APPLICATION OF (SIMULATED) MULTI-POINT SOLAR ENERGETIC PARTICLE OBSERVATIONS ON SPACE WEATHER

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1 Introduction

Solar Energetic particles (SEPs) are accelerated during solar eruptions. As they traverse the interplanetary space to be observed by in situ instruments in Sun-observing spacecraft, their propagation is guided by the interplanetary magnetic field, which is in a shape of the Parker spiral, superposed by turbulent fluctuations.

In near-Earth space and in the Earth's atmosphere, the SEPs constitute a Space Weather hazard to technology and humans in space and high-latitude aviation (Jones+ 2005; Jiggens+ 2014). For this reason, considerable effort has been to forecast the space weather risk of SEPs. The SEP forecasting methods are typically of empirical nature, relying on statistics of past SEP events, or utilizing physical models of SEP propagation from their origin to Earth (see, e.g. Whitman+ 2023, also Damini Bhagwath's poster #8 in this meeting). As the goal of these approaches is to forecast Space Weather at Earth, the models typically only utilize the observations and forecast the of SEP events at Earth.

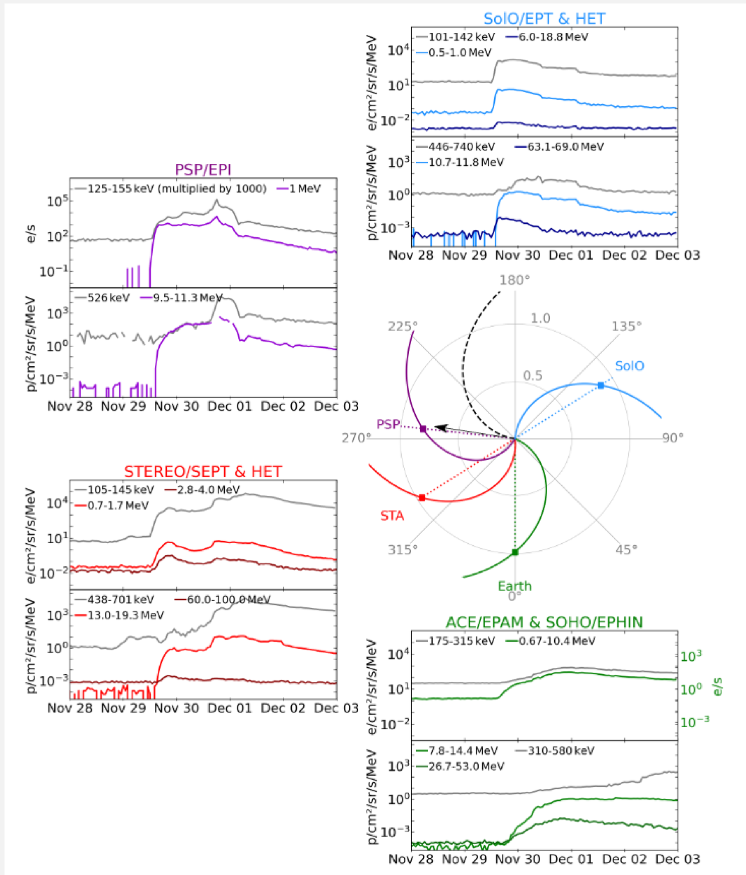


Figure 1. A wide SEP event observed by multiple spacecraft (Kollhoff+ 2021).

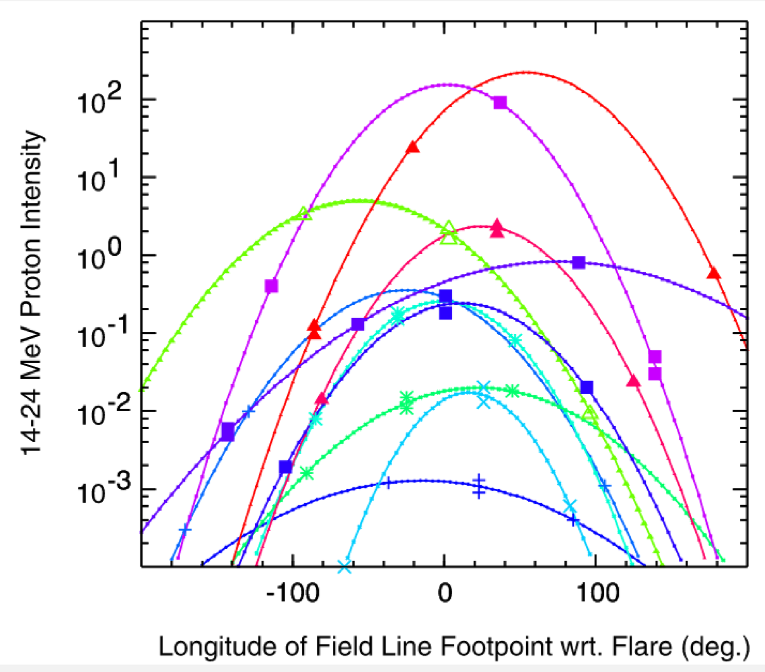


Figure 2. Gaussian fits to peak SEP intensities (Richardson+ 2014).

Since the launch of the STEREO spacecraft in 2007, we have been able to continuously observe SEP events (or lack thereof) from at least two different locations at 1 au heliocentric distance. These observations have revealed the varying faces of individual SEP events depending on observer locations (see Figure 1). Statistical results have shown that the location of the highest SEP peak intensity at 1 au can have magnetic connection significantly deviating from the corresponding flare location, with $\Delta\phi = \phi_{flare} - \phi_{footpoint} = -15° \pm 35°$ (Richardson+ 2014, see Figure 2). This, and the uncertainty in the SEP source width, may be a significant source of uncertainty in SEP forecasting.

In this presentation, we discuss the potential of using multi-spacecraft SEP observations for Space Weather forecasting. We use 3D full-orbit SEP transport simulations within turbulent heliosphere (Laitinen+ 2023a, 2023b), varying SEP source size, the temporal injection profile and the interplanetary space transport conditions, see the Laitinen papers for further details on the turbulence model. We discuss how differences in these parameters can complicate single-point SEP observations, and how multi-point observations can be used **to continuously improve the forecasting of an ongoing SEP event**.

2 Single-spacecraft observed SEP events

SEP events observed by single SEP events can be very difficult to analyse, particularly at the start of an SEP event. SEP profiles are determined by

- SEP source and observer location, and SEP source size
- Temporal evolution of injection
  - For example Reid-Axford –type, $f(t) = \frac{1}{t} e^{t_a/t - t/t_e}$: from acceleration, t_a to escape, t_e
- Interplanetary turbulence: amount of scattering and field-line meandering the SEPs experience before reaching Earth.

The figures below show examples of 60MeV SEP proton event time-intensity profiles at location connected to the is $8° \times 8°$ (heliolongitude and –latitude) source region, with moderate and low interplanetary magnetic turbulence, with different SEP transport conditions. Similar SEP time profiles (blue and orange curves) can occur due to different combinations of interplanetary turbulence conditions and the temporal evolution of the injection of SEPs at the SEP source.

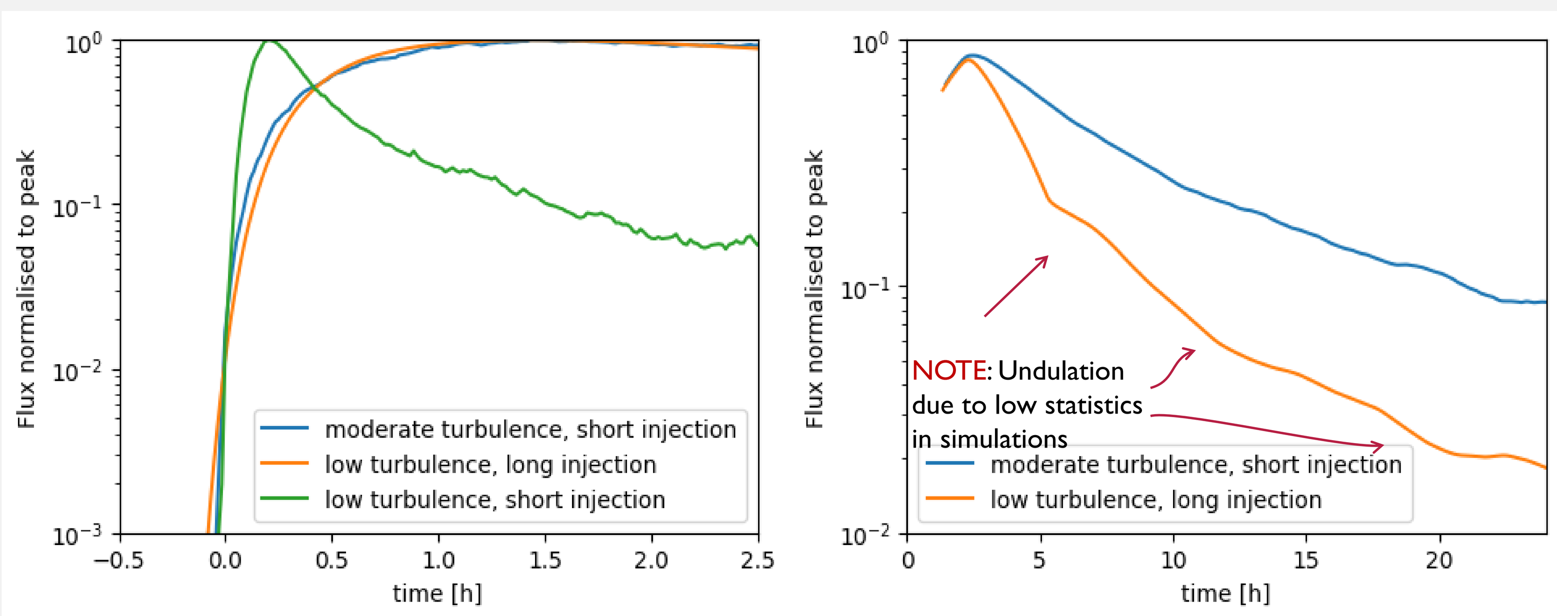
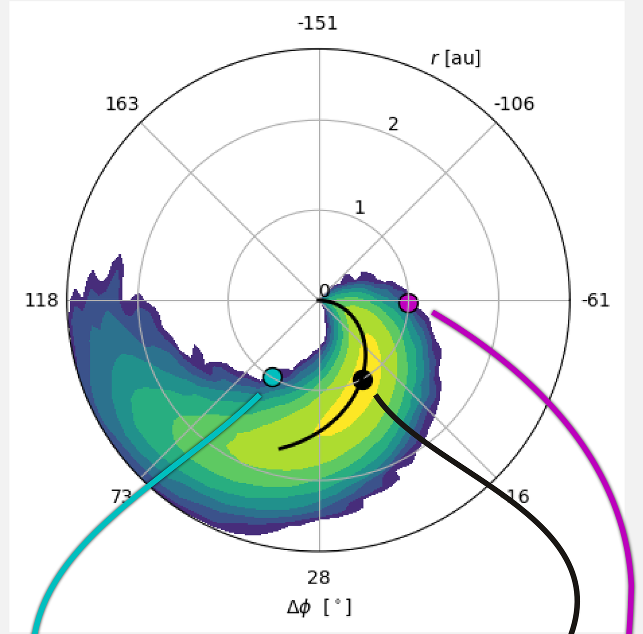


Figure 3. Intensities at 1 au (normalised to peak intensity) of 60 MeV protons simulated in heliosphere with relative magnetic field turbulence variance ${}^{dB^2}/_{B^2} = 0.6$ (moderate) and 0.2 (low turbulence) at 1 au. The SEP source at 2 $r_\odot$ is $8° \times 8°$ wide in heliolongitude and –latitude, and the virtual observer is at 1 au radial distance connected to the centre of the source along Parker magnetic field line. For short injection, the Reid-Axford timescales are $t_a = t_e = 1$ min, and for the long $t_a = 1$ min, $t_e = 60$ min. The time $t = 0$ is chosen to be the time intensities exceed the level of 0.01. **Note: simulation statistics low, to be improved.**

This ambiguity can be addressed by analysing the SEP anisotropy at the early times of the SEP event – the stronger the anisotropy, the weaker the turbulence. However, observations have shown that the anisotropy has heliolongitudinal dependence (Dresing+ 2014): Unveiling the SEP injection time profile, SEP source size, and SEP transport conditions would strongly benefit multi-spacecraft observations of the SEP event. The implications from modelling is a significant work that we will address in near future.

3 Effect of source width and observer location



SEPs can reach wide range of heliolongitudes, due to both the SEP interplanetary transport and the SEP source size. Here we show three virtual observers, one connected to the centre of the SEP source along Parker spiral (**black** circle), and one **60° west** and **east** (magenta and cyan circles). As seen in the figure below, for a narrow source ($8°$, left), the SEP profiles over 7 days are very different from each other. However, for a wide source ($80°$, right), the profiles are similar, with only peak intensity different. It is difficult to infer the observer location or SEP event evolution from single-spacecraft observations.

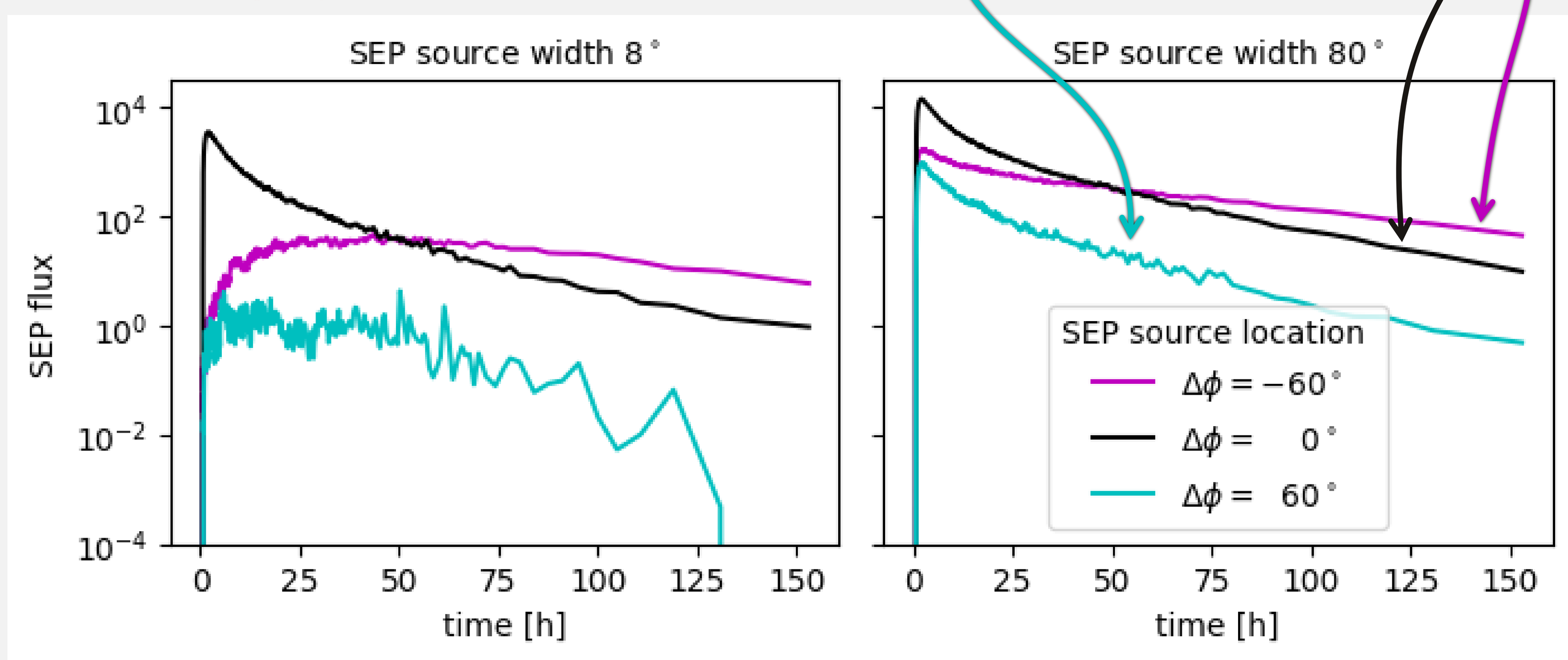
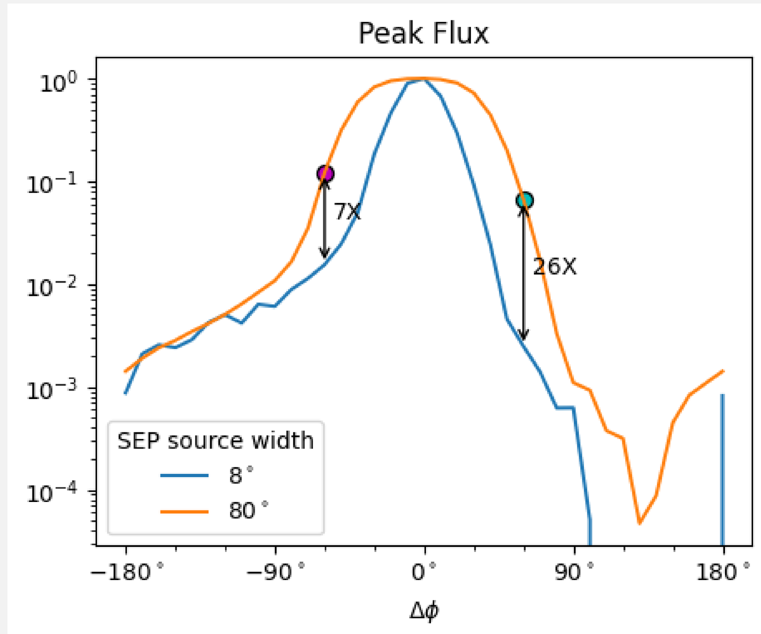
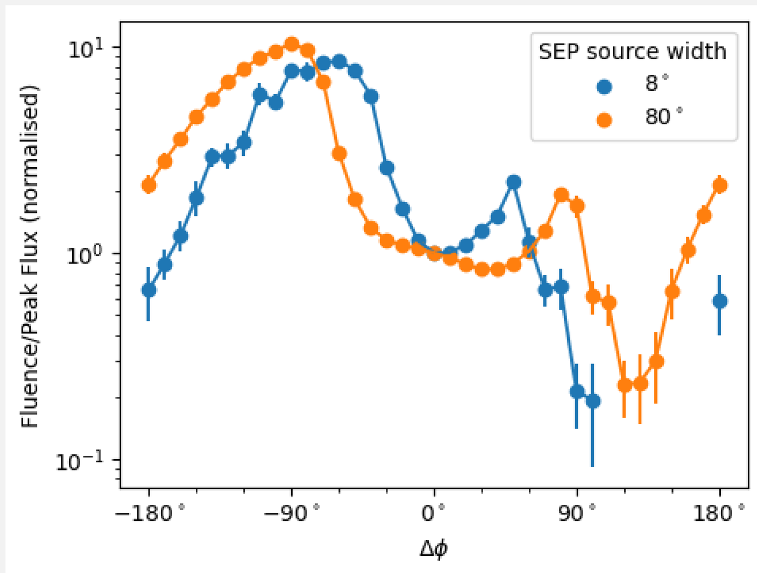


Figure 4. 60-MeV proton intensities at three different heliospheric locations, as shown in the top right panel (showing SEP intensity as a function of heliospheric location at 3 hours after injection). The Reid-Axford injection parameters are $t_a = 1$ min, $t_e = 60$ min.

In the figures on the right, we show SEP event peak flux and total fluence, normalised to their maximum for all $\Delta\phi$ locations. As we can see, both the peak flux and fluence depend strongly on the observer location and the source width and are asymmetric respect to $\Delta\phi = 0°$. In the panel below we demonstrate that the relation between the peak flux to the total fluence of SEPs also varies with location and width. As can be seen, we can infer the total fluence from the peak flux only if we know the spacecraft location and the SEP source size (as well as transport conditions, TBD).





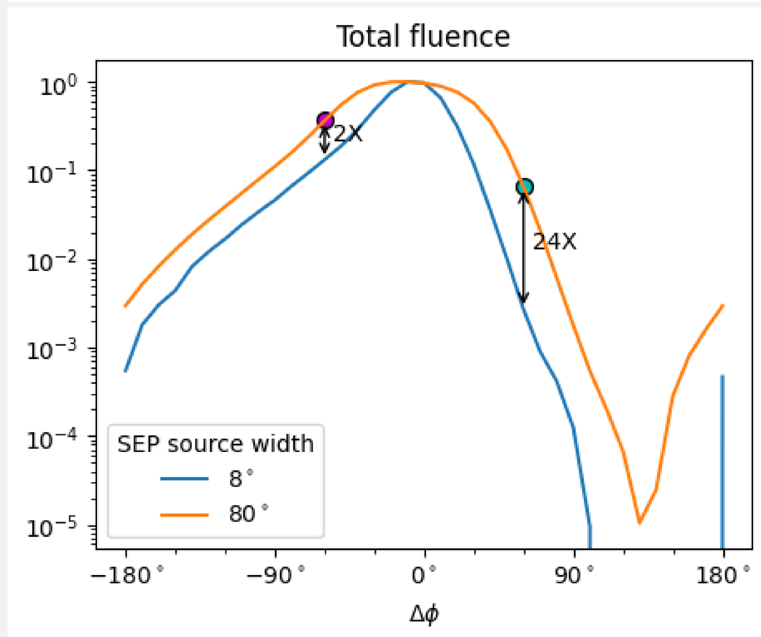


Figure 4. 60-MeV peak intensities (top right) and total fluences (bottom right) as a function of SEP source width and observer location, normalised to maximum values in $\Delta\phi$ coordinate. The bottom left shows the ratio of fluence and peak flux (normalised to its value at $\Delta\phi = 0°$), as a function of heliolongitude and the SEP source width.

4 Onset and peak times

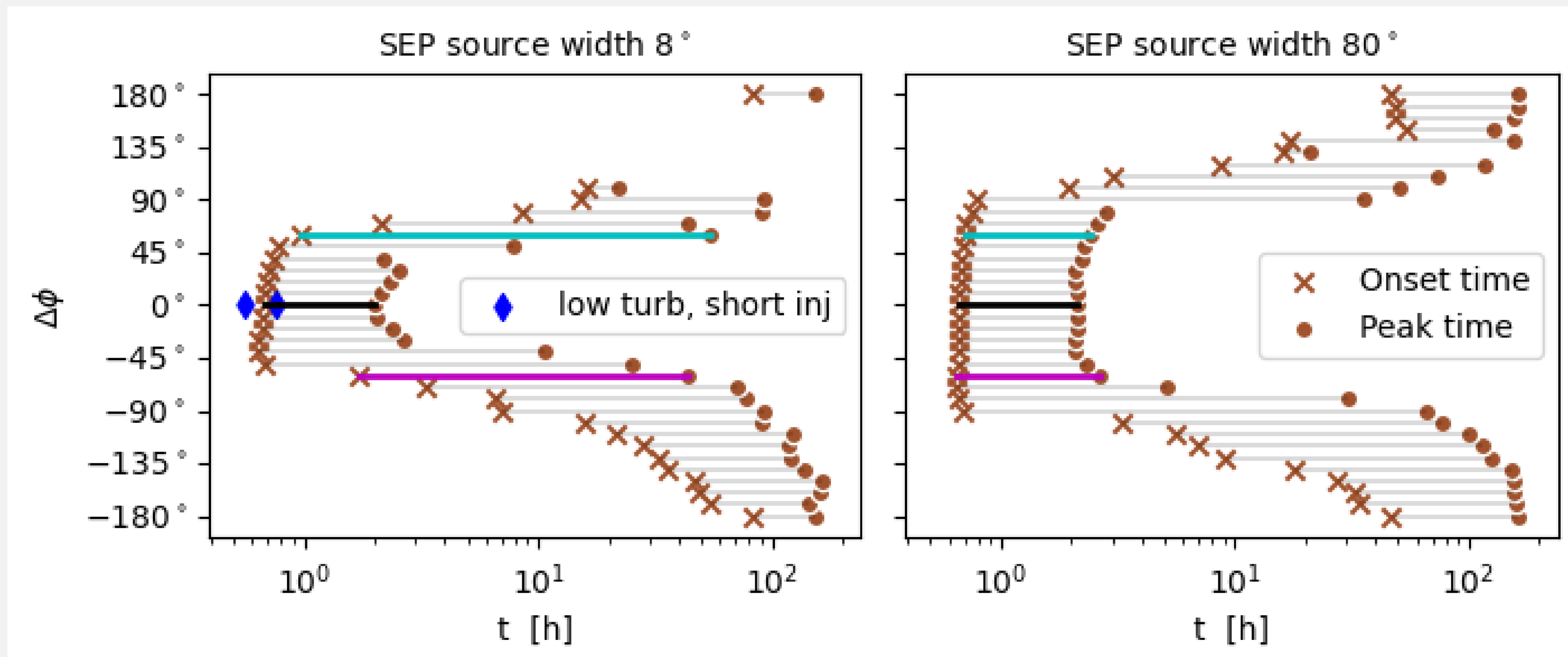


Figure 5. Onset and peak injection times (sienna crosses and circles respectively) for 60-MeV proton intensities as a function of heliolongitude $\Delta\phi$ for moderate turbulence. The three heliospheric locations shown in Figure 3 are depicted with thick lines. We also show the low-turbulence case from Figure 3 with blue diamond symbols.

Onset and peak times depend strongly on the interplanetary turbulence conditions (see panel 2), however they also depend on the SEP source properties and observer location. In the figure above, we show the onset (sienna circle) and peak (sienna cross) times for observers at different heliolongitudes (y-axis), for narrow and wide SEP sources (left and right panels, respectively). We also show the low-turbulence case with blue diamonds. For a single observer, it is difficult to infer SEP event evolution from the onset and peak times.

5 Summary

In this work we have shown SEP event features that would be difficult to interpret from a single-observer perspective, and would benefit from a multi-spacecraft view. We find that

- SEP event profile shape depends on transport conditions, temporal injection evolution, SEP source and observer location.
- Inferring the injection from initial time profile alone is difficult as it also depends on SEP transport conditions (TBD: anisotropy analysis helps, but anisotropy depends on observer location).
- SEP onset and peak times, and peak intensity, have clear dependence on observer location and the source width.
- Multi-spacecraft observations of SEP may help in constraining the SEP source width, as well as the observer location, and **help improve forecasting the Space Weather effect of an ongoing SEP event.**

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