Forecasting space weather storms driven by sheath regions of Coronal Mass Ejections

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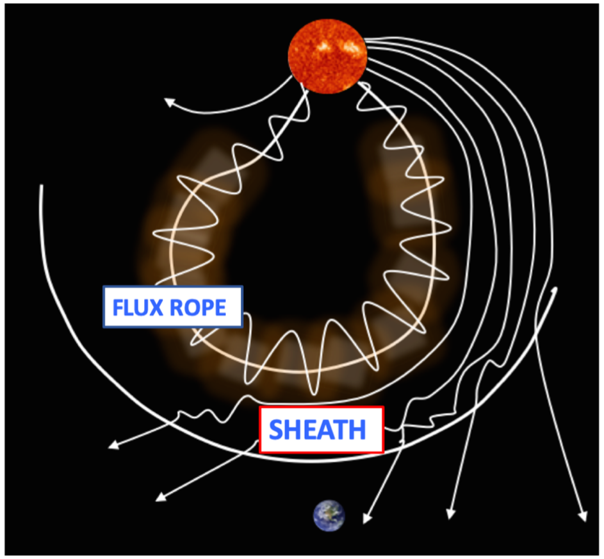
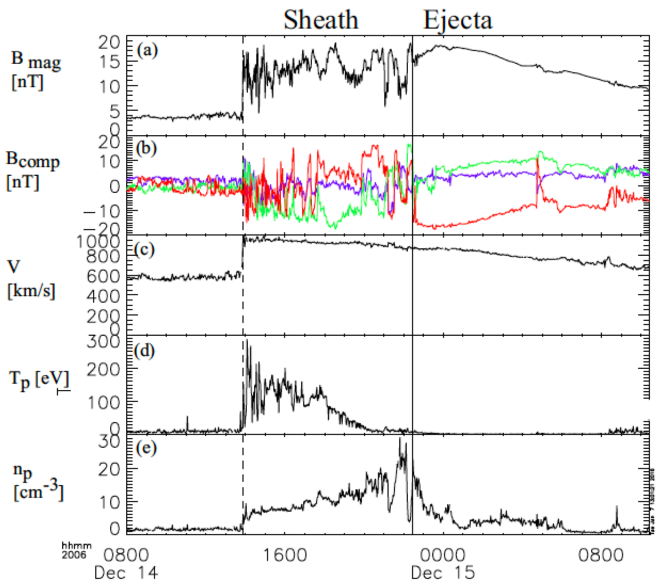
CME sheaths in interplanetary space





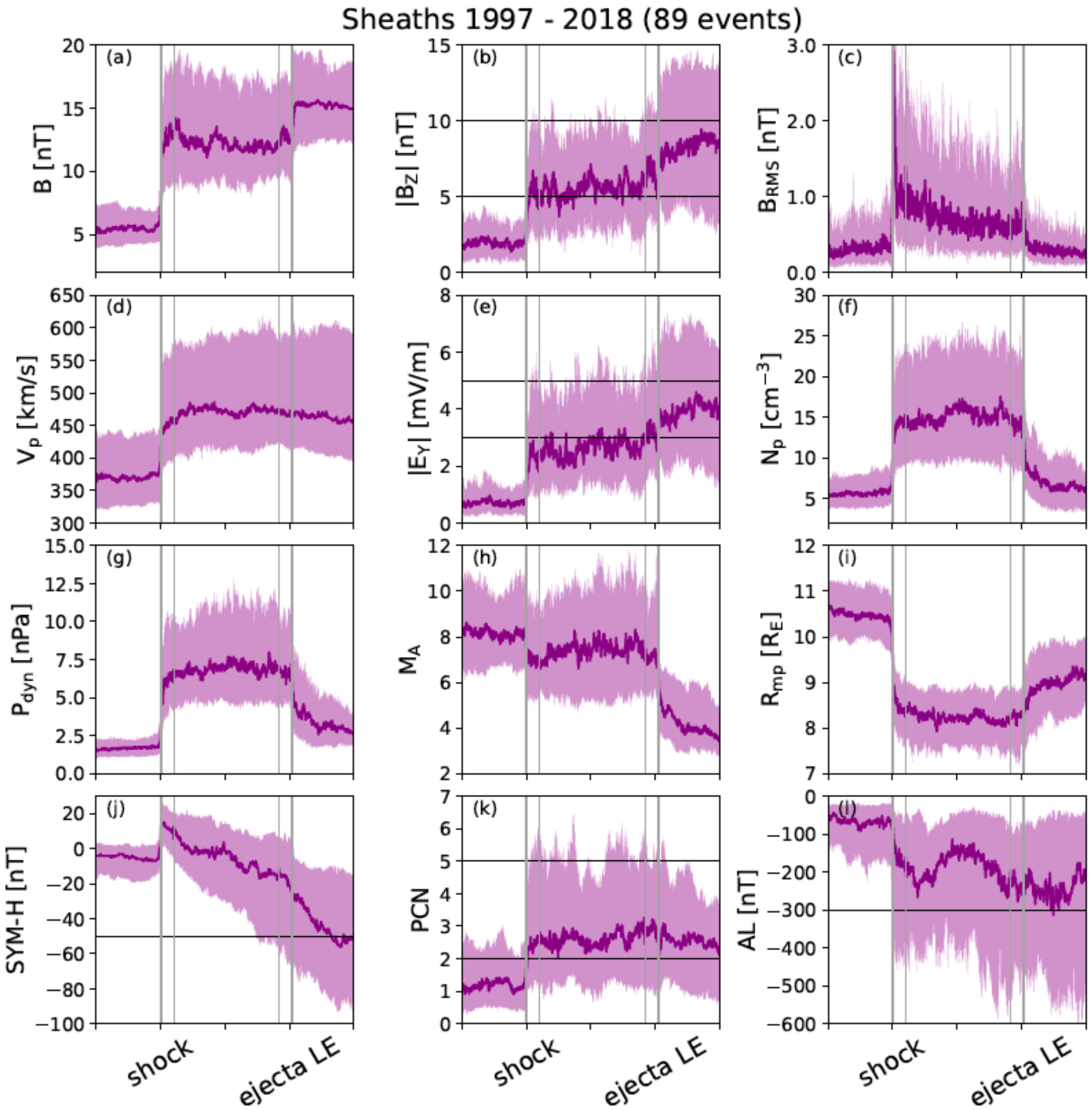
CME-driven sheath regions are turbulent and compressed regions that form gradually ahead of the ejecta (flux rope). They are combination of propagation and expansion sheaths.

Sheaths are characterized by high solar wind dynamic pressure and variable magnetic field. Solar wind plasma and magnetic field parameters can vary considerably from the shock to the ejecta leading edge.

Fluctuations are likely generated in different manner close to the shock (compression, temperature anisotropies) and close to ejecta leading edge (field line draping about the ejecta, pile-up)

Kilpua, Koskinen, & Pulkkinen, Coronal Mass Ejections and Their Sheath Regions in Interplanetary Space
Living Reviews in Solar Physics, doi: 10.1007/s11214-017-0411-3, 2017

Overall sheath properties



superposed epoch analysis (SEA) of 89 sheaths (between solid vertical lines) in the near-Earth solar wind.

All sheaths are re-sampled to the average duration (10.2 hours), excluding the 1-hour regions adjacent to the shock and ejecta leading edge (LE)

1st row: B magnitude, north-south component, root-mean-square of B
2nd row: speed, electric field, density
3rd row: dynamic pressure, Alfven Mach number, subsolar magnetopause position from the Shue et al., 1998 model
4th row: geomagnetic indices SYMH-H, Northern Polar Cap index, AL

Kilpua et al., Space Weather, 2019

CME sheaths and space weather

- Efficient and frequent drivers of intense geomagnetic storms
- Couple strongly with the Earth's magnetosphere
- Can drive a strong storm even when the CME ejecta is missed/non-geoeffective → "surprise storms"
- strong high-latitude response ("auroral storms"), leading to large geomagnetically induced currents (Huttunen et al. 2008)
- compress globally the magnetosphere
- "wave storms" in the inner magnetosphere (Kalliokoski et al, 2019)
- deep and sustained depletions of Van Allen belt electron fluxes (Hietala et al., 2014; Kilpua et al., 2015)

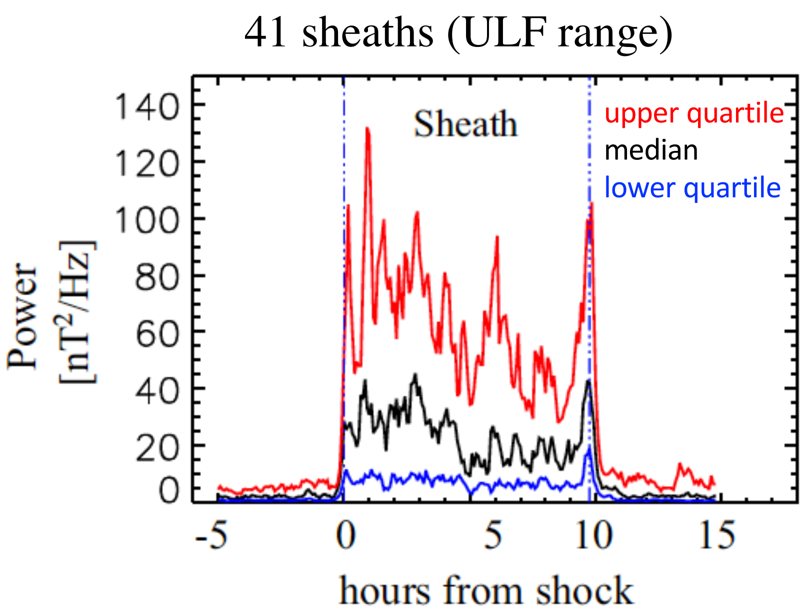
Kilpua et al., Geoeffective Properties of Solar Transients and Stream Interaction Regions
Space Science Reviews, doi: 10.1007/s41116-017-0009-6, 2017

Motivation & Outline

There are relatively little studies of magnetic field fluctuations/turbulence and small-scale structures in CME sheaths and how they connect to the driver (CME/shock) properties. This knowledge is important for understanding how sheaths form, how they interact with the near-Earth space and for space weather forecasting purposes.

We report here the results of our recent studies investigating in detail magnetic field fluctuations in CME-driven sheaths in the near-Earth solar wind (L1) using high-resolution magnetic field data. We have studied fluctuation power, spectral slopes, intermittency and compressibility.

Average sheath fluctuation properties



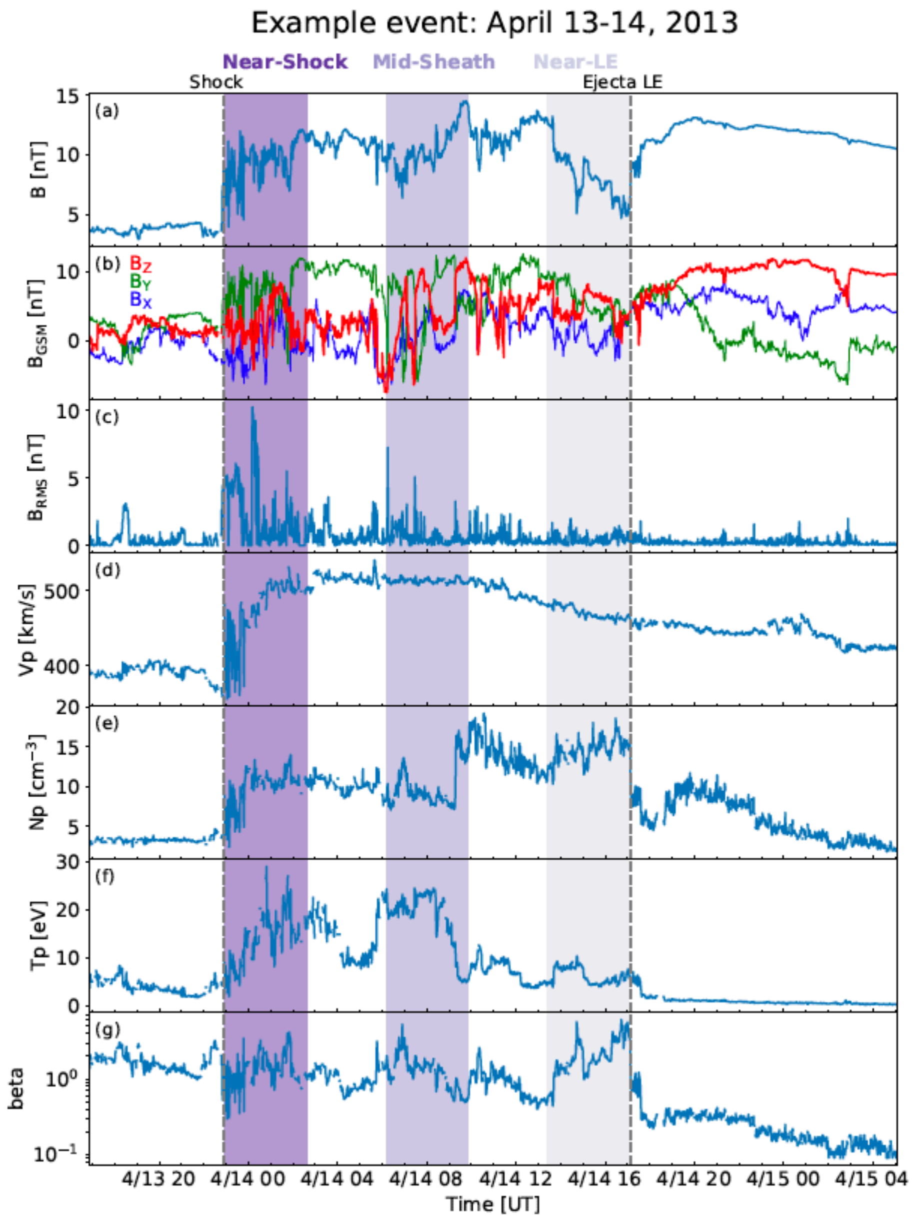
Kilpua et al., Ann. Geo. 2013

	Power [nT^2]	Anisotropy	Compressibility
Solar wind ahead	0.8 ± 1.0	10 ± 6	0.07 ± 0.04
Sheath	9.3 ± 10.8	5 ± 3	0.15 ± 0.08
Flux rope	1.0 ± 1.8	36 ± 23	0.02 ± 0.01

Moissard et al., J. Geophys. Res., 2013

Sheaths have significantly higher B fluctuation power as well as lower anisotropy and higher compressibility than the ambient solar wind. These studies found that the fluctuation power is highest for the fast CMEs with strong magnetic fields that are crossed from the intermediate distances from the nose of the CME/shock.

Sheath sub-regions



Kilpua et al., Space Weather, 2019

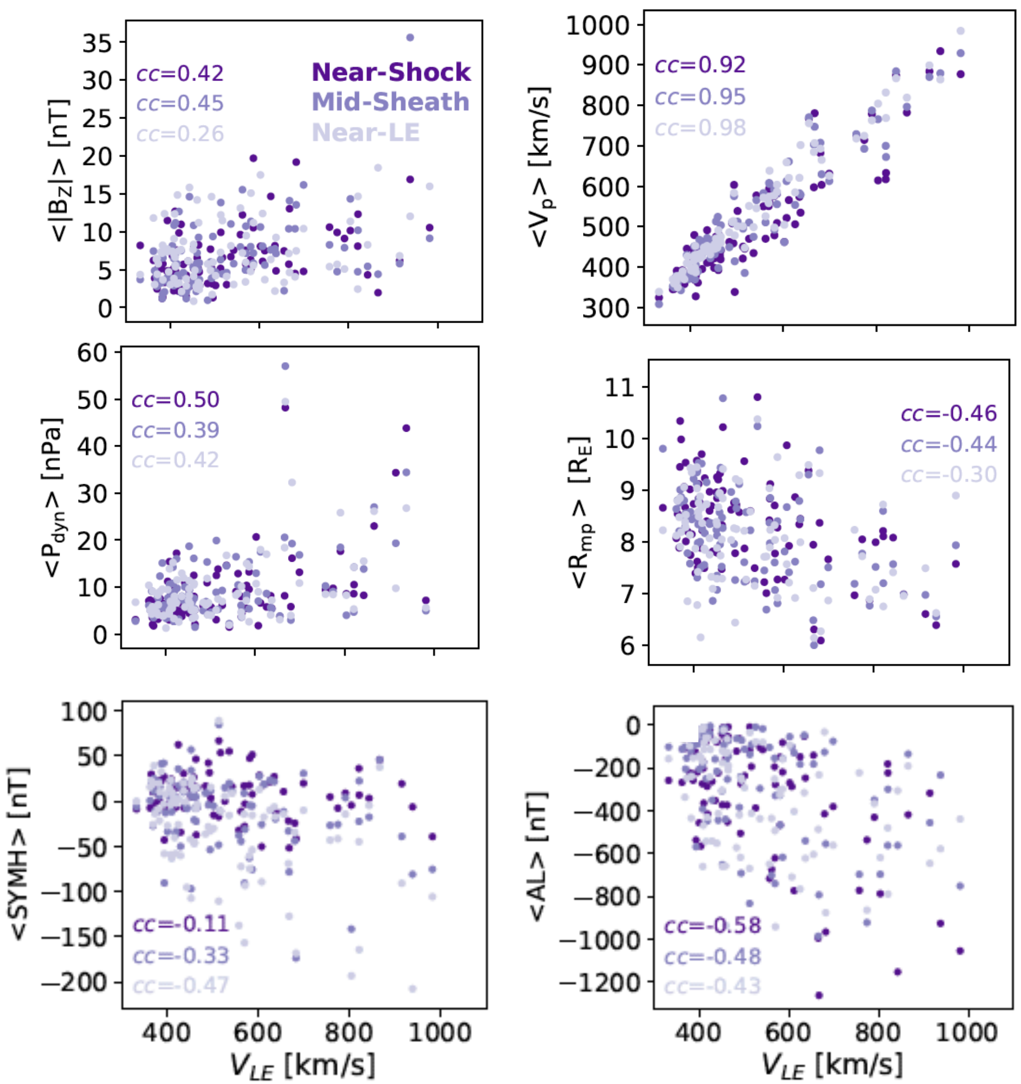
Solar wind properties can vary substantially within a sheath from the shock to the ejecta leading edge (LE) → we divided sheaths in different sub-regions of a fixed (2-hours) duration

Near-Shock: adjacent to the shock

Mid-Sheath: in the middle of the sheath

Near-LE: adjacent to the ejecta LE

Sheath properties & ejecta speed

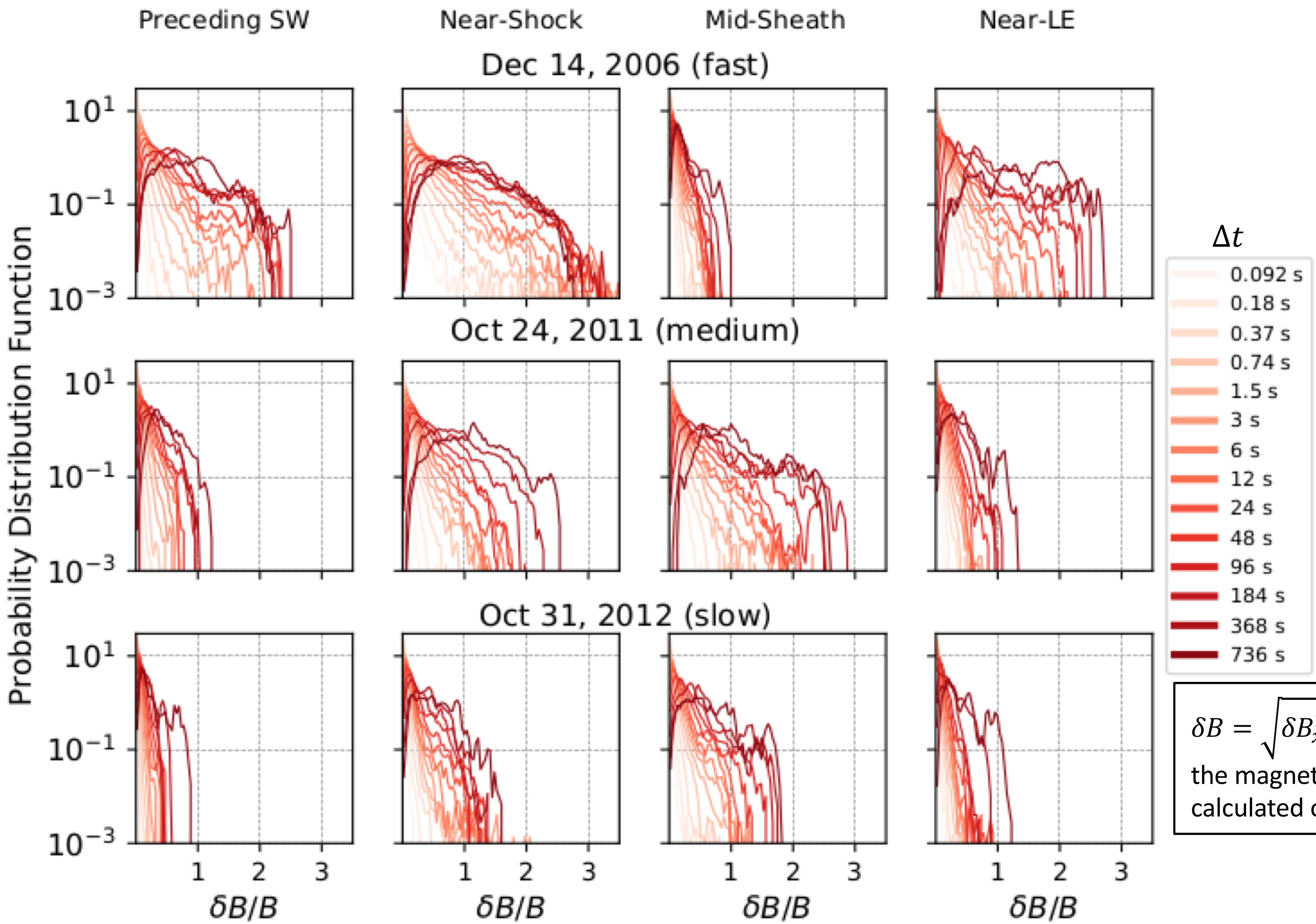


Average speed in the sheath ($<V_p>$) has a strong positive correlation with the ejecta leading edge speed (V_{LE}) for all three sub-regions.

For magnetic field north-south component (B_Z), dynamic pressure (P_{dyn}), sub-solar magnetopause position (R_{mp}), and the AL index correlations are mostly moderate and highest for the Near-Shock region. For the SYM-H index moderate correlation exists only with the Near-LE region

Kilpua et al., Space Weather, 2019

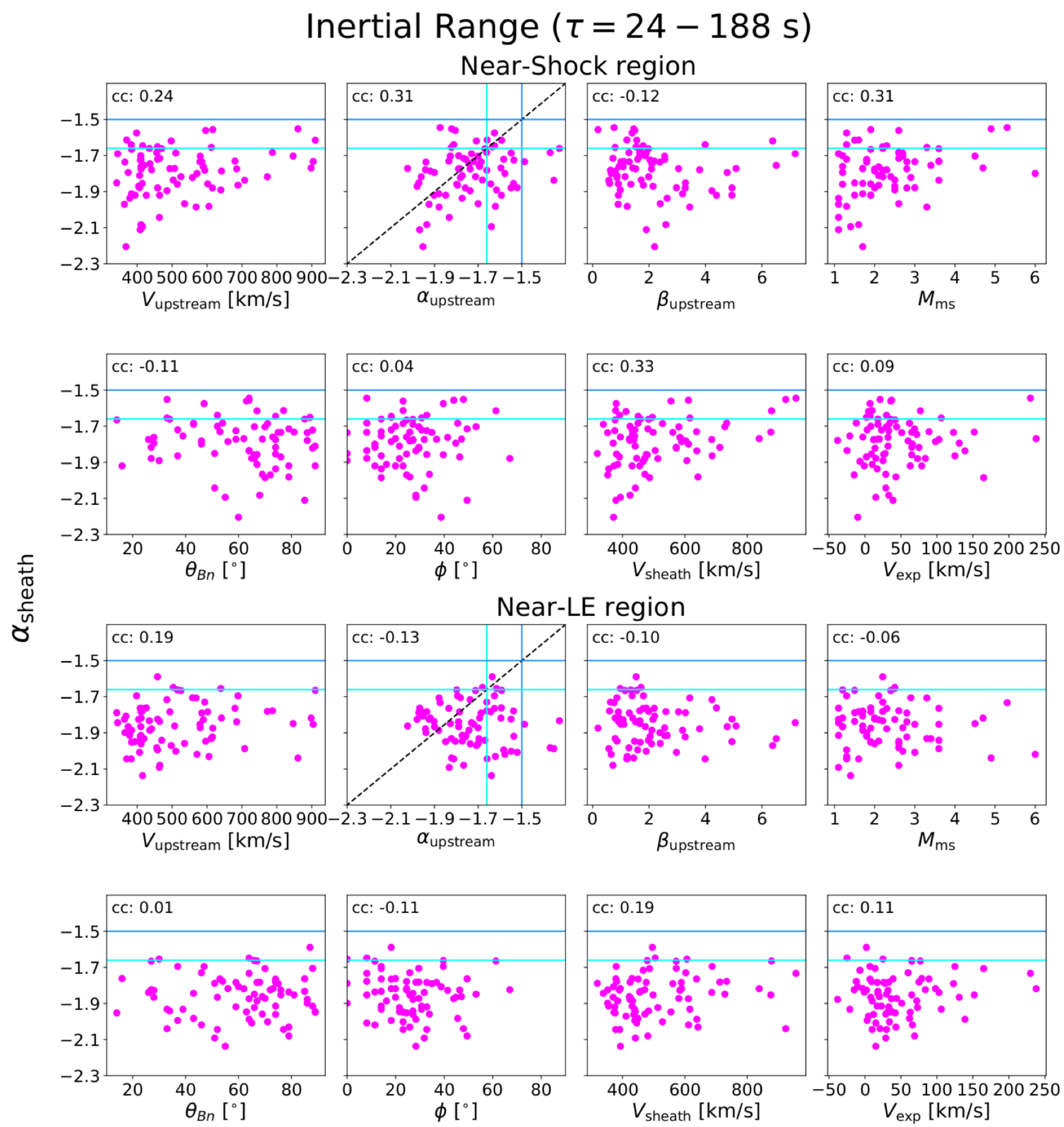
Normalized fluctuations: 3 sheaths



$\delta B = \sqrt{\delta B_x^2 + \delta B_y^2 + \delta B_z^2}$ and B is the magnetic field amplitude calculated over the interval Δt

Kilpua, et al., Ann. Geophys, 2020

Spectral index dependencies



Sheaths have g steeper spectral slopes than Kolmogorov's (-1.67) or Kraichnan's (-1.5), and they generally steepen from solar wind ahead. No clear trends with upstream, CME or shock parameters → new fluctuations generated in the sheath/pre-existing modified

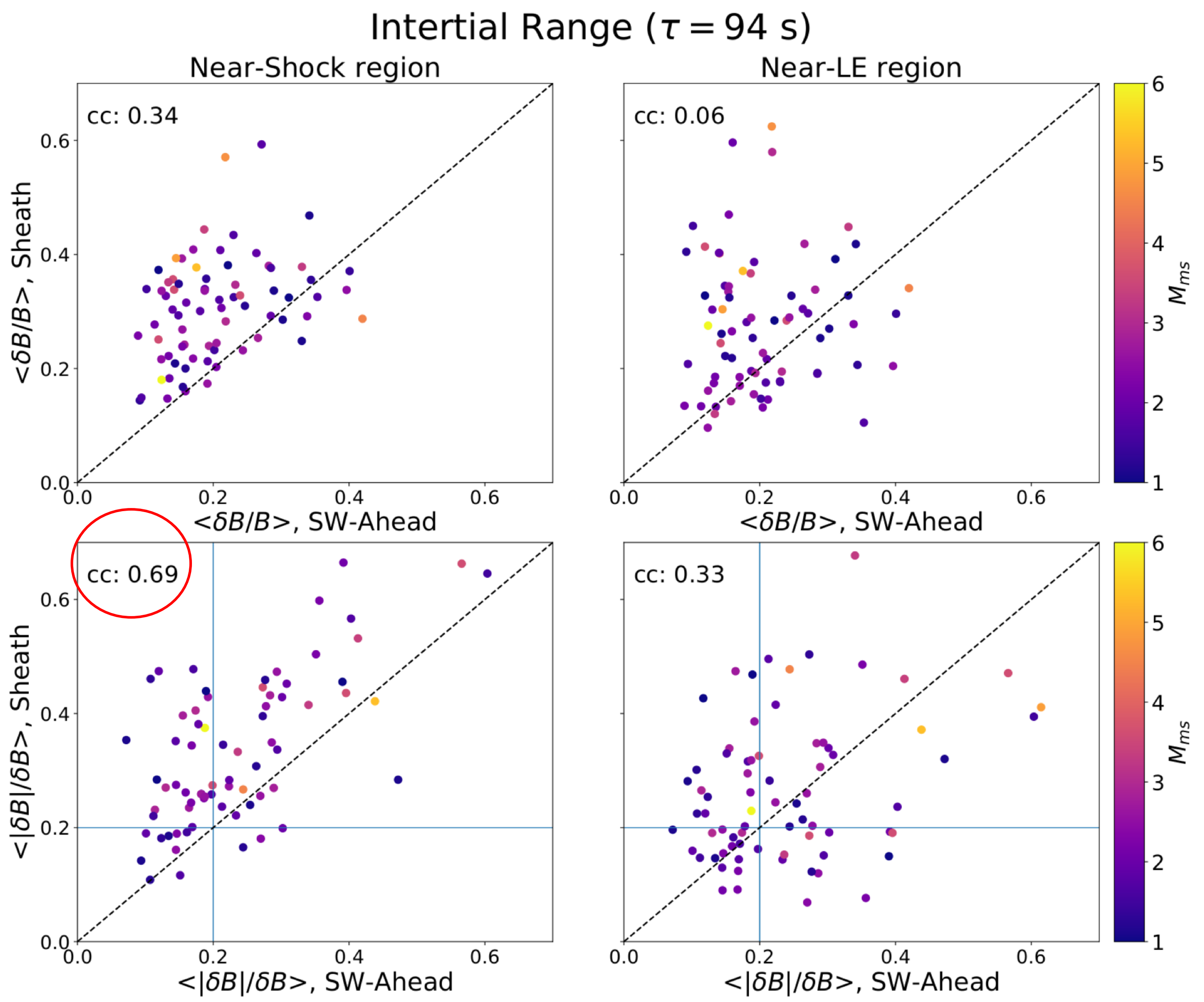
α_{sheath}: specral index in the sheath
$\alpha_{upstream}$: specral index in the upstream wind
$\beta_{upstream}$: plasma beta upstream
M_{ms}: Shock Mach number
θ_{Bn}: shock angle
ϕ: angle between radial direction and shock normal (~distance from the shock nose)
V_{sheath}: sheath speed
V_{exp}: expansion speed of the ejecta

Kilpua et al., submitted to Frontiers

Fluctuation amplitudes & compressibility

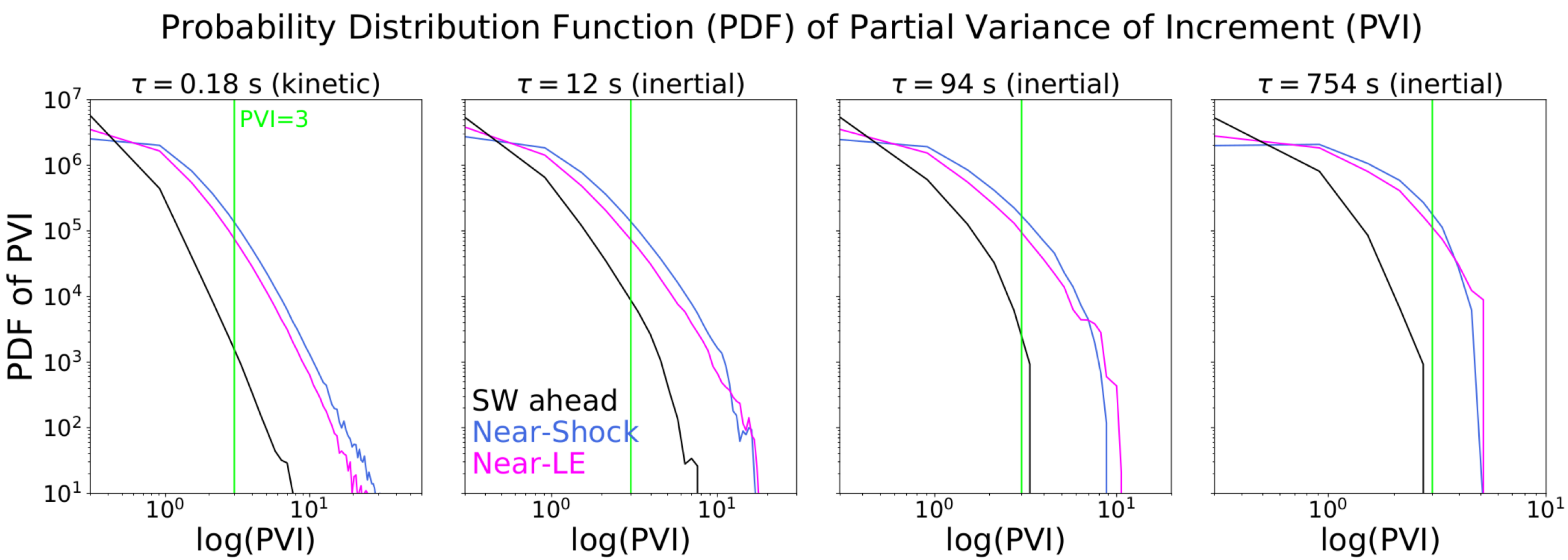
normalized fluctuation amplitudes

compressibility



Kilpua et al., submitted to Frontiers

Intermittent structures in sheaths

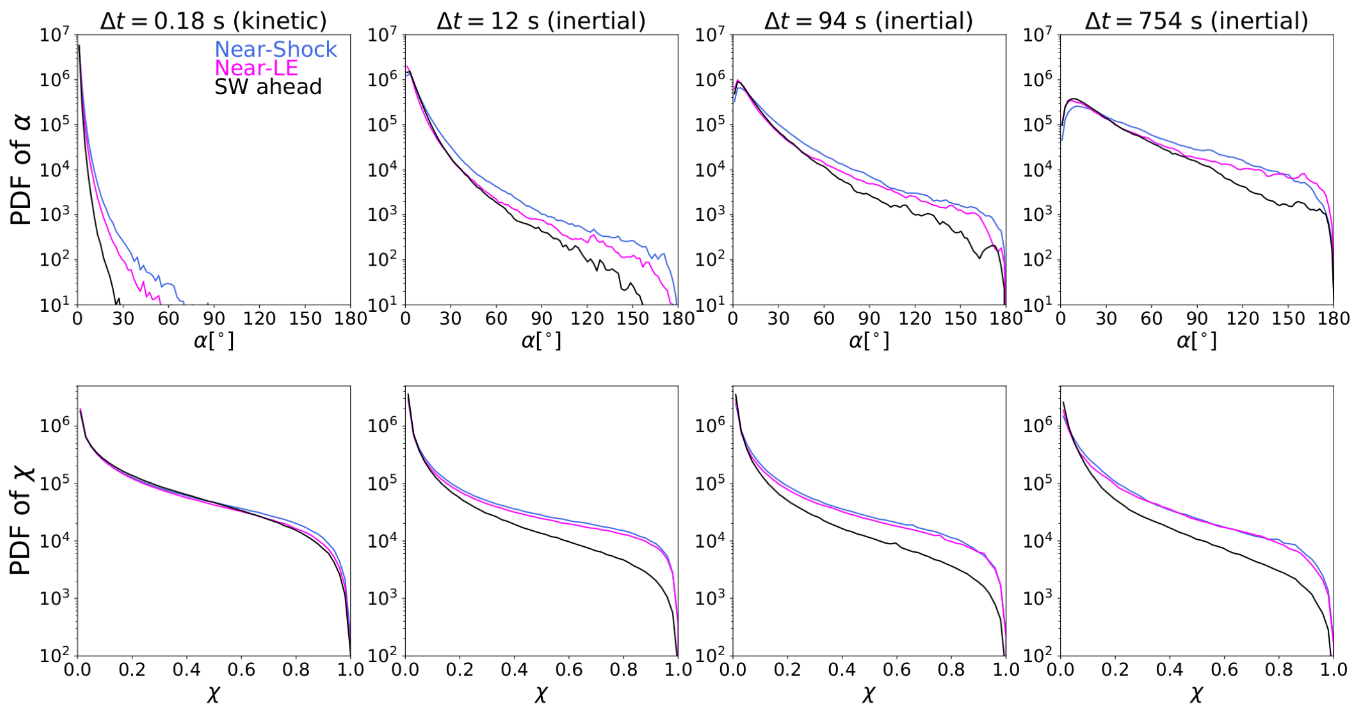


Sheaths have much higher PVI values than the solar wind ahead (the green lines show $\mathrm{PVI} = 3$ that is considered the threshold for intermittent structures). → sheaths have clearly more intermittent structures

Kilpua et al., submitted to Frontiers

Rotation and degree of B change

Probability Distribution Function (PDF) of α and χ



$$\alpha(t,\Delta t) = cos^{-1}\left[\frac{\mathbf{B}(t)\cdot\mathbf{B}(t+\Delta t)}{|\mathbf{B}(t)||\mathbf{B}(t+\Delta t)|}\right]$$

$$\chi(t,\Delta t) = \frac{|\delta B/B - 2\sin(\frac{\alpha}{2})|}{\delta B/B}$$

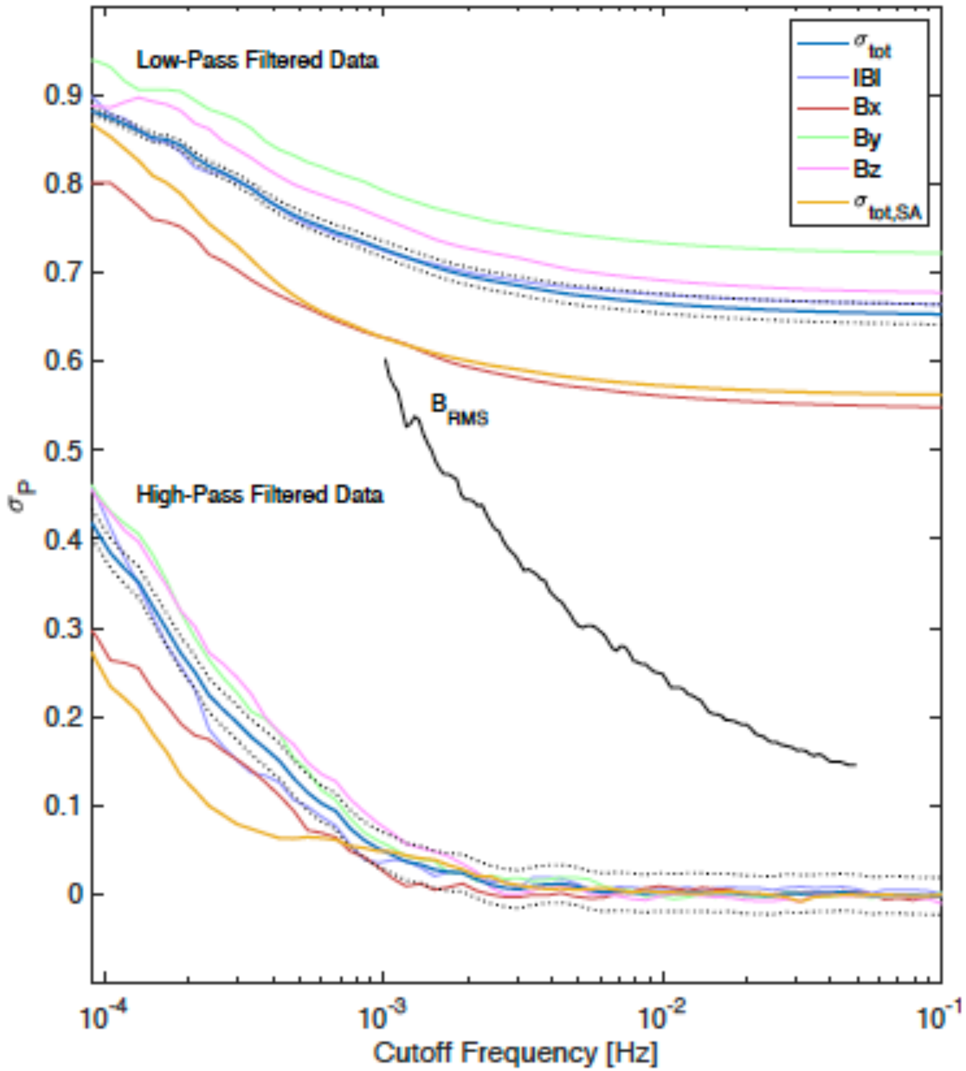
$\chi = 0$: pure rotation

$\chi = 1$: pure compression

Magnetic field rotation angle α and χ-values (measure of the degree of the change in the B magnitude during a rotation) larger in the sheath than in the solar wind ahead. → enhanced presence of intermittent structures and more compressible fluctuations

Kilpua et al., submitted to Frontiers

Coherence of large-scale structures



Two-point measurements analysed for 29 closely spaced spacecraft (ACE and Wind). Pearson correlation coefficients of magnetic field measurements as a function of frequency for both low- and high-pass filtered data

→ global magnetic fields are embedded in sheaths (e.g., Planar Magnetic Structures)

→ high-pass filtered data shows low correlations suggesting that fluctuations are spatially very limited.

Ala-lahti et al., J. Geophys. Res., 2020

Summary

- Sheaths are one of the main key structures in interplanetary CMEs and significant drivers of space weather
- They are compressed and turbulent structures, whose small-scale properties and formation are not yet well understood
- Fluctuation power is much higher in the sheath than in the ambient (one reason for the enhanced geoeffectivity?)
- Sheaths embed fluctuations that have relatively large normalized amplitude, compressibility and intermittency
- Sheaths modify pre-existing fluctuations and generate new ones
- Some correlations with CME/shock properties, but not very clear and consistent trends, coherence scales are also small

→ challenge for space weather forecasting