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Solar Energetic Particles: new multi-spacecraft views with Solar Orbiter and Parker Solar Probe

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Solar Energetic Particles (SEPs) can be detected in the heliosphere following their acceleration during solar flares and coronal mass ejections (CMEs). They are a key component of the space radiation environment, affecting space weather. SEP observables, including intensity profiles, spectra, composition and anisotropies, carry signatures of the energisation processes and of propagation effects experienced while the particles travel through the interplanetary magnetic field. The launch of Solar Orbiter (SolO) and Parker Solar Probe (PSP) opened new possibilities in the study of SEPs: using their in-situ measurements, combined with those of other spacecraft such as STEREO A, SOHO and planetary missions, SEP data at several (e.g. 5 or more) locations in the heliosphere are available for a large number of events for the first time. These include events where SolO or PSP are close to the Sun, thus close to the acceleration region and minimising propagation effects. In others multiple observations at wide longitudinal separation are available. Here we review recent multi-point observations taken with the SolO Energetic Particle Detector (EPD) and the PSP Integrated Science Investigation of the Sun (IS⊙IS) and discuss how the new data, in conjunction with models, can be used to better understand SEP acceleration and transport.

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1. Introduction

This paper, based on a highlight talk presented at ICRC 2025, reviews recent results on Solar Energetic Particles (SEPs) from the Solar Orbiter and Parker Solar Probe missions. A large number of scientific results from these missions have been published and it will not be possible to present them all in the available space. Therefore the focus of the present paper will be on multi-spacecraft aspects, where a combination of Solar Orbiter and Parker Solar Probe data, together with observations from other heliospheric spacecraft, is key to the analysis.

Solar Orbiter (SolO), is an ESA-NASA mission, launched in 2020 [12]. The spacecraft comprises a suite of ten instruments, some of which are remote-sensing, imaging the corona and the photosphere of the Sun, while others are in-situ instruments, directly measuring the solar wind, energetic particles, and the magnetic field at the location of the spacecraft. Key features of its trajectory are that it samples the inner heliosphere down to distances of 0.29 au from the Sun and it includes out-of-ecliptic orbits, reaching heliographic latitudes up to 33°.

Parker Solar Probe (PSP) is a NASA mission, launched in 2018 [6]. PSP has four instruments: three in-situ instruments measuring plasma and energetic particles, and one remote-sensing imager to view the solar wind close to the Sun and into the heliosphere. The trajectory of PSP brings the spacecraft closer to the Sun than any other human-made object, with closest approach being at 0.04 au, corresponding to 9 solar radii.

SEPs are the result of solar eruptive activity, in many cases including both a solar flare and a coronal mass ejection (CME) [3, 8]. They are thought to be accelerated at the shock driven by the CME through the corona and interplanetary space and during flare-associated magnetic reconnection. These ions and electrons propagate through the interplanetary magnetic field (IMF), which on average has the shape of a Parker spiral, with turbulence and interplanetary structures superimposed on it. The acceleration and propagation together determine the SEP intensities measured at a spacecraft and their variation with particle species, energy and instrument look direction. One of the top-level science questions of SolO is *how do solar eruptions produce energetic particle radiation that fills the heliosphere?* [12], while one of the objectives of Parker Solar Probe is *to explore mechanisms that accelerate and transport energetic particles* [6]. Therefore the science of SEPs is at the heart of both these missions.

Key science questions in SEP physics concern the details of the acceleration process: where, for how long, and how are particles accelerated? Flares are localized, while CMEs accelerate particles by driving shocks through interplanetary space: these are extended and can continue to accelerate particles long after the initial eruptive event. There are also questions concerning propagation—how do SEPs propagate across the average magnetic field? How does turbulence in the IMF and near interplanetary shocks affect propagation? Finally it is important to quantify the relative role of acceleration and propagation in shaping SEP observables.

Together SolO and PSP provide a unique opportunity to study SEPs closer to their acceleration region than ever before. Combining their measurements with those of other missions such as STEREO A, near Earth spacecraft and planetary missions such as BepiColombo and Maven, we are in a unique position to carry out multi-point observations of SEPs over multiple longitudes and radial distances from the Sun. In addition to multi-point observations this paper will present also an example of how modelling of SEPs is key to the interpretation of the data.

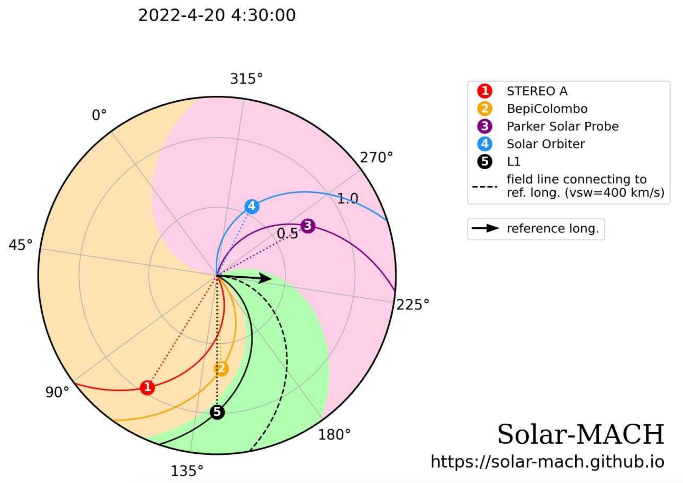

Figure 1: Multi-spacecraft configuration in the inner heliosphere during an SEP event on 2022-04-20. The Sun is at the centre and the numbered dots indicate spacecraft locations (see legend). The black arrow represents the longitude of the active region source of the solar eruption. Spiral shaped lines show magnetic field lines through the spacecraft based on a Parker spiral model. The green shaded area represents locations magnetically well connected to the source, while the peach and pink shaded areas are not well connected [5].

2. Observations

The SolO and PSP data discussed in this review are mainly from two instruments: the Energetic Particle Detector, EPD, on SolO [14] and the Integrated Science Investigation of the Sun, IS⊙IS, on PSP [10]. These instruments cover a wide range of energies and species of SEPs. For a full description of the instrument capabilities please refer to the detailed instrument papers [10, 14].

Figure 1 shows an example of a multispacecraft configuration in the heliosphere for an SEP event in 2022: here the various spacecraft are indicated by the filled circles and the spiral-shaped lines show the average interplanetary magnetic field lines through the spacecraft based on a Parker spiral model. The arrow indicates the longitude at the Sun of the active region associated with the event. It is customary in SEP studies to define the connection angle $\Delta\phi$ as:

$$\Delta\phi = \phi_{AR} - \phi_{ftpt} \quad (1)$$

where ϕ_{AR} is the longitude of the active region source of the eruptive event and ϕ_{ftpt} is the longitude of the footpoint of the Parker spiral magnetic field line through the observer. A negative $\Delta\phi$ indicates a source region to the east of the spacecraft footpoint, while a positive $\Delta\phi$ a source to its west. Figure 1 shows that for a given event an observer may be located in a region with good magnetic connection to the source (the green area in Figure 1, with small $|\Delta\phi|$) or may have a less favourable magnetic connection (the peach coloured area, with large positive $\Delta\phi$, and pink area, with large negative $\Delta\phi$). Since SEPs propagate preferentially along the magnetic field direction, the type of magnetic connection to the source of the event has a strong influence on the observed SEP intensities and their time evolution.

Figure 2 presents an example of multi-spacecraft SEP observations for the event of 2023-03-13, combining information from multiple spacecraft [4], for high energy and low energy protons. As

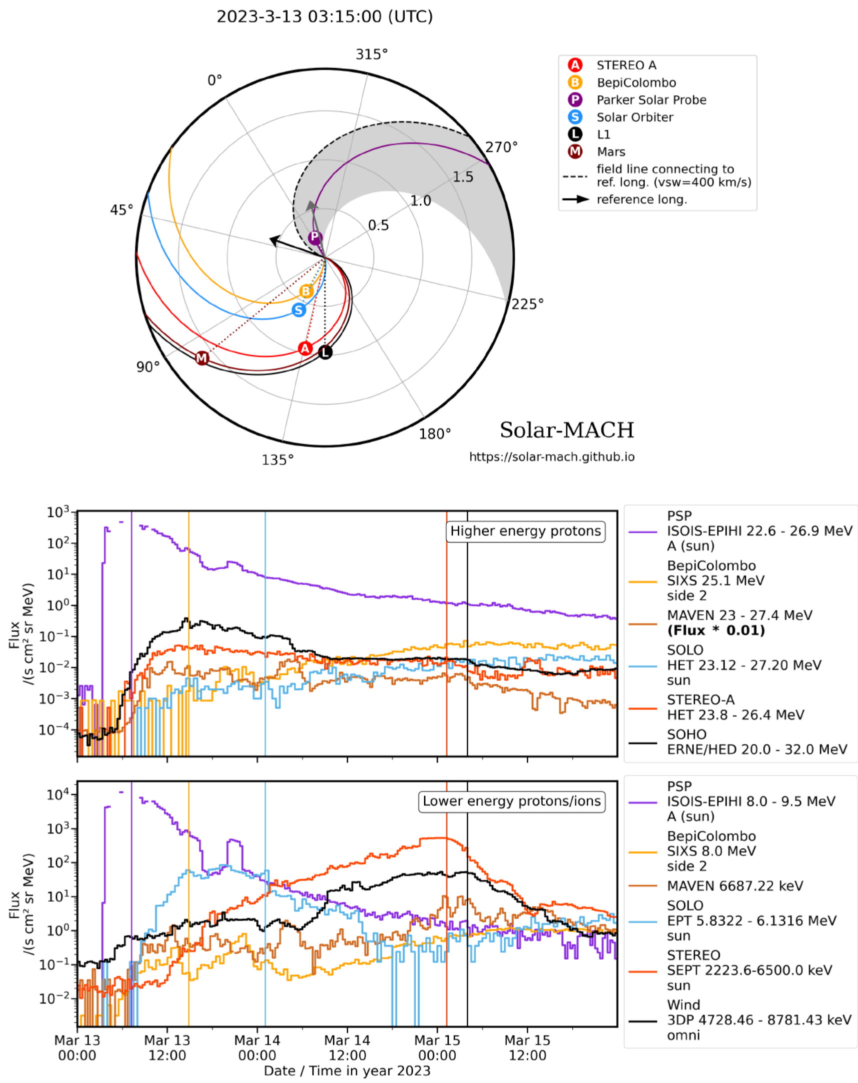

Figure 2: Multi-spacecraft configuration and proton intensities versus time at multiple locations for the SEP event on 2023-03-13 [4].

shown in the top panel, displaying the spacecraft configuration, PSP was well connected to the source and it was also quite close to the Sun. This is reflected in the measured SEP intensities, showing a very high peak intensity and a very sharp rise phase. On the other hand SolO and BepiColombo, both located near 0.5 au but at larger $|\Delta\phi|$ compared to PSP, see a completely different type of profile with low peak flux and a very slow rise: in fact the event is rather unremarkable at these two spacecraft. At locations near Earth (see the L1 and STEREO A data points in the top panel of Figure 2), which have a less favourable connection (larger $|\Delta\phi|$ and distance of 1 au from the Sun), surprisingly the event has a higher peak intensity and a sharper rise compared to the measurements at BepiColombo. It is challenging to make sense of the details of the intensity profiles seen in these observations: later in the paper, the role of modelling in the interpretation will be discussed.

Historically, in the analysis of SEP events, there has been a tendency to discriminate between

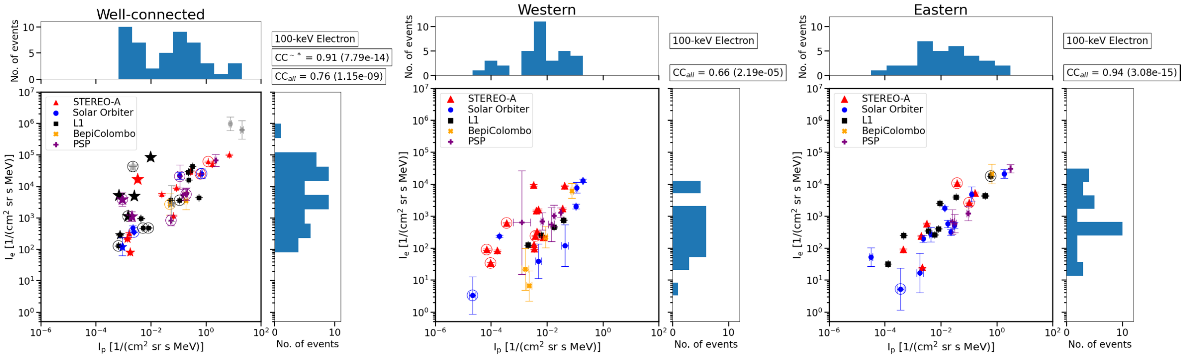

Figure 3: Peak intensities of 100 keV electrons versus those of ≥25 MeV protons, for well connected events (*left*), not well connected events with $\Delta\phi$>0 (*middle*) and not well connected event $\Delta\phi$<0 [5].

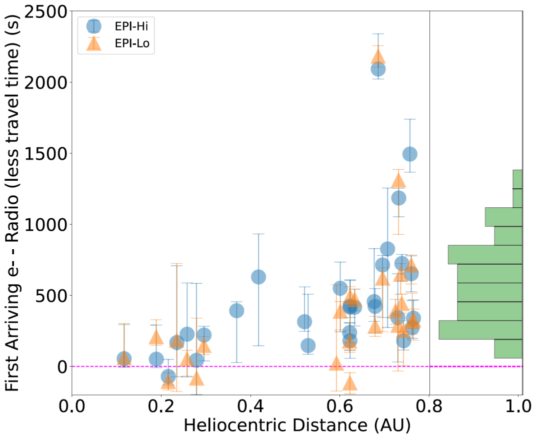

Figure 4: Release delay versus heliocentric distance for ~82 keV electrons (*blue circles*) and ~760 keV electrons (*orange triangles*). The release delay is defined as the time between the estimated solar release time of the electrons and the onset of the type III radio emission at 2MHz [11].

"electron events" and "proton events". However it is now clear that in most events both species are accelerated. Figure 3 displays electron versus proton peak intensities in a number of events observed by multiple spacecraft [5]. There is a clear correlation between the two in the majority of cases. In the left panel, however, associated with spacecraft in the well-connected range of longitudes, a set of events with higher electron intensities are observed: these are thought to be caused by flare acceleration as opposed to CME-driven shock acceleration. The results suggests that there is a common acceleration mechanism for proton and electrons in most events with an additional class of electron-rich events for well-connected observers.

Another long-standing question concerns release delays—the apparent delay between a flare's electromagnetic emission signatures and the time when particles appear to be first released at the Sun. From plots of SEP intensity versus time at a spacecraft it is possible to derive arrival times at that location: knowing the particle speed and assuming that the the path lenth travelled by the particles is the length of the Parker spiral, a recent study [11] obtained the apparent release time of the electrons at the Sun and calculated its delayed compared to the time of the associated flare type

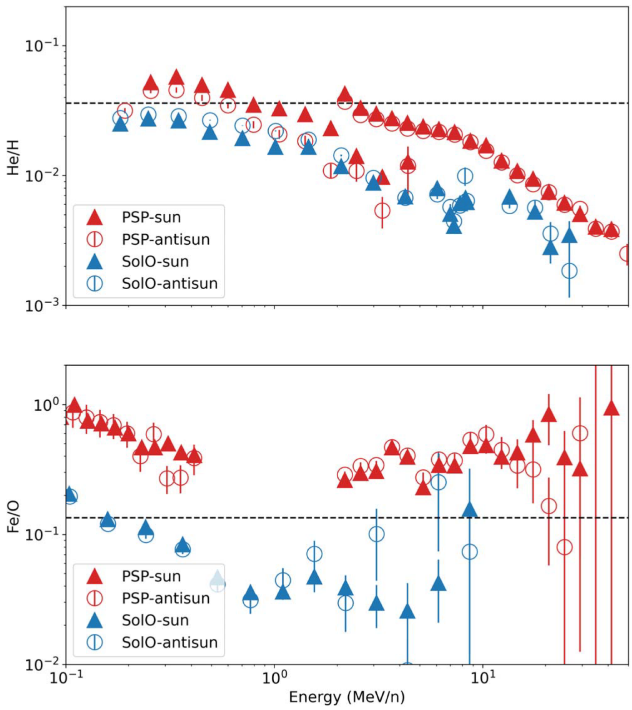

Figure 5: Fe/O and ^{4}He/H ratios measured by SolO (*blue*) and PSP (*red*) in the sunward and antisunward directions as a function of particle energy, for the event of 2023-05-16 [17].

III radio burst. Data in Figure 4 shows the release delay versus radial distance of the spacecraft for a set of 41 events. Close to the Sun the release delay is short, while at larger distances there is a wide spread of delays. The plot demonstrates that the average release delay increases with distance from the Sun, suggesting that transport effects rather than delayed acceleration are the cause of the observed pattern.

A powerful diagnostic enabled by SolO and PSP instruments is the capability of comparing composition at different locations in interplanetary space. Differences in the values of the event-averaged Fe/O ratio have been suggested to indicate different contributions from flare and CME-driven shock acceleration. In Figure 5 He/H and Fe/O ratios versus particle energy are shown [17], for an event where PSP had a very good magnetic connection to the source of the event, while the SolO location maps back to a longitude at the Sun that is more distant from the source region (larger $|\Delta\phi|$). Figure 5 shows that the Fe/O ratio differs greatly at the two spacecraft. It has been proposed that at the well connected spacecraft this is due additional Fe from the solar flare, in addition to a contribution from the coronal mass ejection shock [17].

A series of strong solar eruptions in May 2024 produced a series of SEP enhancements in interplanetary space. Composition measurements from SolO, PSP and ACE for this time period are shown in Figure 6 [13]. The three panels display three separate time ranges and show Fe/O ratios versus energy. The relative location of the three spacecraft remained fairly constant during the time range. Figure 6 shows that in all panels there is a trend for the ratio to increase with particle energy at the different locations. This is contrary to traditional diffusive shock acceleration (DSA) predictions, which would expect decreases [13].

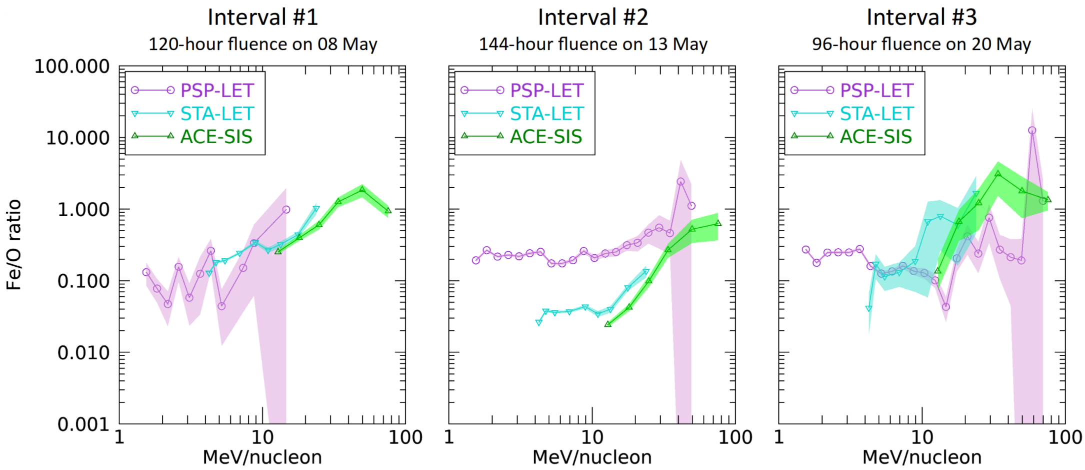

Figure 6: Fe/O fluence ratio versus particle energy for three time intervals during the May 2024 SEP events. Data points are from three spacecraft: ACE (*green*), STEREO A (*cyan*) and PSP (*violet*) [13].

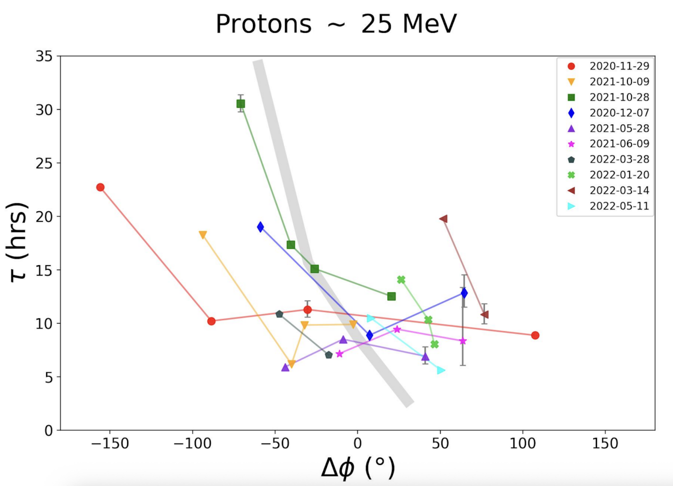

Figure 7: Decay time constant τ versus longitudinal separation $\Delta\phi$ for ~25 MeV protons during 11 SEP events. Lines connect data points for a single event from spacecraft at different locations [7].

Many SEP events show long decay phases, with a gradual decline in intensities. In many cases the decay follows an exponential trend: this can be fitted to derive a decay time constant. Using multiple spacecraft data a recent study derived the decay time constant τ for a set of 11 SEP events [7]. The dependence of τ on the observer's magnetic connection to the source region, expressed by the angular separation $\Delta\phi$ was studied, as shown in Figure 7. Within individual events a trend for τ to decrease with $\Delta\phi$ was found. This trend may be linked to corotation of magnetic flux tubes or variable acceleration along shock fronts [7].

3. Transport modelling

In their travel through the heliosphere SEPs are guided by the IMF. They mostly propagate parallel to the average IMF but observations have shown that particles can reach longitudes far away

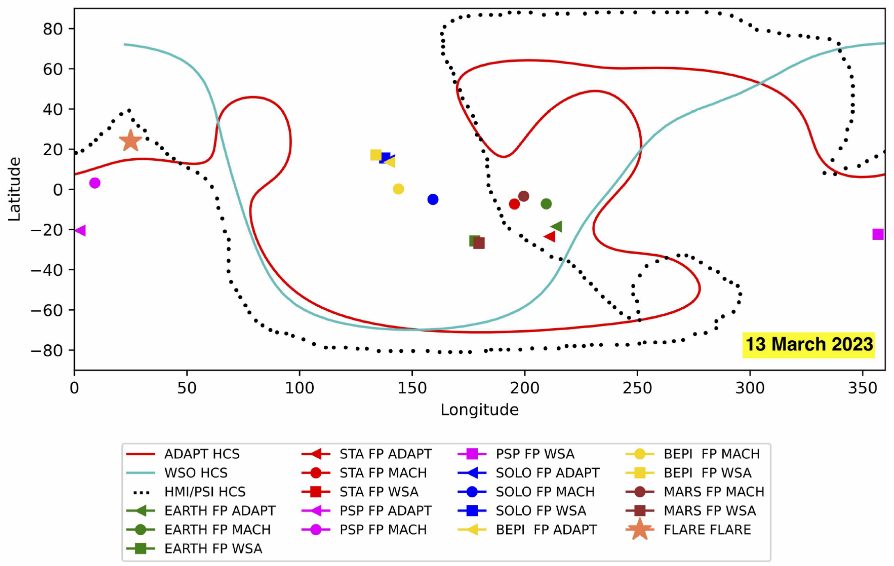

Figure 8: Heliospheric current sheet configuration at the solar source surface during the 2023-03-13 SEP event from three models: ADAPT (*red solid line*), WSO (*blue solid line*) and HMI/PSI (*dotted black line*) [16]. The star shows the location of the solar flare associated to the event. The other symbols show the locations of magnetic footpoints of the field line through the various spacecraft, calculated using three different methodologies.

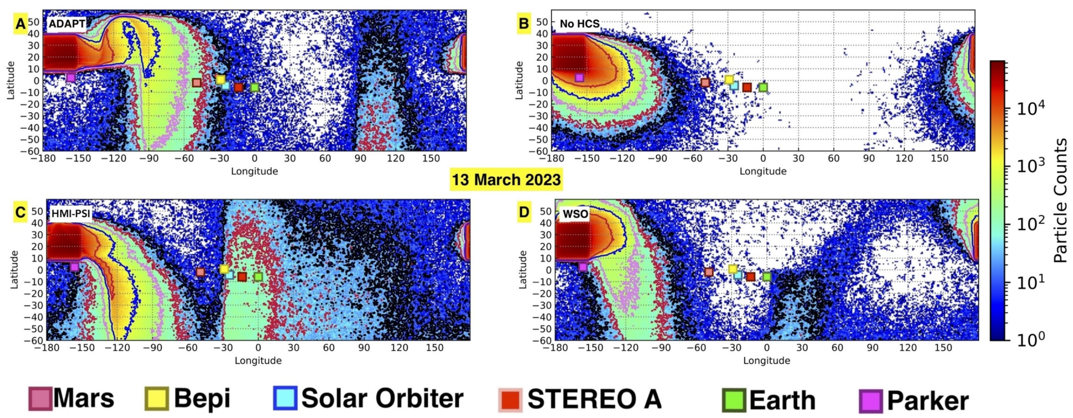

Figure 9: Maps of proton crossings of a sphere at 1 au from the Sun from 3D test particle simulations of the 2023-03-13 SEP event [16]. Panel B does not include a HCS, while panels A, C and D include a HCS obtained from the ADAPT, HMI/PSI and WSO models respectively.

from the well connected regions, i.e. they experience perpendicular transport. Various mechanism may be responsible for this: in addition to pitch-angle scattering, turbulence causes motion across the average field, described in some models as cross-field diffusion [15] and in other approaches as magnetic field line meandering [9]. In addition guiding-center drifts (gradient and curvature) associated with the large-scale structure of the IMF help to produce broader spatial distributions of particles [2].

Another mechanism for cross-field propagation is drift along the heliospheric current sheet

(HCS), the surface within the heliosphere that separates the two magnetic polarities of the IMF. The HCS has a complicated 3D shape because of the tilt between the rotation and magnetic axes of the Sun. When charged particles encounter the HCS, their motion is drastically changed because the guiding centre approximation breaks down: the particles experience motion across the field along the HCS, spreading in longitude and latitude [1]. The HCS drift is in opposite directions depending on the polarity of the IMF (A^+ or A^-). Particles released at a source region close to the HCS may drift towards it as a result of gradient and curvature drifts and once they reach the HCS they propagate along it via HCS drift [1, 2].

Transport along the HCS may explain why spacecraft near the HCS observe higher SEP peak intensities than others which appear better connected to the source region but are far from the current sheet. For the 2023-03-13 event, shown in Figure 2, modelling of the HCS and of the footpoints of the observing spacecraft, shown in Figure 8, demonstrates that STEREO A and L1 spacecraft footpoints were close to the HCS compared to BepiColombo and SolO footpoints [16]. 3D test particle simulations of the event, shown in Figure 9, explored the spatial distributions of SEPs in the heliosphere during the event and produced intensity profiles at the observing spacecraft, using three different models of the HCS. The results showed that models including the HCS reproduce the observed global spread of SEPs far better than those without it and that the low intensities at BepiColombo and SolO may have resulted from their lack of proximity to the HCS [16].

4. Conclusions

Thanks to SolO and PSP, together with STEREO A, near-Earth and planetary missions, we now have at our disposal a unique fleet of spacecraft, providing unprecedented multipoint views of SEPs. New observations have been found to challenge standard DSA models of shock acceleration and show that transport plays a key role in shaping SEP observables.

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