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Transition to a State of Zero Magnetic Helicity: Observations in the Near-Sun Solar Wind

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1 REDUCED MAGNETIC FIELD SPECTRA

From a single-spacecraft time series we can only measure the reduced power spectral tensor [e.g., Wicks et al. 2012]:

$$\mathcal{P}^r_{ij}(\omega') = \int \mathcal{P}_{ij}(\mathbf{k})\delta[\omega' - (\mathbf{k}\cdot\mathbf{V} + \omega)]d^3\mathbf{k} \equiv \delta B^*_i(\omega')\cdot\delta B_j(\omega')$$

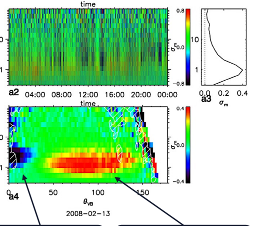
Taylor's hypothesis (TH) assumes $|\omega| \ll |\mathbf{k}\cdot\mathbf{V}|$ [Matthaeus & Goldstein 1982]:

$$\omega' = \omega + \mathbf{k}\cdot\mathbf{V} \simeq \mathbf{k}\cdot\mathbf{V} \qquad \boxed{\mathbf{V} = \mathbf{v}_{sw} - \mathbf{v}_{sc}}$$

At 1 au, $v_A \ll v_{sw}$ and $v_{sc} \ll v_{sw}$, TH is usually well-satisfied for Alfvénic fluctuations, even at sub-ion scales [Howes et al. 2014, Klein et al. 2014a]

The validity of TH for PSP measurements is questionable, however, under certain conditions, a modified version of TH can be used [e.g., Klein et al. 2015]

Credit: He et al. 2011



AIC/FMW waves from instabilities

KAW-like turbulent fluctuations

See Telloni & Bruno [2016], Woodham et al. [2019] for details

Magnetic helicity:

$$\sigma_m \equiv \frac{k_r H'^r_m}{|\delta\mathbf{B}|^2} = \frac{2\,\mathrm{Im}\{\mathcal{P}^r_{TN}\}}{\mathrm{Tr}\{\mathcal{P}^r_{ij}\}}$$

Magnetic compressibility:

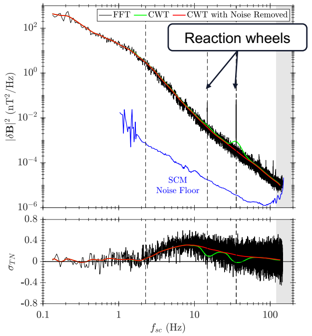
$$C_\parallel = \frac{\delta B^2_\parallel}{\delta B^2} \equiv \frac{\delta B^2_z}{\delta B^2_x + \delta B^2_y + \delta B^2_z}$$

Previous studies [e.g., Horbury et al. 2008, He et al. 2011, Kiyani et al. 2013] use θ_{vB} as a proxy for θ_{kB} to probe spectral anisotropy of the turbulence

2 DATA AND PRE-PROCESSING

We use the high resolution (256 Sa/Cy) merged magnetic field dataset from FIELDS, which allows us probe sub-ion scale turbulence [Bowen et al. 2020]

S/C reaction wheels generate tones in the magnetic spectra, significantly affecting wavelet transform, and therefore spectral slope, etc.

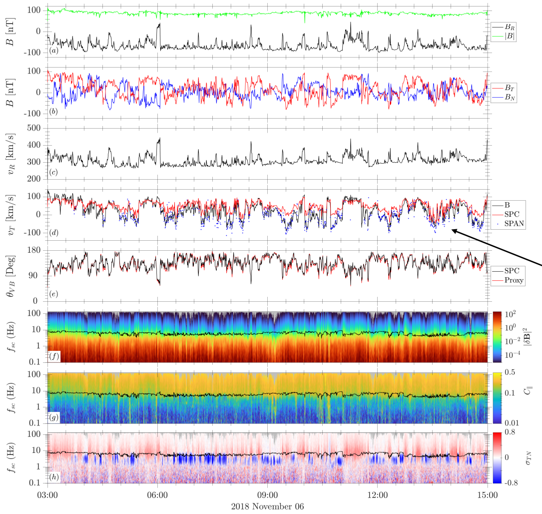


We first remove these artificial tones using a STFT with adaptive window length tuned to confine power to a single frequency bin

We also use proton data from the SWEAP Faraday cup [SPC; Case et al. 2020], which consist of fits to a reduced 1D velocity distribution function (VDF) at 4 Sa/Cy

In tandem, we utilise proton core fits to SPAN 3D proton VDFs where possible (~30 s resolution) [see Woodham et al. 2021b]

3 INTERVAL SELECTION AND ANALYSIS METHODS



We study a 12-hour interval at perihelion during E1, where PSP was connected to an equatorial coronal hole [Bale et al. 2019, Badman et al. 2020]

Average parameters
$v_{sw} \sim 320$ km/s
$v_A \sim 100$ km/s
$d_p \sim 12.1$ km
$\rho_p \sim 7.5$ km

We use both SPC and SPAN velocity measurements to check the accuracy of v_T component

During this interval, we find that both $V \sim 3v_A$ and $V \sim 10\delta v$, suggesting marginally validity of TH during our interval

To probe the spectral anisotropy of the turbulence, we bin power, helicity, compressibility spectra averaged over 10 s intervals as a function of θ_{vB} and $k_R\rho_p$ ($\Delta\theta_{vB} = 6°$, $\delta\log_{10}(k_R\rho_p) = 0.2$)

Following Woodham et al. [2021a], we also calculate the different components of helicity from fluctuations with $\mathbf{k}$ quasi-parallel (σ_{xy}) and oblique (σ_{yz}) to $\mathbf{B}_0$

We neglect the frequencies of any spectra where signal-to-noise ratio < 3 [e.g., see Woodham et al. 2018] to ensure that we remove any non-physical signatures resulting from instrumental noise

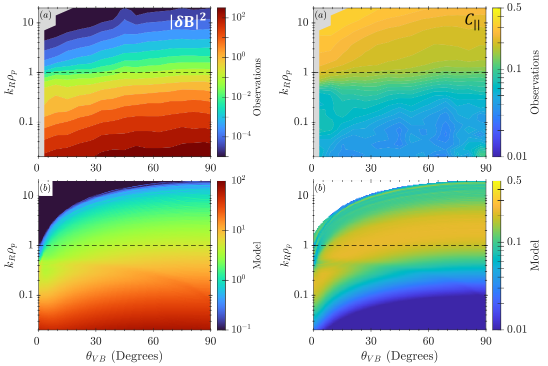
Following He et al. [2012], we compare observations with a model distribution of linear Alfvén waves, consisting of a critically balanced turbulence and instabilities

4 POWER AND MAGNETIC COMPRESSIBILITY

We find that the power anisotropy is consistent with previous studies [e.g., Horbury et al. 2008, Duan et al. 2021]

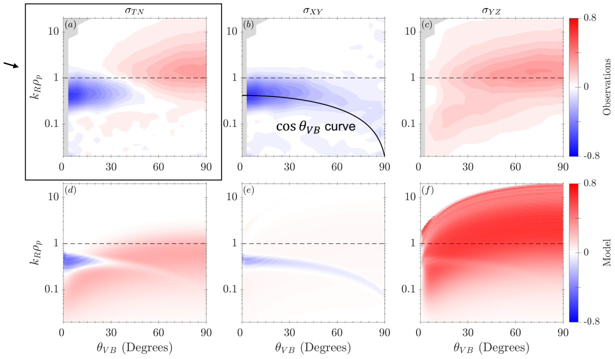
Increase in $C_{||}$ close to $k_R\rho_p \sim 1$ has also been reported before [e.g., Alexandrova et al., 2008; Sahraoui et al., 2010]

Above sub-ion scales, spectral features appear qualitatively very similar to 1 au observations despite stark different in magnetic field topology



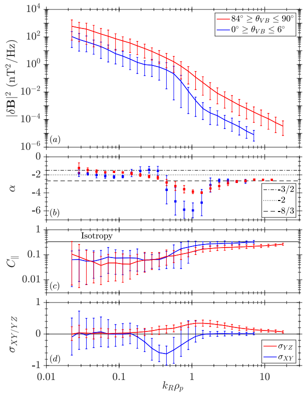
5 MAGNETIC HELICITY

'Classic' magnetic helicity [e.g. He et al. 2011, Klein et al. 2014, Huang et al. 2020], extended to $k_R\rho_p > 10$



We find a very good agreement between model and observations. Consistent with AIC/FMW waves driven by ion-scale instabilities [e.g., Woodham et al. 2019] and KAW turbulence (Howes & Quataert 2010)

6 ONE-DIMENSIONAL CUTS



We also see a slow decrease in the helicity (σ_{yz}) at scales smaller than $k_R\rho_p \sim 1$

This effect is seen at 1 AU ***but*** the decrease this is attributed to instrumental noise or power aliasing [e.g., see Klein et al. 2014, Woodham et al. 2018]

We account for instrumental noise during our analysis, pointing to a physical explanation for this signature

Several possible interpretations:

- Increasing balance of KAW turbulence - consistent with both helicity barrier [Meyrand et al. 2020] and dispersive KAW range [Voitenko & De Keyser 2016]
- Non-helical fluctuations begin to dominate the signal over KAWs, maybe due to increasing intermittency [Chhiber et al. 2021] at these scales

7 SUMMARY AND CONCLUSIONS

- We investigate the spectral anisotropy of Alfvénic turbulence from the inertial range to sub-ion scales using PSP data from E1, including power, magnetic compressibility and magnetic helicity
- By comparing PSP observations with model spectra of linear Alfvén waves, we find a good agreement with a model of critically balanced turbulence plus ion-scale instabilities, consistent with the many previous studies performed at 1 au
- We expand upon past studies, finding that the magnetic helicity exhibits a physical decrease towards smaller scales in the sub-ion range. This decrease in helicity can be interpreted in several ways and further work is ongoing to try to identify which physical process is the most likely.

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