Investigating the Evolution of Turbulent Cascade Rate using Solar Orbiter and Parker Solar Probe

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Background and Objectives

- Solar wind consists of a mixture of charged particles in a plasma state expanding outwards from the Sun.
- Turbulence within plasmas consists of interacting fluctuations in the magnetic fields and particle velocities.
- Magnetohydrodynamics (MHD) describes dynamics on spatial scales that are larger than the intrinsic scale lengths of plasma [1].
- MHD turbulence theory describes how energy cascades between different length scale fluctuations under assumptions such as incompressibility of plasma.

The energy cascade rate (ε) can be computed using a third-order structure function:

$$Y^{\pm}(l) = \langle \hat{\boldsymbol{l}} \cdot \Delta \mathbf{z}^{\mp}(\boldsymbol{r}, l) |\Delta \mathbf{z}^{\pm}(\boldsymbol{r}, l)|^2 \rangle = -\frac{4}{3}\varepsilon l$$

$$\mathbf{z}^{\pm} = \boldsymbol{V_P} \pm \frac{\boldsymbol{B}}{\sqrt{\mu_0 m_P N_P}}$$

Equation 1a *– Third-order structure functions,* ***1b*** *– Elsässer variables [2]*

l	Lag (separation)
$\boldsymbol{r}$	Position
V_P	Velocity
m_P	Mass of proton
N_P	Proton number density
$\boldsymbol{B}$	Magnetic field

The **objectives** of our analysis are to determine:

1. Whether it is possible to compute energy cascade rates using third-order structure functions.
2. How energy cascade rates vary with heliocentric distance using spacecraft **Solar Orbiter (SolO)** and **Parker Solar Probe (PSP).**

Method and Instruments

- Energy cascade rates are computed at different heliocentric distances from *equation 1a* using SolO and PSP.
- Estimated propagation time is considered when identifying which intervals to investigate as seen in *figure 1* [3]. Scenario A is the ideal alignment and scenario B is the alignment used in this investigation.
- The orange shaded region in *figure 2* was identified as a suitable range over which PSP and SolO are closest to conjunction.

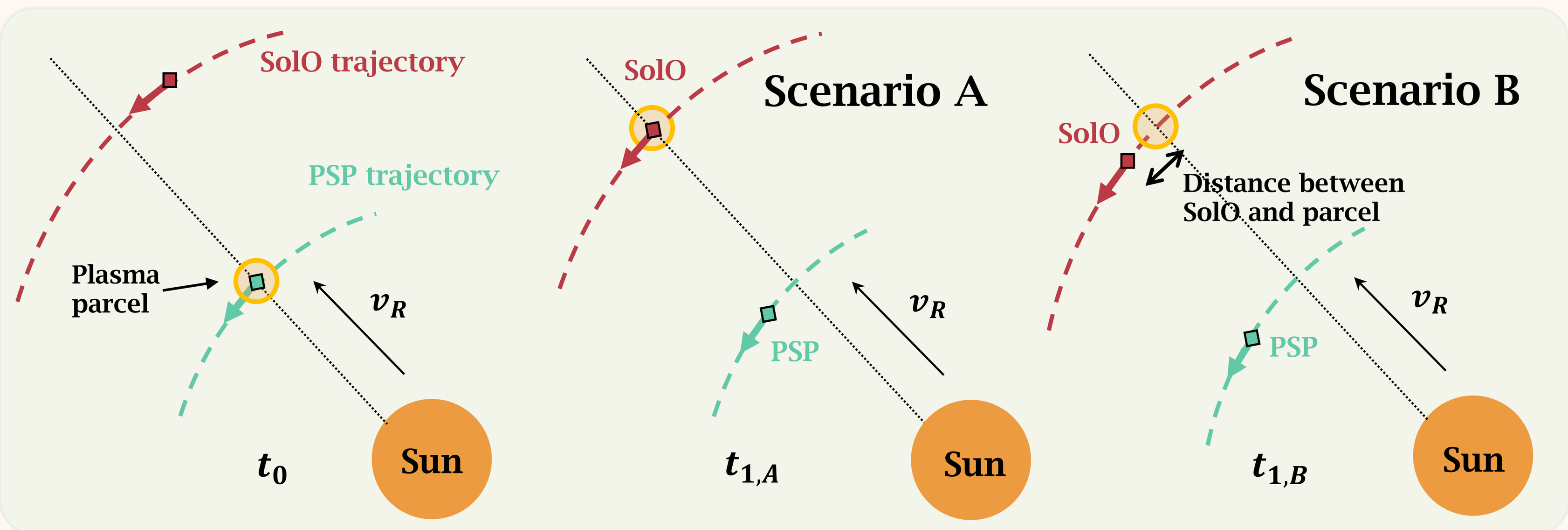

Figure 1 *- Shows a plasma parcel travelling outwards from the Sun, reaching PSP at* $\boldsymbol{t_0}$*.* $\boldsymbol{t_{1,A}} < \boldsymbol{t_{1,B}}$ *such that* $\boldsymbol{t_{1,A}}$ *is the time when SolO encounters the parcel under investigation.*

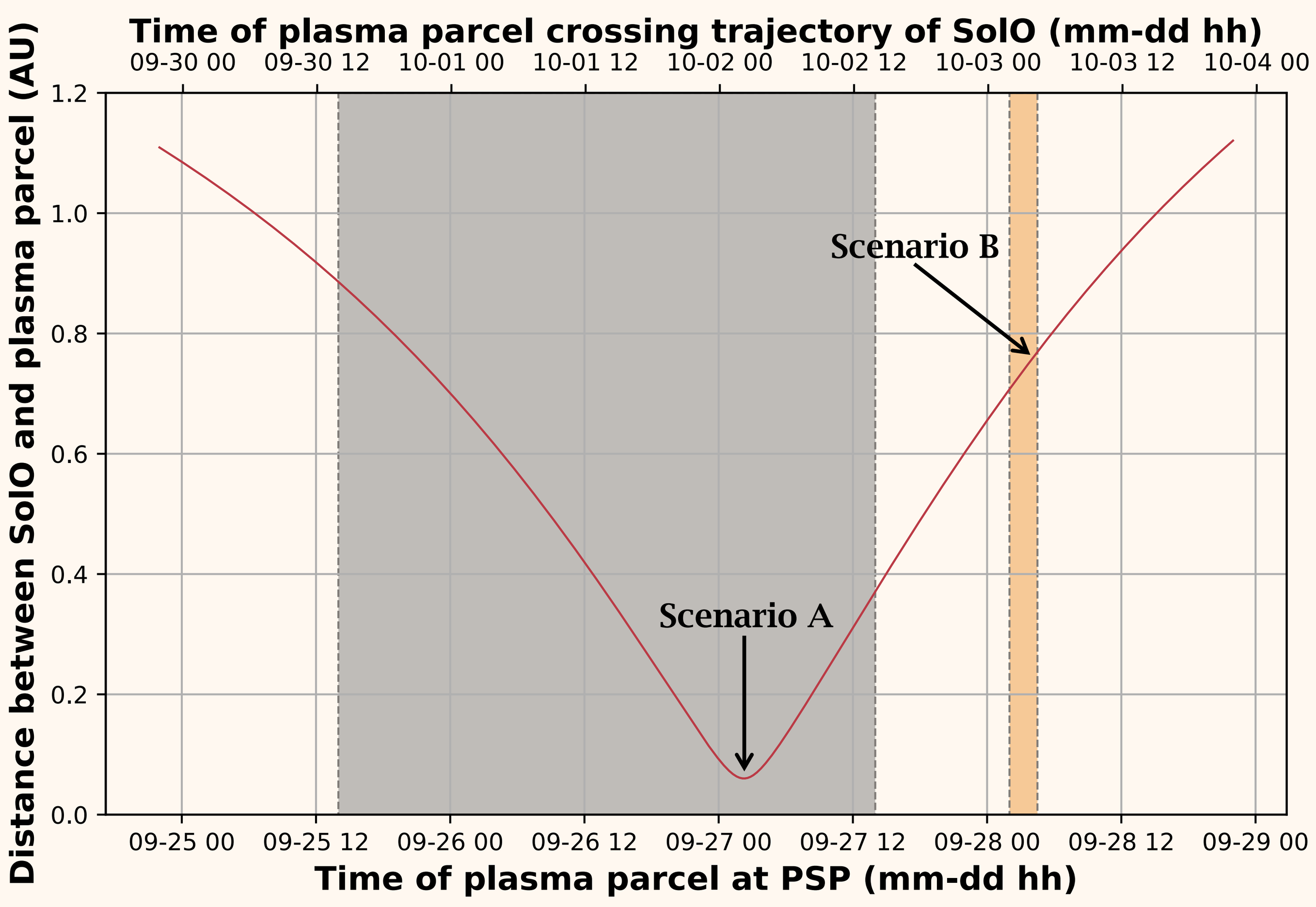

Figure 2 *- Gaps in data sets are shown by the area shaded in grey. Selected region for analysis is shaded orange. Suitable intervals within this region were found by analysing extended intervals of 12 hours.*

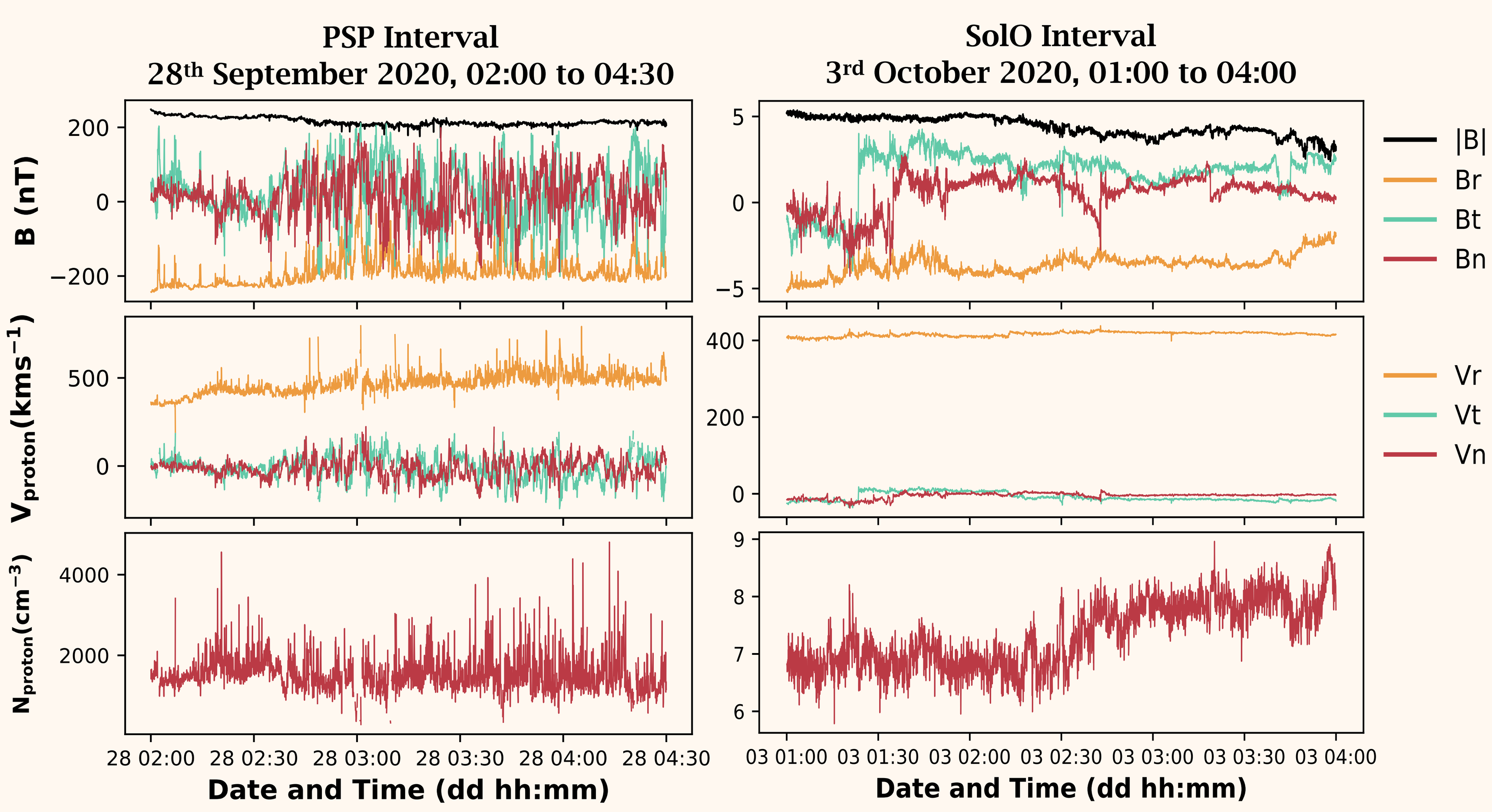

Figure 3 *- Timeseries of variables* $\boldsymbol{B}$*,* $\boldsymbol{V_{Proton}}$ *and* N_{Proton} *for PSP interval (left) and SolO interval (right) used to compute cascade rate. Inhomogeneities in the timeseries and their effects on cascade rate have also been considered while choosing intervals.*

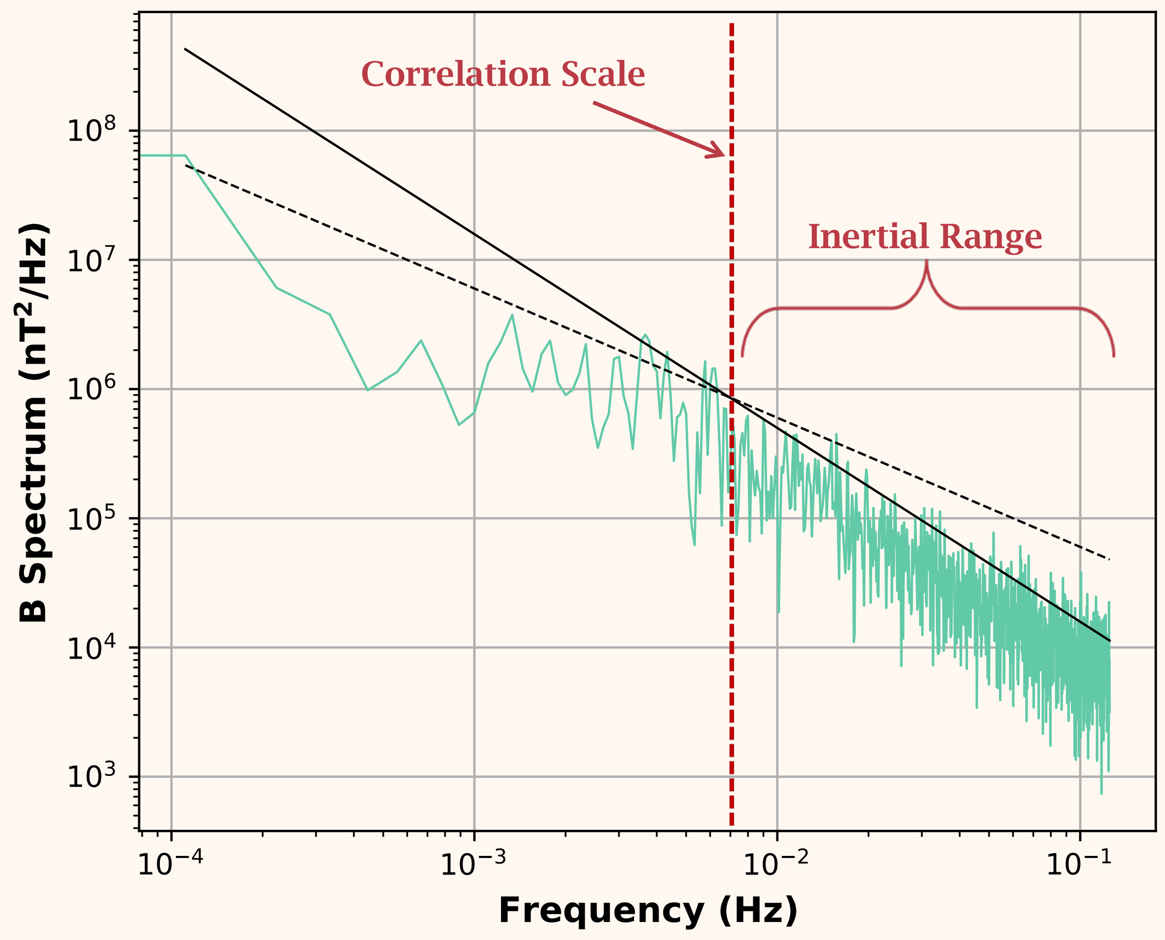

Figure 4 *- Power spectrum for Parker Solar Probe interval (2:00 to 4:30 am on 28th September 2020).*

The energy containing scales of the spectrum show a f^{-1} relationship.

The correlation scale is the largest turbulent eddy. Scales smaller than this (higher frequencies) are the inertial range where the spectrum follows $f^{-3/2}$ [4]. This is the range we are interested in.

Results

- Cascade rates are calculated using the gradient of the function $Y^{\pm}(l)$ (see *equation 1a*).
- Power spectrum plots (see *figure 4*) help identify suitable linear regions to use.
- The energy cascade rate, ε, is greater at PSP than at SolO implying that ε decreases as heliocentric distance increases (see *table 1*).

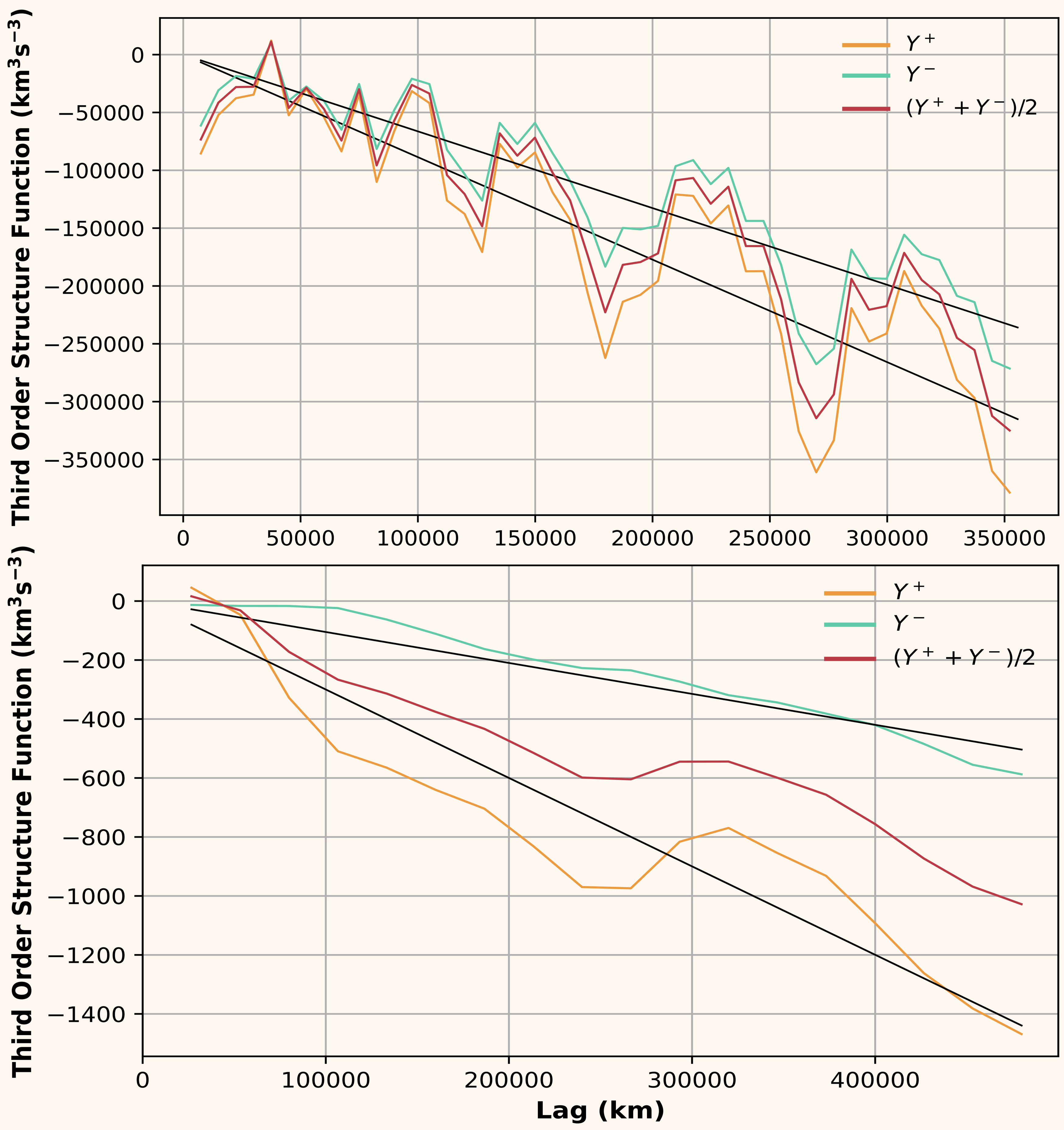

Figure 5 *- Third-Order Structure Functions plotted against lag for PSP interval (top) and SolO interval (bottom).*
$\varepsilon^{\pm} = -3/4 \times (\text{gradient of } Y^{\pm}(l))$

ε_{PSP}	**3.9 x 10⁵ Jkg⁻¹s⁻¹**
ε_{SolO}	**1.5 x 10³ Jkg⁻¹s⁻¹**

Table 1 *- Energy cascade rate is computed using gradients of plots in figure 5 for PSP and SolO.*
$\varepsilon = (\varepsilon^+ + \varepsilon^-)/2$

Conclusion

- Magnetic field and particle data from two spacecraft are used to determine the cascade rate at different heliocentric distances from the Sun.
- Using length scales within the inertial range gives a positive value for cascade rate implying that energy is transferred from large scales to small scales – this is in line with theory.
- Cascade rate decreases with heliocentric distance which implies that the net rate of energy transfer decreases.
- These results will help further understanding of how the turbulent dynamics are evolving in space and time.

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[1] D. Biskamp, *Magnetohydrodynamic Turbulence.* Cambridge University Press, 2003.
[2] H. Politano & A. Pouquet, 1998b, *Geophys. Res. Lett.*, 25, 273
[3] D. Telloni *et al*, 2021 *ApJL* 912 L21
[4] R. Bruno and V. Carbone, *Living reviews in solar physics*, vol. 10, no. 1, 2013.

Acknowledgments:
We thank Dr. Julia Stawarz for her support throughout this project.