Scales of Magnetic Complexity and Coherence within ICMEs: Estimates from Spacecraft Swarms in Global Heliospheric Simulations

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(1) Motivation, methods and objectives

Motivation: the interaction with large-scale solar wind structures, e.g. high-speed streams (HSSs), stream interaction regions (SIRs), and the heliospheric current/plasma sheet (HCS/HPS) can alter the global and local properties of interplanetary coronal mass ejections (ICMEs). These include:

- magnetic complexity, i.e. the degree of similarity/deviation from an ideal FR configuration (Winslow+ 2016, 2021)
- coherence, i.e. the ability to respond to external perturbations in a coherent manner (Owens+ 2017, 2020)

The scarcity of multiple spacecraft crossings through individual ICMEs prevents a comprehensive understanding of how complexity and coherence evolve during propagation.

Methods: to overcome current observational limitations, we investigate the evolution of ICME structures using global heliospheric simulations (based on Scolini+ 2021):

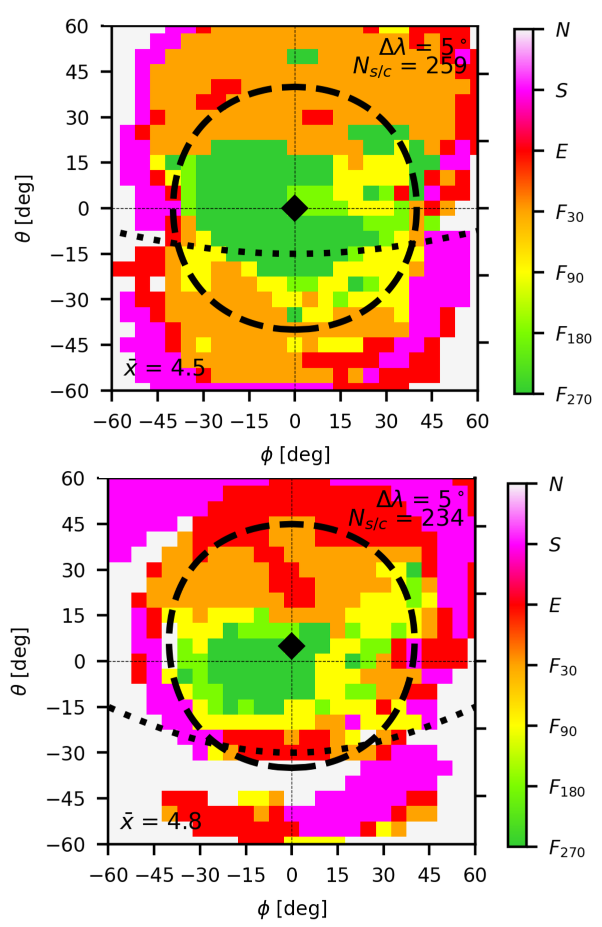
- 3D MHD simulations with EUHFORIA (Pomoell & Poedts 2018) + spheromak CME model (Verbeke+ 2019)
  - Fast CME with initial half width of 45° and low-inclination flux-rope magnetic structure, in the solar equatorial plane
- Swarm of 18944 simulated spacecraft between 0.1 and 1.6 au uniformly separated by $\Delta\lambda = 5°$ (lon/lat) and $\Delta r = 0.1$ au
- Spatial scale of magnetic complexity and coherence based on frequency and *Moran's I* spatial autocorrelation (Moran 1950) of magnetic ejecta (ME) types (Scolini+ 2021) detected in situ, and on correlation of magnetic field components at different spacecraft/observer (Lugaz+ 2018)

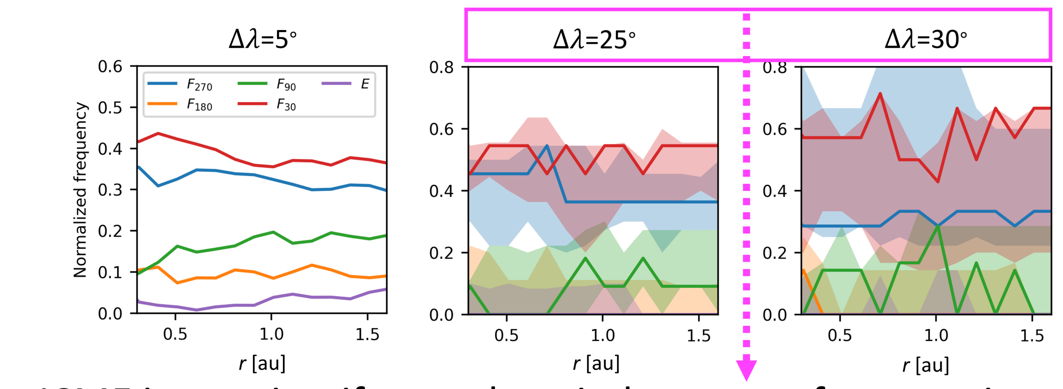
Questions addressed: (1) What is the spatial distribution of magnetic complexity within ICMEs? (2) Across what spatial scales could ICMEs behave as coherent objects? (3) How does this depend on the heliocentric distance and the interaction history of a given ICME?

(2) Modeling results

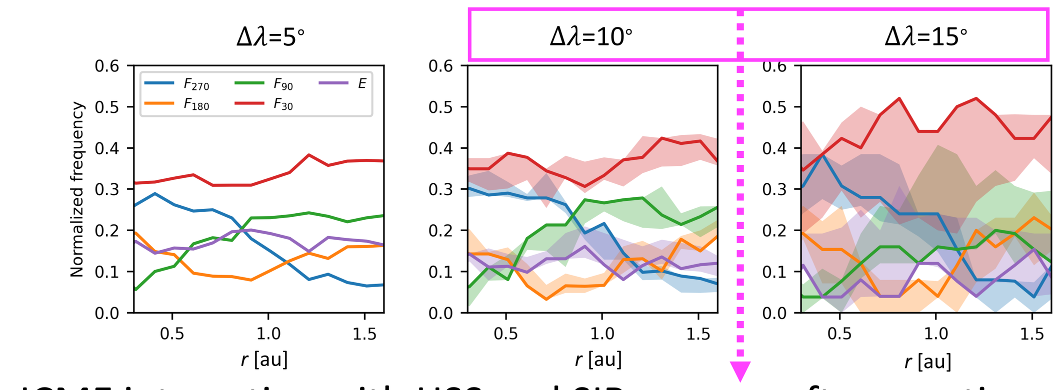
Scale of magnetic complexity: frequency of ME types

ME type distribution @ 1 au





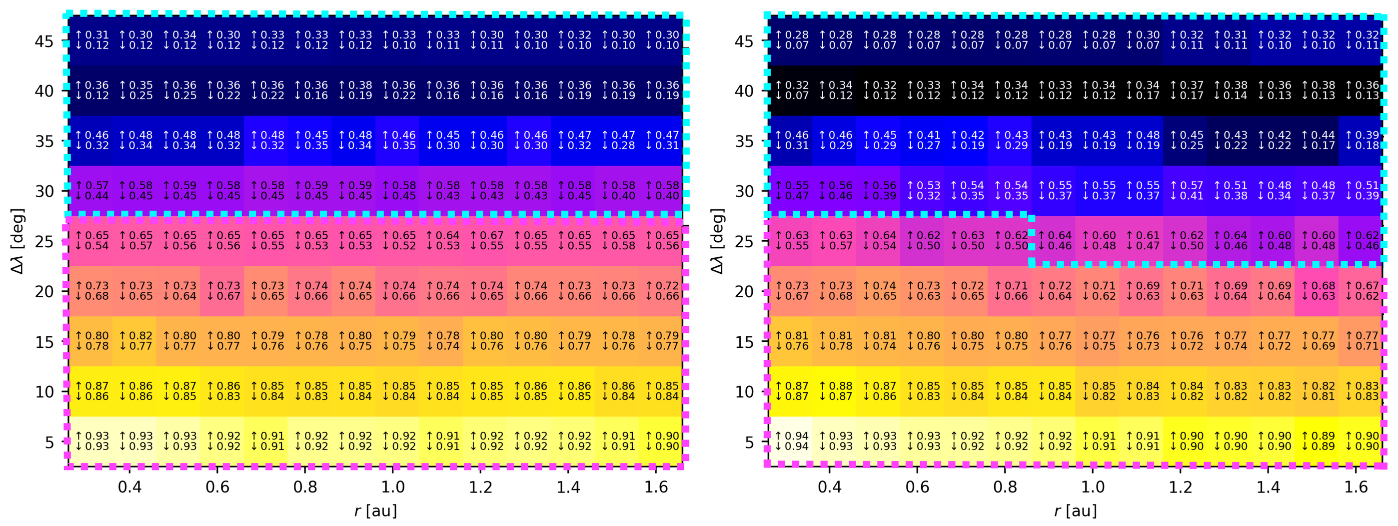
ICME in quasi-uniform solar wind: spacecraft separations up to 25° able to reproduce frequency of ME types



ICME interacting with HSS and SIR: spacecraft separations ≤10° needed to reproduce the frequency of ME types

Scale of magnetic complexity: spatial autocorrelation of ME types

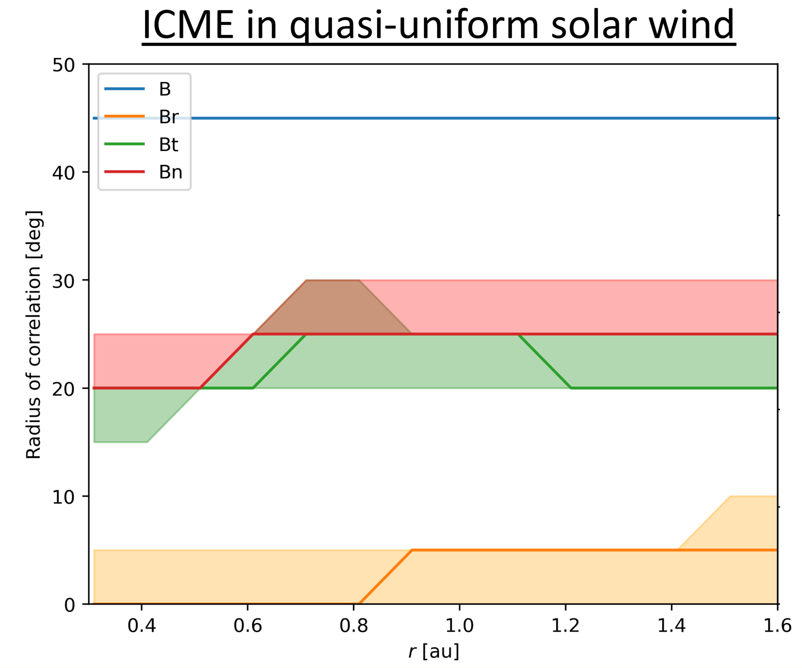
ICME in quasi-uniform solar wind | ICME interacting with HSS and SIR



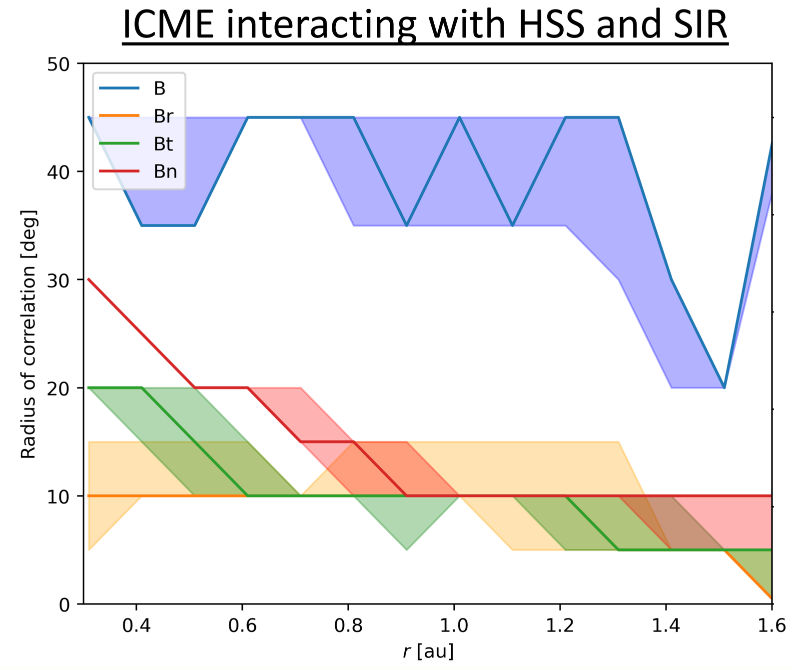
Moran's I: $I < 0.5$: high complexity distribution; $I \geq 0.5$: low complexity distribution.

Scale of magnetic coherence with respect to a central observer

ICME in quasi-uniform solar wind



ICME interacting with HSS and SIR



(3) Discussion and conclusions

Key results:

- Scales of magnetic complexity and coherence within an ICME are reduced by interactions with other structures
- Global complexity can be characterized by as little as 7-12 spacecraft separated by 25° for an ICME not interacting with other structures; minimum number of spacecraft rises to 50-65 (separated by 10°) if interactions occur
- Scales of coherence extend by 45° (B), 20°-30° (B_ϕ), 15°-30° (B_θ), and 0°-10° (B_r) around a central observer if no interactions occur, but are reduced by a factor of 3 to 6 by interactions with other structures
- Complexity is higher (lower) in the west (east) flank, while the scale of coherence is smaller (larger) in the west (east) flank due to Parker spiral effects

Implications for ecliptic missions:

- Simulated ICMEs have a lower complexity and higher coherence along magnetic axis compared to $\perp$ directions
- A minimum of ~6 spacecraft separated by 15° are necessary to characterize the evolution of ICME magnetic complexity in the ecliptic plane, which increases to ~9 spacecraft (at 10° separation) in case of interactions
- Near-ecliptic missions alone are not able to characterize the ICME global, off-ecliptic complexity

Future work: targeted investigations using more realistic numerical simulations + data from recent missions

Selected references:

Moran (1950), *Biometrika,* 37, 1/2, 10.2307/2332142

Pomoell & Poedts (2018), *SWSC,* 8, A35, 10.1051/swsc/2018020

Scolini+ (2021), *ApJL,* 916, L15, 10.3847/2041-8213/ac0d58

Verbeke+ (2019), *A&A,* 627, A111, 10.1051/0004-6361/201834702