [22, and references therein]. The passage of CME-driven shocks at 1 AU with near-relativistic electron intensity enhancements, however, are rare [21].

Owing to the large variety of shock structures and their effects on energetic particles [23], the determination of the radial variation of the shock efficiency in particle acceleration would require the observation at two different radial distances of the same CME-driven shock through the same region of its front and under similar upstream conditions. This multipoint observation seems to be purely coincidental. Therefore, the determination of the radial evolution of the shock efficiency as particle accelerator has to rely on modelling efforts [6, 13 and references therein]. According to the diffusive shock acceleration (DSA) theory, particles gain their energy by a Fermi process involving multiple traversals of the shock by the energetic particles moving back and forth across the shock [24]. In the context of the DSA theory, the stronger fields, the larger Alfvénic wave amplitudes, the smaller particle gyroradii, the larger densities and injections rates, allow for a more efficient particle acceleration closer to the Sun than at 1 AU [24]. The maximum energy (due to finite shock life time) that energetic particles can reach via DSA is estimated to approximately scale with distance as $\sim r^2$ [24]. Thus, if the cutoff energy is, e.g. $\sim 1$ MeV/n at 1 AU, then it is $\sim 20$ MeV/n at 0.22 AU. Therefore, plasma, field and particle data taken close to the Sun will allow us to study particle acceleration at shocks at much higher energies than those usually observed at 1 AU.

For the DSA mechanism to be applicable, turbulence in the upstream and downstream regions of the shock must be present in order to provide the necessary particle scattering [24]. Accelerated particles may also be able to amplify such turbulence. The presence of amplified waves at 1 AU has been reported only in a few exceptional cases that include strong shocks, intense ESP events, but then only waves resonant with proton energies below MeV have been detected [17, 25, 26, 27]. Models of particle propagation predict that these amplified waves will be easy to observe close to the Sun when the shocks are still powerful producers of energetic particles [28]. Whereas the tests to the DSA theory based on observations at 1 AU have shown only partial agreement [25, 27], we expect that observations close to the Sun will provide multiple examples of strong shocks and intense ESP events, where to test these theoretical models. Both particle and Alfvén-wave intensities are expected to be at much higher level closer to the Sun than at 1 AU and then the ESP events would be easy to observe and interpret. However, elevated particle intensities may also modify the shock structure and act as a mechanism for the formation and evolution of the shock [29]. Therefore, the combined analyses of plasma, magnetic field and particle observations close to the Sun are essential to determine the evolution of the shock properties and the self-regulated interaction between particles and shocks. For this study to be successful, it is essential to go as close as possible to the Sun where most of the particle acceleration at high energies is expected to occur.

The Helios observations have allowed us to determine how the properties of the interplanetary shocks evolve within 1 AU. Volkmer and Neubauer [30] studied 185 interplanetary shocks observed by Helios-1 and Helios-2 between 0.3 and 1.0 AU. These authors found that some characteristic shock parameters such as the fast sound Mach number, the magnetic field ratio $B_2/B_1$, the relative density ratio $(n_2-n_1)/n_1$, the pressure ratio $P_2/P_1$, and the direction of the shock normal exhibit no significant dependence on the radial distance. Only the shock normal velocity $V_s$ in the rest frame of reference of the ambient plasma was observed to decrease with increasing solar distance of the shock (Fig.7). These scatter plots show also the large variety of shock parameters observed and their influence on the deduced radial variations. The number and variety of shocks close to the Sun is expected to increase as the distance to the Sun decreases [31]. The effects that these shocks
will produce on energetic particles are also expected to be diverse.

The angle $\theta_{Bn}$ between the shock normal and the direction of the upstream magnetic field plays an essential role in determining the mechanism of particle acceleration at shocks [17]. Fig. 8 shows the frequency distribution of $\theta_{Bn}$ in three different ranges of the heliocentric radial distance as determined by Helios measurements [30]. There is a trend for more quasi-perpendicular shocks in the distance interval 0.75-1.0 AU. This trend has also been observed using only shock observations at 1 AU [23 and references therein]. Whereas Helios-1 measurements show also a trend for more quasi-perpendicular shocks within 0.5 AU, Helios-2 data show a trend for more quasi-parallel shocks in the inner intervals. The discrepancy at small distances between Helios-1 and Helios-2 was interpreted by Volkmer and Neubauer [30] as a result of the different upstream magnetic field sampled by the two spacecraft during their short perihelion approaches. The presence of more quasi-parallel shocks closer to the Sun will help us to test DSA theory and determine the dependence of the SEP event characteristics on the shock properties [32].

2.4. Galactic Cosmic Rays

Galactic cosmic ray (GCR) modulation throughout the solar cycle has also been observed within 1 AU [1]. The modulation is not simply characterized by a smooth decrease and increase in GCR intensities, but a series of decays and recoveries on short time scales (~days) that are superimposed on the overall evolution of the time-intensities. These local decreases in GCR intensities are caused by either the passage of interplanetary coronal mass ejections (ICMEs) and associated shocks (i.e. Forbush decreases) or by recurrent high-speed solar wind streams [3]. Fig. 9 shows the case of a Forbush decrease observed first by Helios-2 at 0.4 AU and 5 degrees west from the Earth and later by IMP-8 at 1 AU [33]. Although the $>$60 MeV proton intensity depression caused by the ICME seems to be stronger at 0.4 AU than at 1 AU, longitudinal as well as latitudinal effects need to be considered when doing these radial comparisons [34].

During the passage of ICMEs, energetic particles can be used to trace the magnetic field connectivity back to the Sun and infer both the topology of the ICMEs and the field line lengths [Malandraki et al., this issue]. ICMEs may be formed by a random mix of intertwined volumes of magnetic open and closed field lines [35]. Measurements from SolO and IHS can be used to estimate the opening up of the assumed closed CME structures as they propagate away from the Sun.

Combining data from Helios-1 and IMP-8 for the solar minimum period 1975-76, Muller-Mellin and Wibberenz [36] determined the integral radial gradient between 0.3 and 1.0 AU of $>$51 MeV proton intensities.
Jovian electrons have also been observed within 1 AU [37]. Fig. 10 shows ~6 MeV electron intensities as measured by IMP-8 at 1 AU and by Mariner-10 from 0.5 to 0.9 AU. Electron intensities were modulated by two series of CIRs. Owing to the orbit of Mariner-10 with respect to Jupiter, the periodicity of electron enhancements at Mariner-10 was of ~7 months. Eraker and Simpson [37] indicated that the Jovian electron gradients were variable, even may reverse signs. However, as shown in Fig. 10, these gradients were always small. Other studies (see references within [37]) indicate that the electron gradients are always small and positive. See Heber et al. [this issue] for a description of possible Jovian electron observations within 1 AU of the Sun.

Figure 9. Solar wind proton temperature $T_p$, >60 MeV proton intensity, and ~4 MeV proton intensity as observed by Helios-2 (a) and IMP-8 (b). The black area indicates depressions in $T_p$ identified as the passage of the ICME. The >60 MeV proton intensities show the characteristic two-step cosmic ray depression produced by the shock (solid vertical line) and the ICME (region between the two dashed lines) passing first by Helios-2 at 0.4 AU and 5 days and later by IMP-8. Adapted from [33].

2.5. Jovian electrons

At solar quiet times, most of the electrons observed in the range from a few hundred keV up to about 40 MeV are of Jovian origin [2]. They can be observed throughout the inner heliosphere. Near Jupiter, their intensity is modulated with the 10-hour periodicity of the planet’s rotation. Near the Earth, peak intensities occur at times of best connection between the Earth and Jupiter along the IMF average direction every ~13 months. The Jovian electron intensities are also modulated by CIRs [37].

Figure 10. 6 MeV electron intensities at IMP-8 (A) and the corresponding 5.7 MeV electron intensities at Mariner-10 (B). The dashed curves represent the calculated maximum Jovian electron intensity at each spacecraft. The corotation time from Earth to Mariner-10 in days, and the distance of Mariner-10 to the Sun are given between (A) and (B). Adapted from [37].

3. UNSOLVED PROBLEMS REGARDING PARTICLE TRANSPORT AND ACCELERATION IN THE HELIOSPHERE

Observations in the innermost part of the heliosphere of those particle populations whose origins have been established beyond 1 AU (i.e. galactic cosmic rays, CIR particles and Jovian electrons) will provide us with definitive clues regarding the particle transport in the heliosphere. Evaluation of their intensities and anisotropy flows as close to the Sun as possible will help us to discern the mechanisms that enable their transport from their sources to the innermost part of the solar system. Multi-spacecraft analysis of these particle populations, together with a good description of the magnetic connection between observers and particle...
sources, will help us to discern whether perpendicular transport to the mean direction of the magnetic field is required to explain these observations.

By contrast, the proximity of the SoO and IHS missions to the sources of SEPs will help us to reduce considerably the uncertainty introduced by the particle propagation through the inner heliosphere. The reduction of transport processes may enable direct study of time variations in the acceleration and release of SEPs.

Timing studies have established that the release of near-relativistic (>30 keV) electrons at the Sun is often delayed by ~10 minutes with respect to the solar flare emissions and Type III radio bursts [38]. This interpretation has been challenged by Cane [39] who argued that near-relativistic electrons and impacting electrons responsible for the electromagnetic emissions are the same population, and thus the delay in the arrival time of the near-relativistic electrons at 1 AU is due to transport processes from their source to the observer. If the delay of the SEP event onsets is due to scattering processes, as we move closer to the Sun and reduce the number of transport processes undergone by the particles, the delay should be smaller. In a study of 27 electron events with energies >300 keV restricted to solar minimum conditions and observed by the two Helios spacecraft within 0.5 AU of the Sun, Kallenrode and Svestka [40] found good agreement between the onset of solar type III bursts and the inferred electron injections (see comment in [41]). As inferred from Helios observations, the injection of >4 MeV protons may be delayed ~10-14 minutes in large SEP events [42], whereas in small events (associated with impulsive solar flares) the >4 MeV protons may be injected simultaneously with the electrons [42]. The validity of the timing studies based on the analysis of the velocity dispersion effect at the onset of the SEP events and the necessity of observations close to the Sun has been critically reviewed by Kahlert and Ragot [41].

Combination of in-situ data with EUV and X-ray imaging taken close to the Sun, together with γ-ray, neutron and radio plasma wave observations, will greatly help us in identifying plasma motions in the corona and electromagnetic emissions that occur in temporal association with the estimated release time of energetic particles into interplanetary space. Particle sources and their location in the solar corona may vary with time, the energy of the particles, and the type of SEP event we analyze. Combined studies of both the dynamic evolution of the field topology of the particle sources (allowing for the opening up of field lines) and the release of energetic particles are essential to understand the processes of particle acceleration at the Sun (see Klein et al. [this issue] for a description of these processes).

In order to understand the SEP transport processes in the heliosphere, the origin and evolution of the magnetic field fluctuations responsible for the energetic particle scattering need to be resolved. Comparison of transport parameters deduced from the analysis of field fluctuations and from SEP transport models indicates that particles do not interact effectively with the total amount of the observed field fluctuations but only with the component having wave vectors parallel to the magnetic field [43]. The relationship between transport parameters and field fluctuations can be different near the Sun than at 1 AU. The radial evolution of the dynamical character and 3D geometry of the field turbulence will be determined from SoO and IHS observations, and will help us to understand the processes of SEP transport ion the interplanetary medium.

Composition and SEP charge states provide crucial clues regarding both the particle acceleration sites and the acceleration processes. Impulsive solar flares are thought to be the sources of $^3$He ions [44], while $^4$He ions are thought to originate as interstellar neutral atoms that get ionized and picked up by the outward-flowing solar wind [45]. The observation of these two ions close to the Sun will help us to identify their particle sources.

Indeed, observations of anomalously enhanced $^3$He in many ESP events at 1 AU have been interpreted as evidence of CME-driven shock acceleration of remnant material from previous $^3$He-rich events [46]. Small impulsive flares may provide a seed population for further acceleration by the traveling shocks. It is also possible that the concomitant flare observed in large SEP events produces the enhanced $^3$He and heavy ion material that CME-driven shocks re-accelerate. By being closer to the Sun, SoO and IHS will have access to lower energies of the suprathermal ion population than at 1 AU making it possible to extend the energy spectra from solar wind to energetic particles. Additionally, because of the SEP intensity decrease with radial distance, small SEP events associated with impulsive flares will be more easily observed close to the Sun than at 1 AU. Therefore, the observations from SoO and IHS will help us to discern whether small impulsive flares continually refill the inner heliosphere with $^3$He and heavy ion rich material or this suprathermal remnant gets empty at small heliocentric distances faster than at 1 AU. Since small SEP events appear to occur from the same region in series over periods of up to several days, during phases of near-cototation, SoO will be able to discern whether these multiple flares from the same active region play a role in filling the inner heliosphere with suprathermals and
in spreading these ions uniformly over a wide longitudinal span.

Re-acceleration of pickup ions by CIRs and CME-driven shocks has also been proposed as a source of energetic particles [45]. As we move closer to the Sun, we would expect the ions of interstellar origin to become less abundant, while the inner source pickup ions are expected to be more abundant, making them more available for acceleration. SolO and IHS trajectories will allow us to study the variation with radial distance of the relative importance between interstellar and inner source pickup ions.

The interaction between successive CMEs has been suggested as an efficient mechanism for SEP production [47]. A first CME may be caught by a second faster CME resulting in the formation of complex transient streams. Whereas the preceding CME may enhance the field turbulence, distort the IMF topology and create an enhanced energetic particle population; the subsequent CME may re-accelerate very efficiently these energetic particles resulting in higher SEP intensities [47]. The CME-CME interactions may occur at the heliocentric distances that SolO and IHS will directly sample, being able to witness the plasma, field and energetic particle response to this interaction.

Observations close to the Sun will also allow the study of particle propagation in the downstream region of CME-driven shocks [48]. The analysis of particle propagation in these regions is essential to understand the formation of heliospheric energetic particle reservoirs [16]. Close to the Sun, the decays of the particle intensities in a SEP event are faster and thus less affected by subsequent SEP events and not interrupted by other shock passages, allowing for a better estimation of the mechanisms that form energetic particle reservoirs.

4. SUMMARY

The near-Sun phase of SolO and the IHS spacecraft will provide an unprecedented opportunity to identify (1) acceleration mechanisms, (2) locate the source regions of energetic particles, (3) determine the role of plasma turbulence and shock waves in the production of energetic particles, and (4) disentangle the effects of acceleration, injection and propagation to a much greater degree than possible from observations at 1 AU.

Whereas the intensity of the GCRs, Jovian electrons and CIR-particle populations are expected to decrease as we move closer to the Sun, SEP intensities increase, but to a lesser degree from what is recommended for 1 AU particle flux extrapolations [7, 15]. The radial dependences of particle intensities described in section 2 are essential ingredients for the design of instrumentation on board those missions traveling close to the Sun.

The possibility to extend the presently available range of measurements down to 0.22 AU using state-of-the-art instruments that provide high time resolution represents a unique opportunity to address long-standing problems in the physics of energetic particle origin, acceleration and transport. In section 3, I have only addressed a few of these still unsolved (and sometimes controversial) problems. By combining imaging with SEP observations from the SolO and IHS missions, we will be able to (1) identify the particle acceleration sites, (2) estimate the processes of acceleration, (3) differentiate energetic particle populations of different origins, (4) determine the association between the field topology of the active regions and the release of energetic particles, and (5) estimate the distance and conditions where CME-driven shocks accelerate particles. By combining magnetic field, solar wind and energetic particle observations we will be able to determine (1) the radial evolution of the properties of shocks and ESP events, (2) the seed particle populations for the mechanisms of shock acceleration, (3) the radial evolution of the topology of ICMEs, and (4) the influence that waves amplified by energetic particles and magnetic field fluctuations have on the SEP transport.

The ability to study the energetic particle environment as close as ~0.22 AU from the Sun will result in major new insights regarding the location and mechanisms for particle release into the interplanetary medium, particle transport in the heliosphere, and particle acceleration at both the Sun and in the innermost part of the heliosphere.

In conclusion, missions such as SolO and IHS represent a unique opportunity to address long-standing problems in the physics of energetic particles.

5. References


