Radial evolution of magnetic field fluctuations in an ICME sheath

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The work presented here was recently published in ApJ:

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And may also be found on arXiv:

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Please also see our other EGU Online presentations:

Ala-Lahti et al.: Spatial coherence of interplanetary coronal mass ejection-driven sheaths at 1 AU, EGU2020-13474

Fontaine et al.: Turbulent properties of CME-driven sheath regions, EGU2020-18165

Introduction

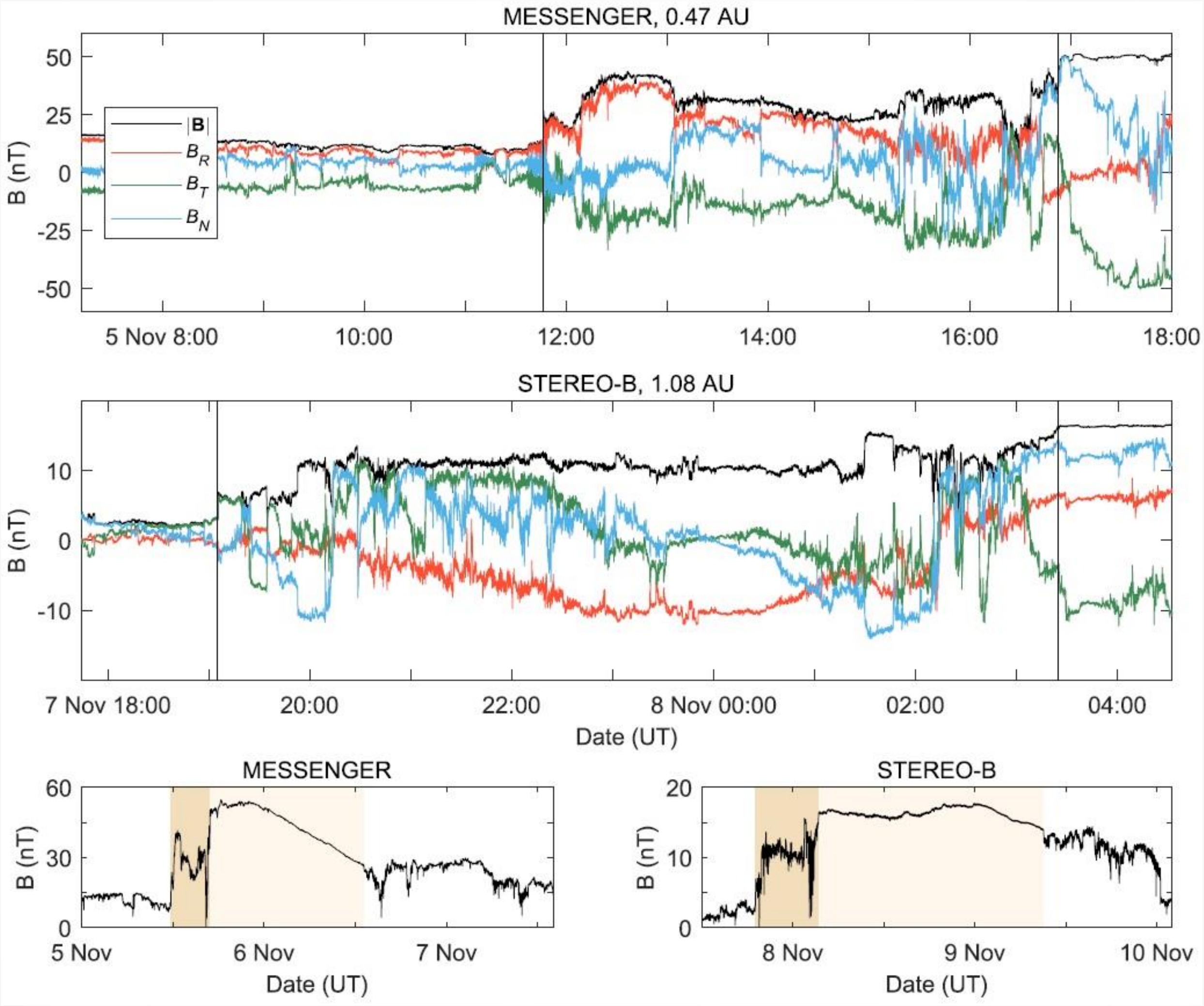
- Fast-moving interplanetary coronal mass ejections (ICMEs) cause pile-ups of slower solar wind ahead called *sheaths*
- ICME sheaths contain hot, dense plasma with a B-field that is high in magnitude and that can be **strongly fluctuating and turbulent** (e.g., Kilpua et al. 2019)
- In addition to ICME ejecta, they can be sources of $-B_z$ and drivers of space weather at Earth
- Sheaths observed at 1 au contain an accumulation of sub-1 au solar wind plasma
- **How do the properties of magnetic field fluctuations in ICME sheaths evolve with radial distance from the Sun?**

The November 2010 line-up event: a case study

- We have studied an ICME sheath observed at MESSENGER (0.47 au) and STEREO-B (1.08 au) while the spacecraft were radially aligned in November 2010. The ICME's flux rope has been studied previously (e.g., Good et al. 2019; Vršnak et al. 2019)
- The sheath bounding the sheath front took ~55 hrs to propagate between the spacecraft, and **changed from a quasi-parallel to quasi-perpendicular geometry** during this time
- The sheath duration grew from ~5 hrs to ~8.33 hrs between the spacecraft, as the sheath both **accumulated new material and expanded**

(*Note that the sheath B-field data at STEREO is absent in some merged B-field/plasma datasets but can be found in the original STEREO MAG data at cdaweb*)

B-field observations



$\delta B / B$ distributions

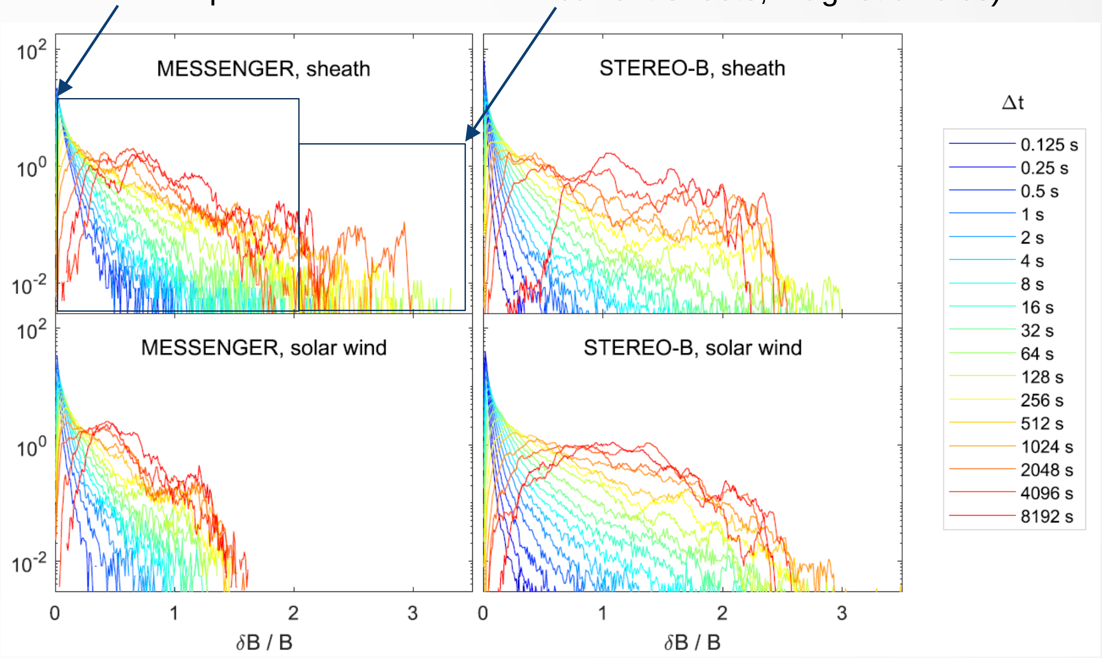
- B-field fluctuates across a range of timescales, Δt
- Define B-field fluctuations as two-point differences in time:

$$\delta B = B(t) - B(t + \Delta t)$$

- Normalise with mean $|B|$ from $t \rightarrow t + \Delta t$ to give $\delta B / B$
- Distributions of $\delta B / B$ for a range of Δt values were found, in the sheath intervals and preceding solar wind at each s/c

Core population, mostly incompressible turbulence

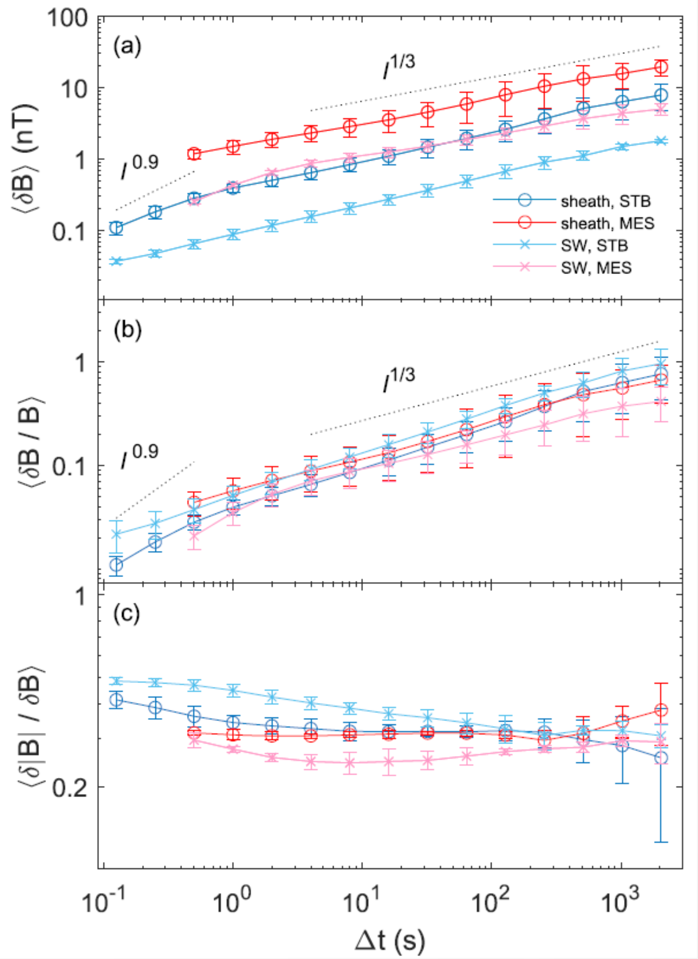
Compressive distribution tails (e.g., current sheets, magnetic holes)



- Distribution shape in each interval varies with Δt as expected for solar wind plasma (e.g., Matteini et al. 2018) → generally less sharply peaked, more gaussian with increasing Δt
- Sheath distributions develop longer compressive tails ($\delta B / B > 2$) at 0.47 au compared to upstream wind → **development of compressive structures, magnetic holes etc.**
- Less difference between sheath and upstream wind at 1.08 au
- Changes in distributions from 0.47 au to 1.08 au largely due to **evolution in turbulence**

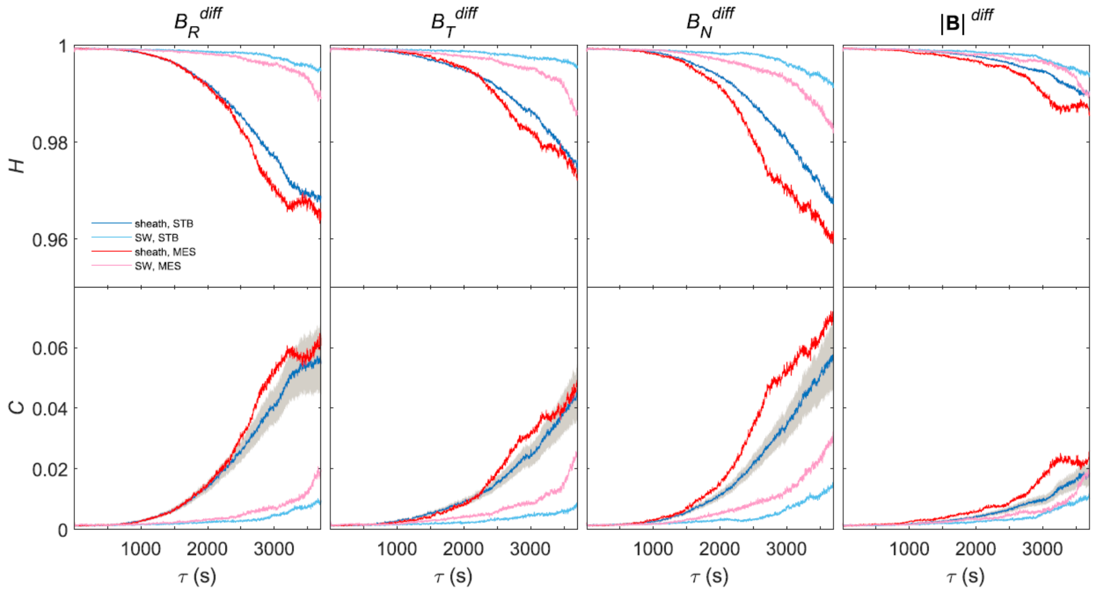
Turbulence and compressibility

- Mean fluctuation amplitudes $\langle \delta B \rangle$ increased by a factor of ~10 from solar wind to sheath at each s/c, and fell by a factor of ~10 from 0.47 to 1.08 au
- Slopes of $\langle \delta B \rangle$ are related to turbulent properties of the fluctuations; slopes at inertial range timescales were calculated in the sheath intervals and upstream wind
- Assuming length scale $l \propto \Delta t$, a $\langle \delta B \rangle \propto l^{1/3}$ relationship is equivalent to the $k^{-5/3}$ scaling of power spectral density in k-space
- At 0.47 au, the l-space slope steepened from 0.29 (i.e. less steep than 1/3 Kolmogorov) in the upstream wind to 0.35 in the sheath → **non-Kolmogorov turbulence or under-developed cascade in upstream wind evolved with transition to sheath**
- **Further steepening to 1.08 au**, with indices of 0.40 and 0.42 (steeper than 1/3 Kolmogorov) in the upstream wind and sheath, respectively → **further evolution of turbulence, possible growth in intermittency**
- **Fluctuation compressibility $\langle \delta |B| / \delta B \rangle$ grew with radial distance**



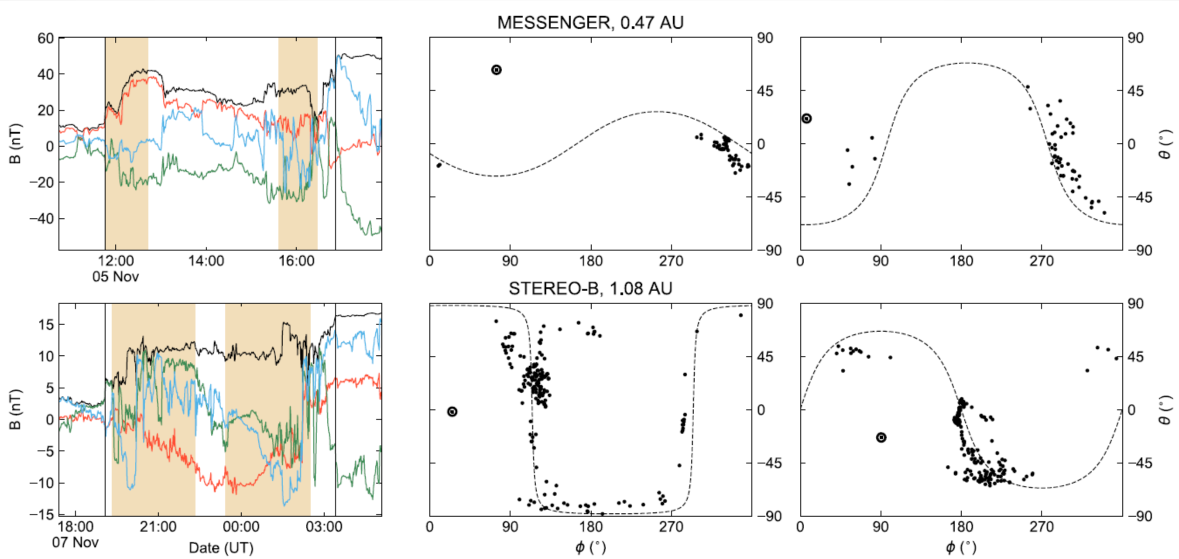
Entropy and complexity

- Permutation entropy (H) and Jensen-Shannon complexity (C) can be used to determine whether a time series is generated by stochastic or chaotic processes, and can indicate the relative abundance of coherent structures vs. stochastic fluctuations
- At intermediate and large fluctuation timescales, **H grew and C fell in the sheath and upstream wind with radial distance**, consistent with the solar wind study of Weygand & Kivelson (2019)
- H was lower and C higher in the sheath compared to the upstream wind at each s/c → **a more complex mix of coherent structure and stochastic fluctuations in the sheath**



The reader is directed to the work of Osmane et al. (2019) and references therein for further details

Planar magnetic structuring



- Sheaths may contain planar magnetic structures (PMSs), within which the B direction over time varies within a plane but not normal to it
- Two PMS intervals were identified in the sheath at both s/c (beige intervals in figure)
- First interval may have been due to field alignment behind the shock, while second may have been due to field draping around the flux rope
- **Growth in PMS with radial distance likely due to accumulation of plasma in sheath with distance, and expansion** (e.g., Lugaz et al. 2020)

Discussion and Summary

- At 0.47 au, the sheath turbulent properties differed significantly to those of the upstream wind → possibly dependent on the q-par shock geometry
- At 1.08 au, the sheath turbulence was more similar to that seen in the upstream wind → the q-perp shock may have caused less modification of the upstream wind turbulence
- Processes occurring near the flux rope leading edge also likely modified the turbulence properties in the sheath
- The steepening of the spectral slope in the sheath with radial distance mirrored that of the upstream wind
- The magnetic field time series was more complex in the sheath compared to the upstream solar wind, suggesting a more complex mix of structures and random fluctuations; complexity in the sheath and upstream wind fell with radial distance
- Planar magnetic structuring became more prevalent with radial distance
- Further case studies are required to build a more statistical picture

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