Radial evolution of magnetic field fluctuations in an ICME sheath

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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

![Graphs showing B-field observations for MESSENGER and STEREO-B at different distances.](image)
**δB/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 \( t \to t + \Delta t \) to give \( \delta B/B \)
- Distributions of \( \delta B/B \) for a range of \( \Delta t \) values were found, in the sheath intervals and preceding solar wind at each s/c
  - Distribution shape in each interval varies with \( \Delta t \) as expected for solar wind plasma (e.g., Matteini et al. 2018) → generally less sharply peaked, more gaussian with increasing \( \Delta t \)
  - 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 $\sim 10$ from solar wind to sheath at each s/c, and fell by a factor of $\sim 10$ 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 $\langle |B|/\delta B \rangle$ 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
References


