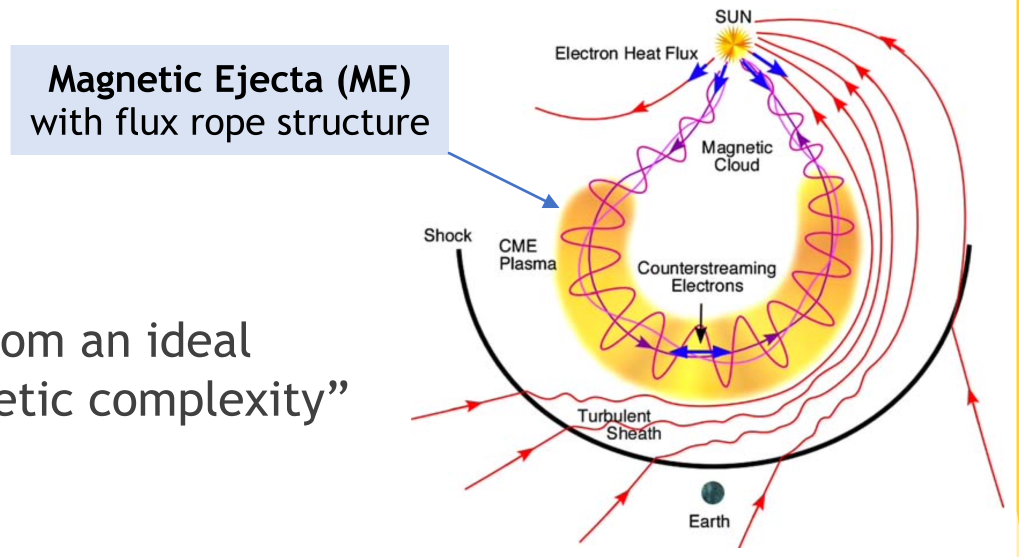
Evolution of Interplanetary Coronal Mass Ejection Complexity: Insights from Radially-Aligned Spacecraft

Camilla Scolini[1,2] (camilla.scolini@unh.edu)
Réka M. Winslow[1], Noé Lugaz[1], Tarik M. Salman[1], Emma E. Davies[1], Antoinette B. Galvin[1]

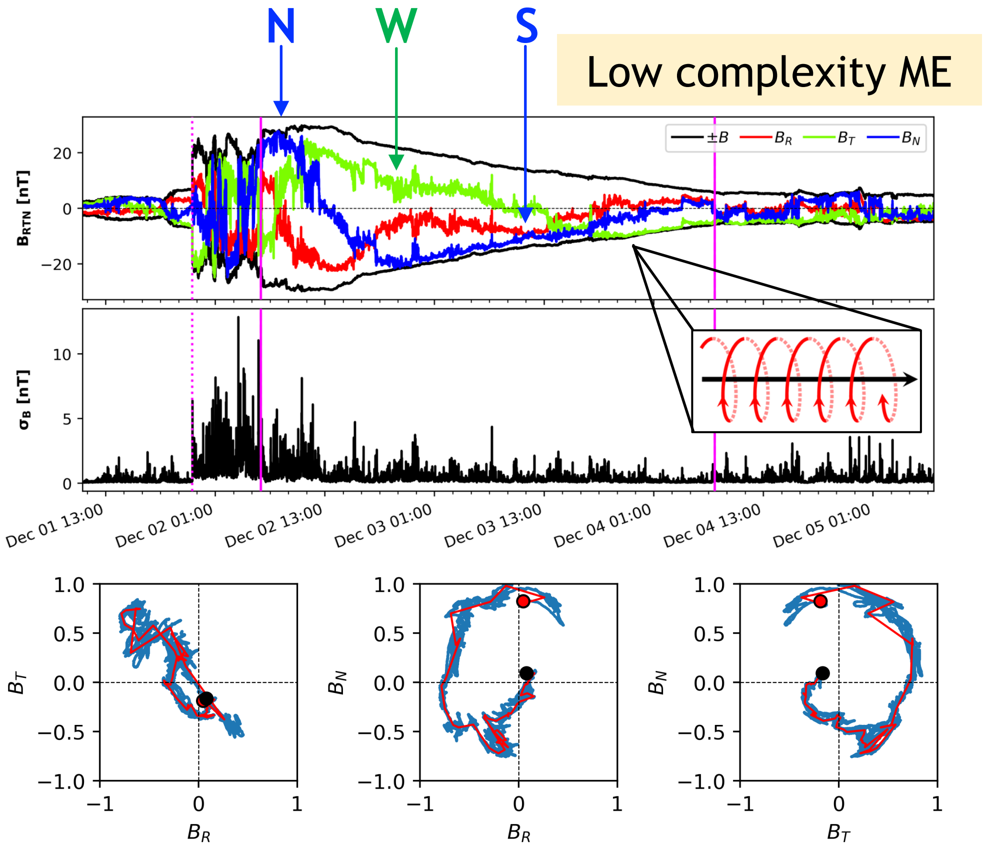
[1]University of New Hampshire, NH, USA
[2]University Corporation for Atmospheric Research, CO, USA

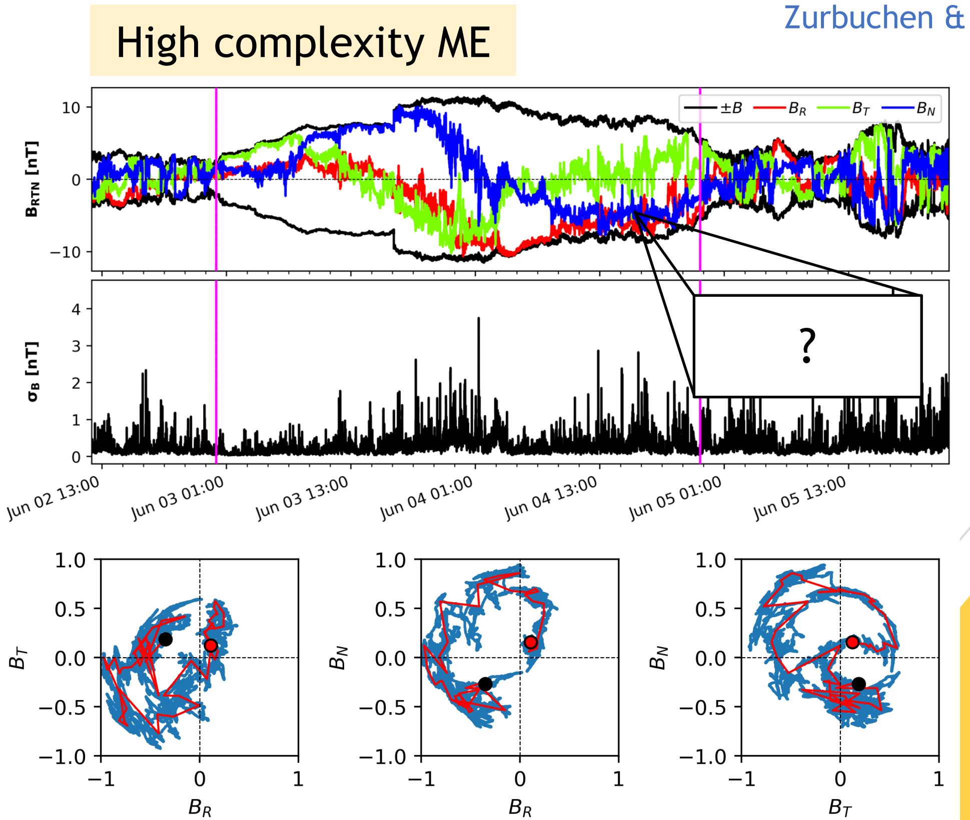
ICME magnetic complexity



Zurbuchen & Richardson (2006)

- MEs have different degrees of similarity/deviation from an ideal flux-rope (FR) structure → different levels of "magnetic complexity"





Motivation

- **Why are some ICMEs more complex than others?**
  - How frequent are magnetic complexity changes? What are the causes of such changes? How do complexity changes affect other in situ ICME properties?

- Interaction with surrounding solar wind can drastically alter ICME properties during propagation (e.g. Manchester+2017) and affect predictions of their space weather impact
  - high-speed streams (HSSs), stream interaction regions (SIRs), heliospheric current/plasma sheet (HCS/HPS) might have key influence on ICME magnetic complexity (Winslow+2016, 2021a, 2021b; Scolini+2021b)

Multi-spacecraft observations of ICMEs in radial alignment

- Statistical investigation
- 31 ICMEs observed between 2008 and 2014 by radially aligned spacecraft (based on catalog by Salman+2020)
  - MESSENGER: 0.31-0.46 AU (orbiting Mercury)
  - Venus Express: 0.7 AU (orbiting Venus)
  - ACE/Wind, STEREO-A/B: 1 AU

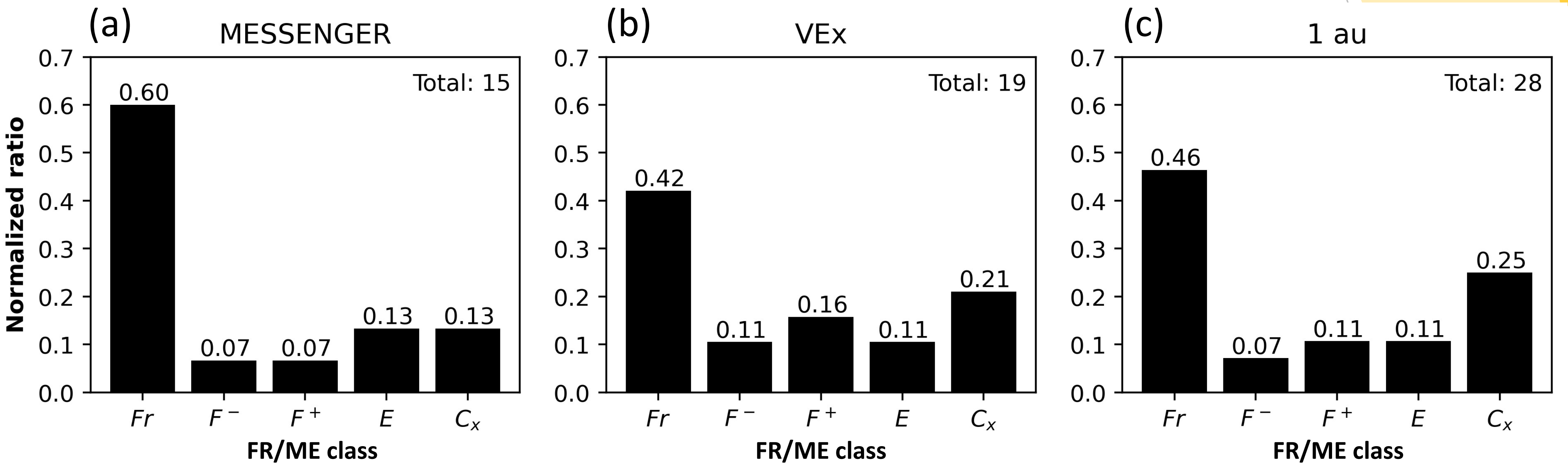
Characterizing magnetic complexity

- Classify all MEs using the classification by Nieves-Chinchilla+2019

Class	Maximum rotation	Complexity level	
F+	$> 180°$	low	→ Spheromak or double FRs
Fr	$90° - 180°$	low	Single FRs, spacecraft crossings close to (Fr) or far away from (F-) FR axis
F-	$< 90°$	low	Single FRs, spacecraft crossings close to (Fr) or far away from (F-) FR axis
E	Unclear rotations	high	Not reproduceable by FR model
Cx	Multiple rotations	high	Not reproduceable by FR model

- A change in magnetic complexity between the inner and outer spacecraft occurs when…
  1. ME class changes → fundamental alterations of the ME magnetic structure
  2. ME undergoes significant re-orientation as determined by magnetic hodograms (for F+, E, Cx events) and in situ fitting models (for Fr/F- events) (linear force-free fitting model by Burlaga+1988 and Lepping+1990)

Results: complexity vs heliocentric distance



ICMEs tend to increase their complexity with heliocentric distance:

- Decrease in Fr/F- types (**67%** @0.3-0.4 AU → **53%** @0.7 AU → **53%** @1 AU)
- Increase in Cx types (**13%** @0.3-0.4 AU → **21%** @0.7 AU → **25%** @1 AU)

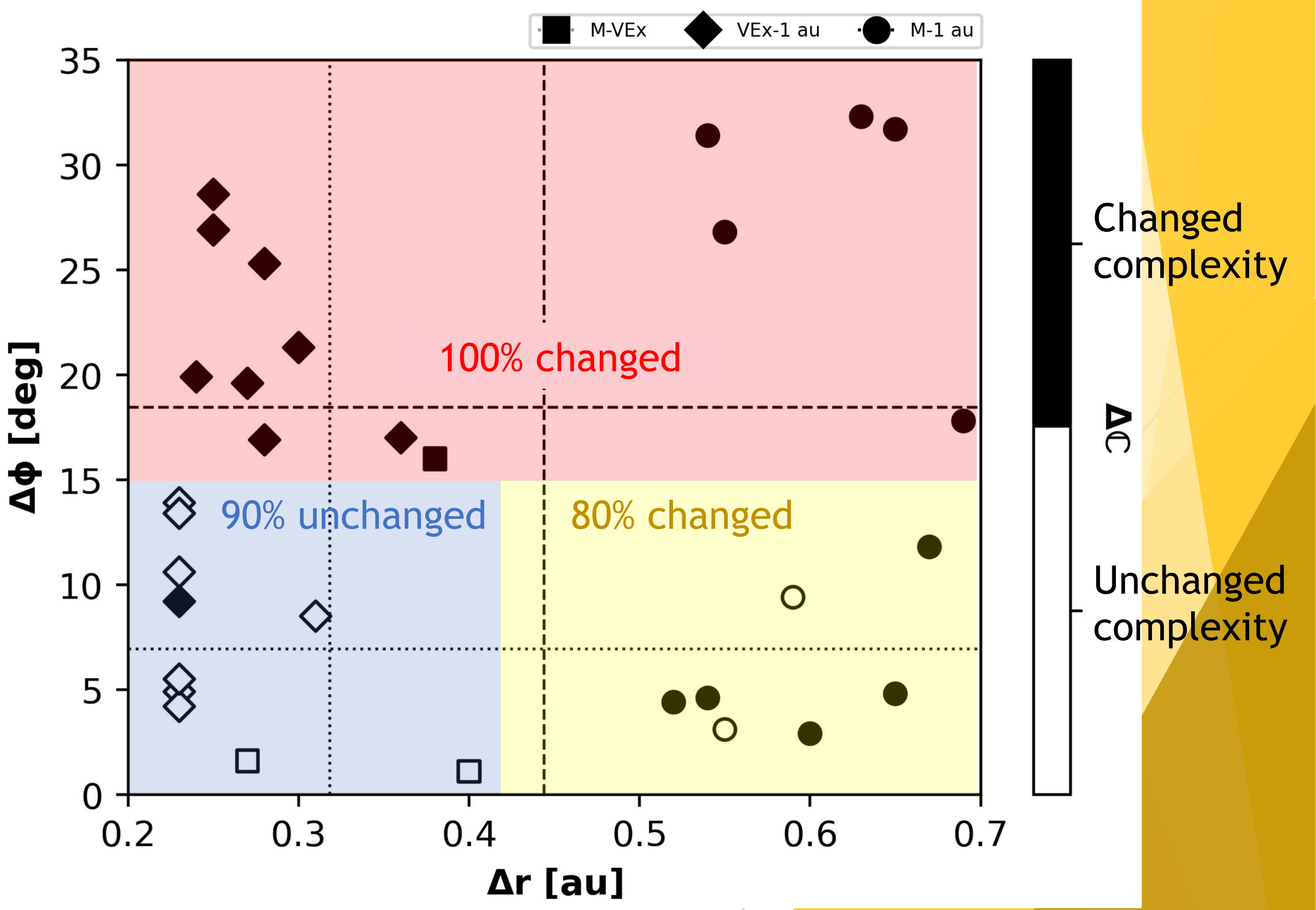
Results: frequency & spacecraft separation

Most ICMEs change complexity during propagation:

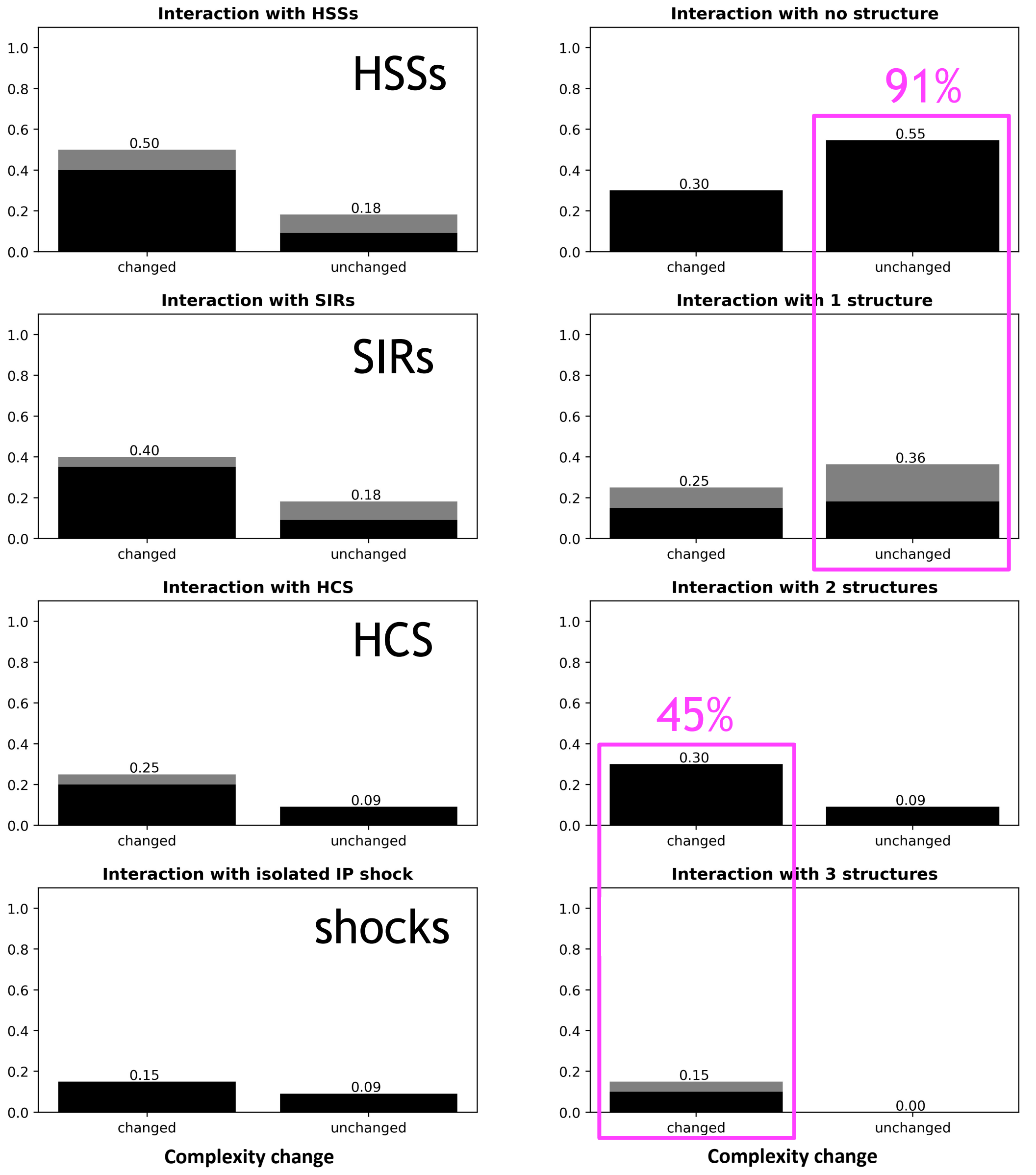
- 42% of ICMEs changed ME class between inner and outer spacecraft
- 23% of ICMEs underwent significant reorientations
- **Total: 65%** changed complexity

Complexity changes and spacecraft separation:

- $\geq 15°$: all ICMEs change complexity → coherence? structure?
- $< 15°$: complexity changes increase with radial separation → propagation effects



Results: drivers of complexity changes



<u>Complexity changes are associated with the presence of other interplanetary structures:</u>

- ~90% of unchanged ICMEs either did not interact with any structure, or only interacted with 1 structure
- ~45% of ICMEs that changed magnetic complexity interacted with ≥ 2 structures
- Complexity drivers:
  1. HSSs (50%)
  2. SIRs (40%)
  3. HCS (25%)
  4. Other interplanetary shocks (15%)

Conclusions and open questions

Results are published as
Scolini et al. (2022), *ApJ*, *927*, *1*
DOI: [10.3847/1538-4357/ac3e60](10.3847/1538-4357/ac3e60)

How frequent are magnetic complexity changes?

- Affect the majority of ICMEs
- ICMEs tend to become more complex with heliocentric distance

What are the causes of such changes?

- Main drivers: interactions with other large-scale solar wind structures

How do complexity changes affect the in situ ICME properties?

- Randomization of ICME properties (e.g. speed-magnetic field relationships)
- Scale of magnetic coherence as large as ~15° within non-interacting ICMEs

Open questions: how do magnetic complexity changes propagate through ICME structures? What are the physical mechanisms mediating such changes?

Contact: camilla.scolini@unh.edu