SHINE Conference 2022: Isotropization and Evolution of Energy-Containing Eddies in Solar Wind Turbulence: Parker Solar Probe, Helios 1, ACE, WIND, and Voyager 1

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Abstract: We examine the radial evolution of correlation lengths perpendicular ($\lambda_C^\perp$) and parallel ($\lambda_C^\parallel$) to the magnetic-field direction, computed from solar wind magnetic-field data measured by Parker Solar Probe (PSP) during its first eight orbits, Helios 1, Advanced Composition Explorer (ACE), WIND, and Voyager 1 spacecraft. Correlation lengths are grouped by an interval's alignment angle; the angle between the magnetic-field and solar wind velocity vectors (Θ_{BV}). We observe an anisotropy in the inner heliosphere within 0.40au, with $\lambda_C^\parallel/\lambda_C^\perp \approx 0.75$ at 0.10au. Results from ACE/WIND support a reversal of the anisotropy, such that $\lambda_C^\parallel/\lambda_C^\perp \approx 1.29$ at 1au. The ratio does not appear to change significantly beyond 1au, although the small number of parallel intervals in the Voyager dataset precludes unambiguous conclusions from being drawn. This study provides insights regarding the radial evolution of the large, most energetic interacting turbulent fluctuations in the heliosphere. We also emphasize the importance of tracking the changes in sampling direction in PSP measurement as the spacecraft approaches the Sun, when using these data to study the radial evolution of turbulence. This can prove to be vital in understanding the more complex dynamics of the solar wind in the inner heliosphere and can assist in improving related simulations.

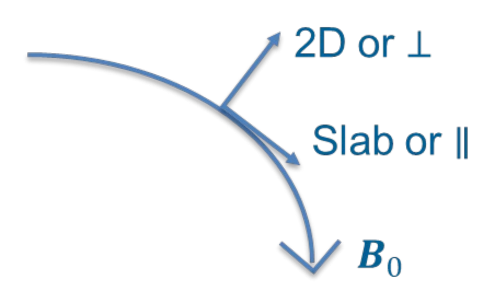
Background

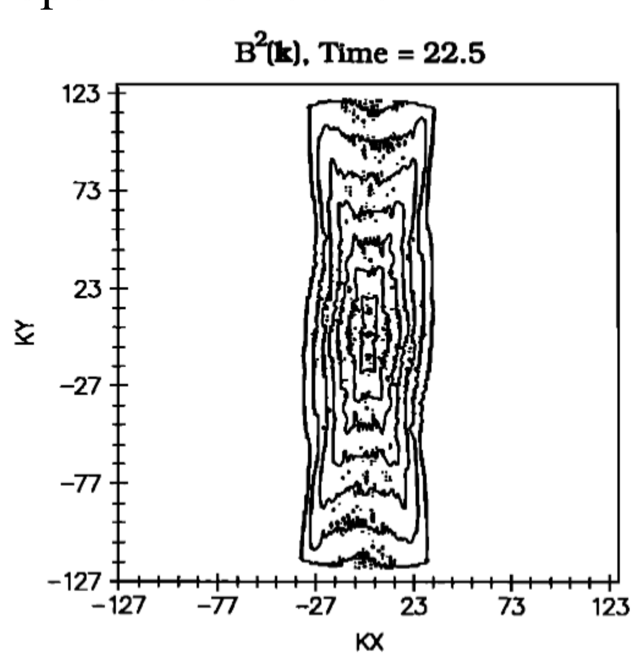
Magnetohydrodynamic regimes – develops and sustains anisotropy relative to the mean magnetic field $\boldsymbol{B}_0$.
Robinson&Rusbridge(1971, PoF); Shebalin+(1983, JPP); Matthaeus+(1990, JGR); Goldreich&Sridhar(1995, ApJ); Dasso+(2005, ApJL); Chhiber+(2020,); DeForest+(2016, ApJ); Zank+(2021, PoP); Oughton&Engelbrecht(2021, NewA)

Oughton+(2015, PTRSL)

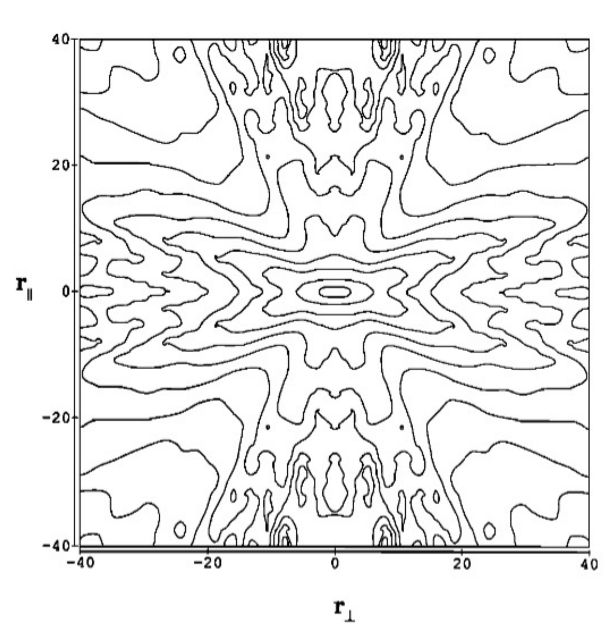
Some types of related anisotropy:
1) **Gradient/Outer scale**
2) Polarization/variance
3) Spectral/correlation

Inertial range





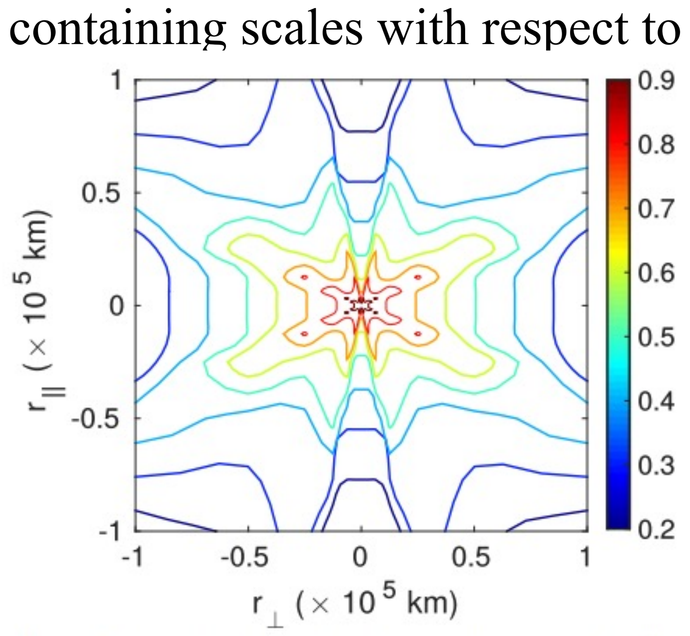
Contours of $\boldsymbol{B}^2(\boldsymbol{k})$ at 22.5 eddy turnover times from a simulation of turbulence driven by velocity shear, which included a strong dc magnetic field in the x direction (preferred direction).



Matthaeus+(1990, JGR)

Contour plot of the two-dimensional correlation function of solar wind fluctuations as a function of distance [10^{10}cm] parallel and perpendicular the mean magnetic field (preferred direction). Observations from ISEE 3 magnetometer data.

⋆ Connection between energy cascaded and size of energy-containing scales with respect to a specific direction relative to $\boldsymbol{B}_0$.



Bandyopadhyay&McComas(2021, ApJ)

Two-dimensional correlation function from first five solar encounters observed by Parker Solar Probe.

⋆ Computed parallel correlation length is less than perpendicular correlation length. This suggests that that more energy is cascaded along $\boldsymbol{B}_0$.

Methodology

Autocorrelation Method 1:

$$\boldsymbol{b} = \boldsymbol{B} - \overline{\boldsymbol{B}}$$

$$\Delta\boldsymbol{b}(\tau) = \boldsymbol{b}(t+\tau) - \boldsymbol{b}(t)$$

$$R_C(\tau) = \frac{<\boldsymbol{b}(t)\cdot\boldsymbol{b}(t+\tau)>}{<\boldsymbol{b}(t)\cdot\boldsymbol{b}(t)>}$$

To resolve correlation scale:
$R_C(\tau_e) = e^{-1}$; τ_e "e–folding" time

Autocorrelation Method 2: **Roy+(2021, ApJL)**

$$R(\tau) = \langle \boldsymbol{B}(t+\tau)\cdot\boldsymbol{B}(t)\rangle - \langle \boldsymbol{B}(t+\tau)\rangle\cdot\langle \boldsymbol{B}(t)\rangle$$

To resolve correlation scale:
$R(\tau_e')/R(0) = e^{-1}$; τ_e' "e–folding" time
Linear-least squares fit: $\log[R(\tau)/R(0)] = -t/\tau_e$ for $\tau \in [0, \tau_e'/2]$

⋆ **Correlation Length**: $\lambda_C = \tau_e V_{SW} \rightarrow$ **Taylor(1938, RSPSA)**

Radial Scaling Expectation: $\lambda_C(R) \sim \sqrt{R}$
Zank+(1996, JGR); Matthaeus+(1996, JPP); Breech+(2008, JGR) Parashar+(2019, ApJ); Cuesta+(2022, ApJS)

Alignment Angle and Angular Channels:

Angle between $\boldsymbol{B}_0$ and $\boldsymbol{V}_{SW}$ (alignment angle):

$$\Theta_{BV} = \cos^{-1}\left(\frac{\langle|\boldsymbol{B}|\rangle\cdot\langle\boldsymbol{V}_{SW}\rangle}{\langle B\rangle\langle V_{SW}\rangle}\right)$$

When the spacecraft velocity is very small compared to $\boldsymbol{V}_{SW}$, simplification leads to winding angle.

Angle between $\boldsymbol{B}_0$ and radial unit vector $\widehat{\boldsymbol{R}}$ (winding angle):

$$\Theta_{BR} = \cos^{-1}\left(\frac{\langle|B_R|\rangle}{\langle B\rangle}\right)$$

The winding angle can be referred to as alignment angle.

Slab or ∥ : $0 < \Theta_{BV}, \Theta_{BR} < 40$
2D or ⊥ : $50 < \Theta_{BV}, \Theta_{BR} < 90$

Data Specifics:

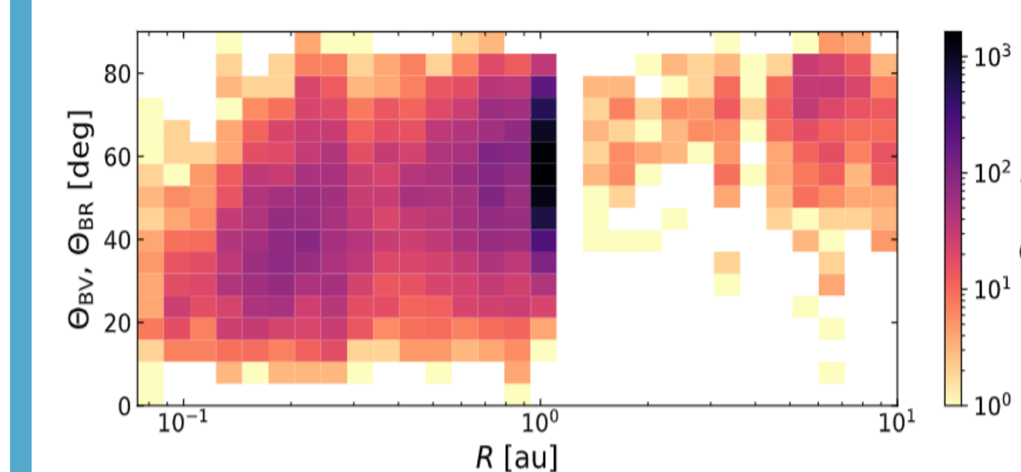
PSP
- Level 2 MAG/Level 3 SPC – 1s res.
- 10/5/2018 – 6/30/2021
- $R < 0.30$au – 1hr interval size
- $R > 0.30$au – 3hr interval size

Helios 1
- All available data from 1974 to 1981
- Results extracted from **Ruiz+(2011, JGR)**
- 1 day interval size

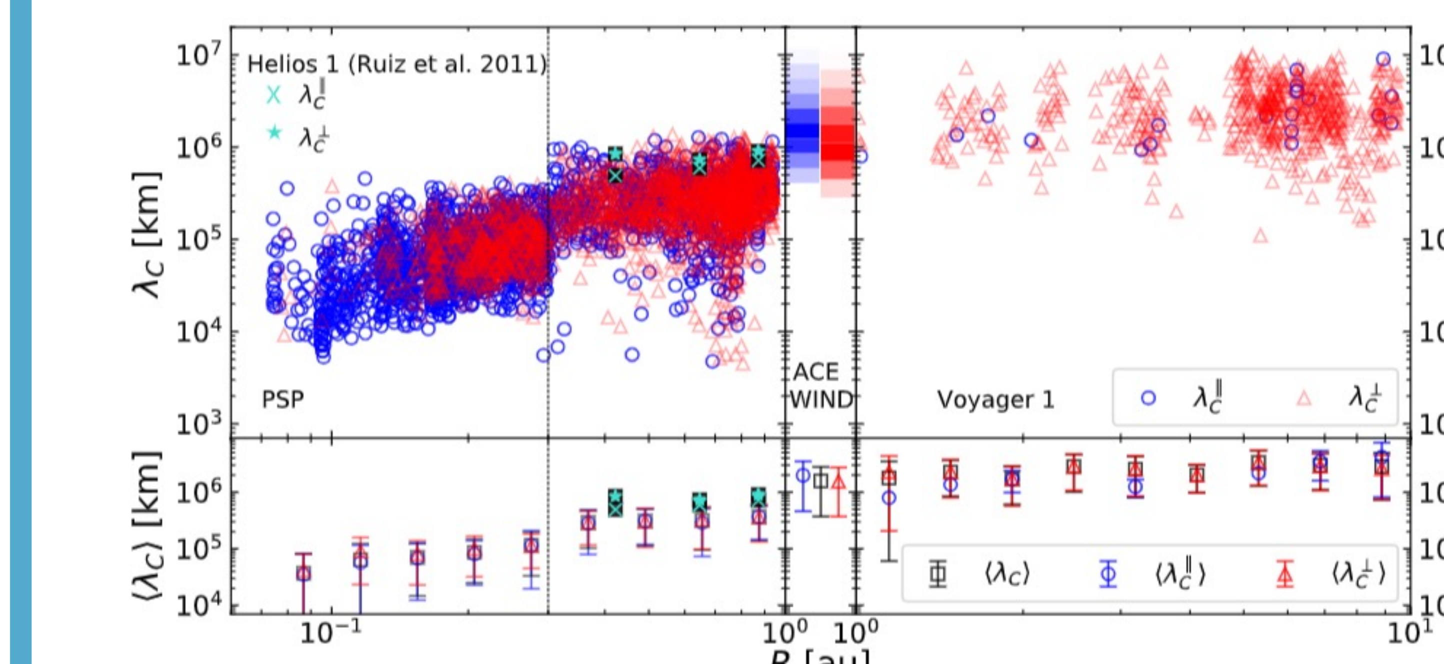
ACE/WIND
- Level 2 MAG/Level 3 SPC – 1min res.
- 2/5/1998 – 3/30/2008 (2/5/2008)
- 1 day interval size

Voyager 1
- Data spanning 1 – 10 au
- Refinement – **Cuesta(2020, MS. thesis)**
- 1 day interval size

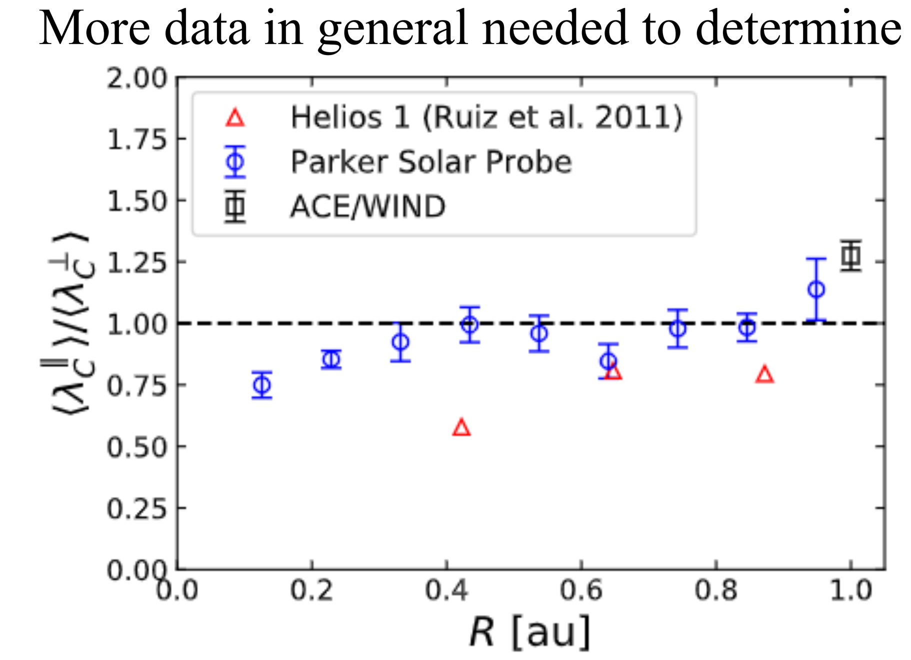
Results



Parker spiral magnetic structure exhibited in evolution of bins with the highest counts at varied heliocentric distances.



Low statistical weight of $\lambda_C^\perp$ for $R < 0.15$au and $\lambda_C^\parallel$ for $R > 1$au.
Larger number of samples required to determine evolution of anisotropy/isotropy past 1au.
More data in general needed to determine anisotropy closer to the Sun.



Isotropization of $\langle\lambda_C^\parallel\rangle/\langle\lambda_C^\perp\rangle$ up to 0.40au.
Variations about isotropy occur at ~0.60au and closer to 1au.
Is the 1au anisotropy sustained or is it a large perturbation from the original isotropized quantity?

Conclusions/Caveats

- Sufficient angular coverage $0.30\text{au} < R < 1\text{au}$
- Clear isotropization moving to 0.40au, variations towards 1au
- Evolution for $R > 1$au requires more data
- Several methods to compute λ_C.
- Angular channels differ between different studies.
- Unable to measure $\lambda_C^\parallel$ and $\lambda_C^\perp$ simultaneously

⋆ ⊥- variations/gradients are nearly "invisible" to PSP close to the sun ⋆

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