On the importance of investigating CME complexity evolution during interplanetary propagation

A White Paper submitted to the Heliophysics 2024–2033 Decadal Survey

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Synopsis

This white paper brings to light the need for comprehensive studies on the evolution of interplanetary coronal mass ejection (ICME) complexity during propagation. To date, few studies of ICME complexity exist. In this white paper, we define ICME complexity and accompanying changes in complexity, describe recent works and their limitations, and outline key science questions that need to be tackled.

In order to be able to address these science questions from a fundamental physics perspective, our main recommendations for the Decadal Survey Committee for Solar & Space Physics (Heliophysics) 2024-2033 are:

- Prioritize spacecraft missions that can obtain comprehensive in situ ICME measurements at multiple heliocentric distances in the inner heliosphere.
- Explore options, through simulations, for optimal spacecraft configuration in terms of radial, longitudinal, and latitudinal spacing to achieve the necessary spatial resolution to fully investigate ICME complexity evolution.
- Once the data are available, focus efforts on comprehensive/holistic studies of ICME complexity evolution, integrating the results from many vantage points.

Fundamental research on ICME complexity changes from the solar corona to 1 AU and beyond is critical to our physical understanding of the evolution and interaction of transients in the inner heliosphere. Furthermore, a complete understanding of such changes is required to understand the space weather impact of ICMEs at different planets.

1 Introduction and early studies

This white paper addresses the need to investigate, from a fundamental physics perspective, the interplanetary evolution of coronal mass ejections (CMEs), and specifically the evolution of their complexity in the inner heliosphere. The absolute complexity of an interplanetary CME (ICME) at any one heliocentric distance is difficult to define in isolation because it needs to be defined relative to a reference state of assumed low complexity [e.g., Jones et al. 2020]. Generally speaking, however, complexity can be understood as the degree of similarity or deviation of a given ICME structure from a "standard" configuration characterized by a magnetic ejecta (ME) or magnetic cloud (MC) with a flux-rope magnetic structure connected back to the Sun by two "legs" (Figure 1). Such a picture, developed through decades of observations and the consideration of a large number of events [e.g., Burlaga et al. 1981; Zurbuchen & Richardson 2006; Kilpua et al. 2017; Luhmann et al. 2020], presupposes the existence of a paradigm accepted by the community as descriptor of a typical, or low complexity, state.

On the other hand, it is much simpler to determine the relative change in a particular ICME's complexity between different heliocentric distances. By ICME complexity changes, we mean any significant changes in the different parts of the ICME structure (sheath/ME) both from a magnetic configuration and plasma characteristics/composition standpoint, that take the ICME from a simple (complex) starting point at one heliocentric distance to be more complex (simple) at a farther heliocentric distance (e.g., Figure 2).

Based on recent papers described in detail below [Richardson & Cane 2010; Winslow et al. 2016, 2021a,b; Scolini et al. 2021, 2022a,b], the hypothesis exists that the complexity of ICMEs increases during propagation in the inner heliosphere mainly due to interaction with large-scale solar wind structures. The assumption is that this would occur regardless of the initial CME complexity state in the corona, i.e., some CMEs will be more complex than others at the time of initiation, however, their individual complexity state is generally expected to be lowest after launch from the Sun and increase during propagation primarily due to interactions with other transients and large-scale structures. Thus far, only a few studies, described below, have addressed this hypothesis directly, largely due to the lack of suitable and comprehensive in situ data of the same ICMEs at multiple heliocentric distances.

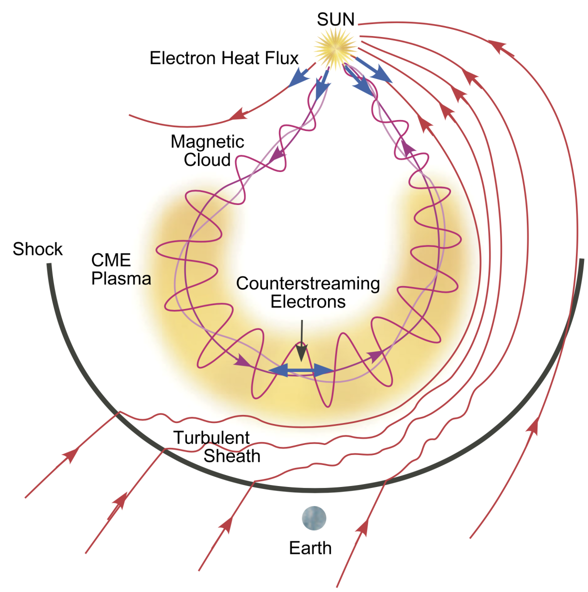

Figure 1: Schematic of an ICME, including a magnetic ejecta with a flux-rope-like magnetic field structure, and the associated shock and sheath. From Luhmann et al. [2020] based on Zurbuchen & Richardson [2006].

However, currently, it is not a certainty that ICME complexity increases with increasing distance, for example, it may be the case that CMEs are formed with a relatively complex internal structure that evolve toward a simpler configuration as they expand outwards. For example, Janvier et al. [2019] found, from superposed epoch analyses of ICMEs between 0.3 and 1 AU, that the overall magnetic field profile of ICMEs became more symmetric as they propagated farther from the Sun, indicating a relaxation mechanism possibly taking place. Furthermore, Florido-Llinas et al. [2020] showed, via modeling with the circular-cylindrical analytic flux rope model [Nieves-Chinchilla et al. 2016], that there are conditions under which flux ropes can expand self-similarly and even become more kink-stable during propagation. It is also possible that certain regions (or substructures) of ICMEs undergo complexity increases while other areas might decrease in complexity during propagation, possibly arising from the fact that the ICME might not behave as a coherent unit [Owens et al. 2017]. Further work is needed to properly classify and characterize such changes in ICMEs. A complete understanding of the changes in the properties of transients as they propagate is required to understand the fundamental physics of the evolution of ICMEs in the solar wind, as well as to understand their space weather impacts at different planets.

Many previous studies have shown that ICME properties evolve as they propagate through the solar wind due to expansion and interaction with the solar wind and transients within it [Manchester et al. 2017]. Through observational and modeling work, studies have shown that during propagation, the ICME flux rope may kink and deform [Odstrčil & Pizzo 1999a; Manchester et al. 2004; Török et al. 2018], reconnection/erosion of internal ICME magnetic flux may occur [Lavraud et al. 2014; Ruffenach et al. 2015], and the ICME may also get deflected [Wang et al. 2014; Kay & Opher 2015] and rotated [Isavnin et al. 2014]. Most importantly, all of the aforementioned effects are amplified by interactions with high-speed streams (HSSs), stream interaction regions (SIRs), the heliospheric current/plasma sheet (HCS/HPS) [Odstrčil & Pizzo 1999b,c; Lavraud & Rouillard 2014; Rodriguez et al. 2016; Zhou & Feng 2017; Liu et al. 2019; Winslow et al. 2021b; Scolini et al. 2021], as well as other ICMEs [e.g. Lugaz et al. 2017], suggesting interactions with other interplanetary structures are a critical factor in the evolution of ICME structures during propagation. Overall, these studies have detailed the types of changes that ICMEs undergo during propagation, however, they have not considered them from the broader view of their overall complexity.

The idea that ICME structures become more and more complex with heliocentric distance has been first inferred from statistical investigations on the fraction of ICMEs that contain MC structures [Burlaga et al. 1981]. At 1 AU, the fraction of non-MC ICMEs is strongly dependent on the solar cycle [Richardson & Cane 2010], indicating that more ICMEs might have interacted with transients in the solar wind during solar maxima than during minima. Meanwhile, studies of individual ICMEs observed by multiple radially aligned spacecraft also proved insightful for our understanding of the various phenomena controlling their evolution and magnetic complexity. They showcased a wide variety of evolutionary behaviors, ranging from essentially self-similar [Nakwacki et al. 2011; Möstl et al. 2012; Good et al. 2015, 2018] to strongly non-ideal [Nieves-Chinchilla et al. 2012; Winslow et al. 2016; Lugaz et al. 2020], posing questions on the frequency and causes of such a large variation of evolutionary trends.

Recent studies on ICME complexity changes [e.g., Winslow et al. 2016, 2021b; Scolini et al. 2022b] have since uncovered many characteristics through which they can manifest: significant changes in flux rope structure and orientation; indications (in solar wind, magnetic field, suprathermal electron, and iron charge state data) that the ICME underwent reconnection, as well as changes in the detection of the MC substructure with heliocentric distance (e.g., if a clear MC configuration is no longer detected at spacecraft farther from the Sun although it was detected at smaller heliocentric distances). Additionally, the mass/density increase with distance in ICME-driven sheaths may affect the ME as it expands, thereby also affecting the complexity evolution [e.g., Temmer et al. 2021]. Similarly, atypical evolution of sheaths (such as significant growth beyond expected values from expansion only, as well large increases in dynamic pressure) can also contribute to complexity changes [e.g., Winslow et al. 2021b].

It is important to note, however, that most studies of ICME complexity to date have not considered complexity changes holistically, i.e., by looking at changes in all aspects of the ICME as opposed to just investigating one or two parameters (e.g., magnetic field configuration). Comprehensive investigations of ICME complexity are needed to test the hypothesis that complexity

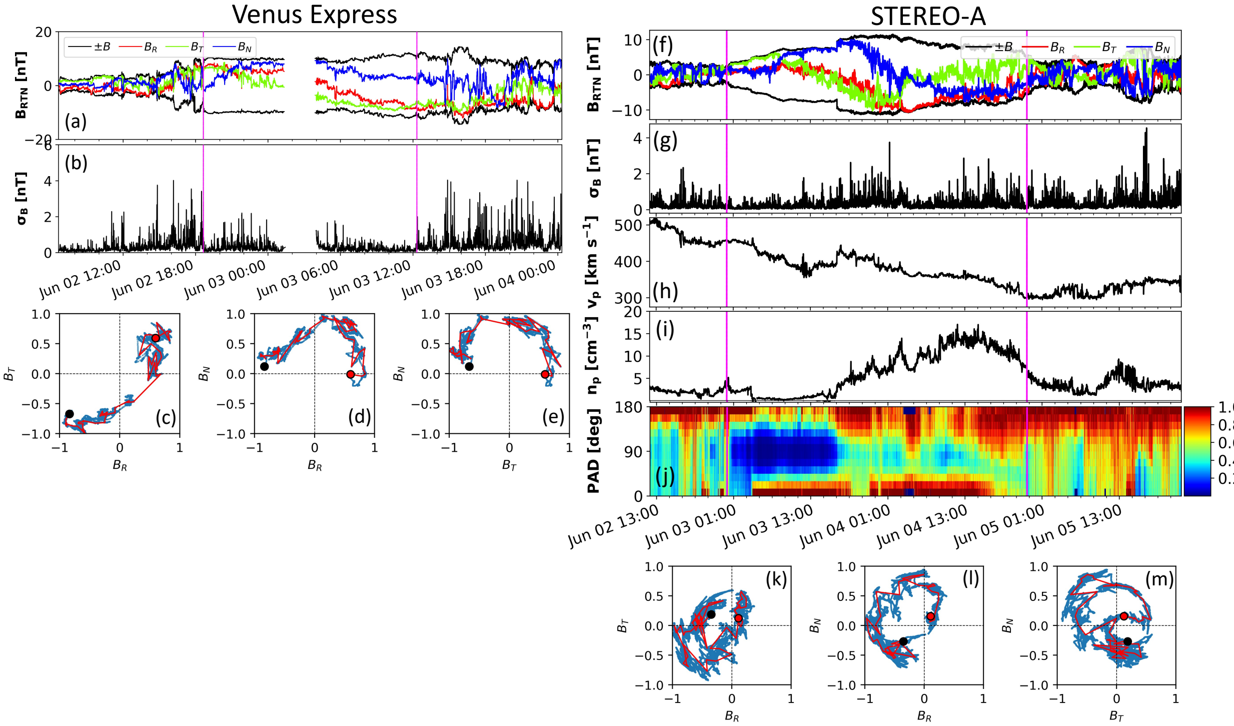

Figure 2: Example of an ICME observed at 0.73 au and 0.96 au by Venus Express (panels a to e) and STEREO-A (panels f to m) in radial alignment (with a longitudinal separation of 9°). The flux-rope magnetic structure observed at the inner spacecraft (panel a) clearly appears as a much more complex, non-MC structure by the time the ICME reaches the outer spacecraft (panel f) due to the interaction with an interplanetary shock. From [Scolini et al. 2022b].

increases with distance, and to understand these complexity changes from a more fundamental physics standpoint.

2 Causes and effects of complexity changes

In-depth analyses of ICME case studies through multi-point spacecraft measurements in radial alignment have first illustrated the impacts that solar wind structures can have on ICMEs. Winslow et al. [2016] showcased an ICME ME that underwent significant deformation causing increased ICME complexity as it propagated from Mercury to 1 au. This increased complexity was found to be due to interaction/reconnection with the HCS and HPS. More recently, Winslow et al. [2021b] presented a comparative analysis of two ICME case studies observed in radial alignment at Mercury and 1 au, of which one propagated essentially self-similarly, while one exhibited major changes to its global structure (affecting both the flux rope and preceding sheath) due to the interaction with an SIR. In a complementary study, Winslow et al. [2021a] investigated an ICME overtaken and accelerated by an HSS that was observed simultaneously by Parker Solar Probe and STEREO-A during a period of close radial alignment. In this case, the ICME interacted with the HSS for at least ∼2.5 days prior to arrival at STEREO-A (i.e. the interaction began well before arrival at either spacecraft), and therefore the flux rope configuration detected in the ICME was the same at both spacecraft. However, the ICME as a whole exhibited significant complexity (e.g. the shorter duration of the flux rope compared to the duration of the entire ME) due to the compressing action of the overtaking HSS.

The expansion of such investigations to a statistical set of events has been long complicated by the limited amount of assets capable of performing high-quality observations of ICME structures at multiple heliocentric distances. When restricting the study to only the magnetic structures of ICMEs [i.e. focusing on MEs and neglecting ICME-driven shocks and sheaths; see, e.g., ME configurations illustrated in Nieves-Chinchilla et al. 2018, 2019], Scolini et al. [2022b] was able to generalize previous case study results and draw statistically-valid conclusions (albeit based on small-number statistics) on the frequency, causes, and effects of magnetic complexity changes on ICME structures. They found, from 31 ICMEs observed in radial alignment between 0.3 and 1 au, that ICMEs tend to increase their magnetic complexity with heliocentric distance, and that these changes are in most cases induced by the interaction with multiple solar wind structures, i.e. HSSs, SIRs, the HCS, or other interplanetary shocks (see Figure 3). On the contrary, ICMEs that preserved their magnetic configuration during propagation tended to either lack any interaction with other interplanetary structures, or to interact only with a single structure. An example of an ICME increasing its magnetic complexity from an inner to an outer observing spacecraft is provided in Figure 2. It is important to mention, however, that this study is a "trailblazer" in the sense that it is a first-of-its-kind statistical study on ICME complexity, and it is far from conclusive or comprehensive. It is based on small-number statistics, the observations used lack plasma data at the inner spacecraft, and it relies on ENLIL model simulations of the background solar wind to identify solar wind structures that the ICME interacted with (i.e., lacks data in the propagation space). More comprehensive statistical studies are needed in the future, which can only be achieved through multiple spacecraft simultaneously probing heliospheric conditions at different heliocentric distances.

Aside from alterations in the magnetic field configuration of ICMEs, Scolini et al. [2022b] also found that complexity changes are statistically correlated with reduced periods of bi-directional suprathermal electron strahls observed within ICMEs, indicative of major alterations to their magnetic topology and connectivity back to the Sun [e.g., Gosling et al. 1987; Kahler & Reames 1991; Shodhan et al. 2000], and randomization of the average ICME internal properties such as the breaking of the speed–magnetic field relationship [e.g., Gonzalez et al. 1998; Owens & Cargill 2002; Owens et al. 2005] that holds for unperturbed ICMEs [Scolini et al. 2022b]. These results caution against the use of inner heliospheric observations to predict the magnetic field strength and orientation at a downstream target location separated by more than $\sim$0.2 au.

Numerical models have allowed us to investigate the effect of solar wind interactions on ICME structures to a level of detail exceeding current observational capabilities. Of particular relevance is the possibility to include simulated spacecraft at orbits and relative positions not available in reality. Taking advantage of such a flexibility, Scolini et al. [2021] quantified the probability of detecting changes in ICME complexity through a swarm of simulated spacecraft placed in perfect radial alignment between 0.1 au and 1.6 au within global heliospheric simulations, given the absence/presence of corotating solar wind structures. Results of this study suggest that HSSs and SIRs dominate contributions to ICME magnetic complexity increases throughout the inner heliosphere.

We underline that such numerical investigations have been performed using global heliospheric models in simplified numerical set-ups, which facilitate the interpretation of propagation effects on different ICME regions. Future studies should address more realistic numerical set-ups and investigations of real ICME events, including comparisons with observations, as well as the use of more sophisticated models (see recommendations in Section 4).

3 Observational gaps: Data products and spacecraft location

When considering observational gaps, we must first consider the kind of measurements available at different spacecraft and locations in the inner heliosphere. Measurements of key solar wind plasma properties, including bulk thermal properties, suprathermal populations,

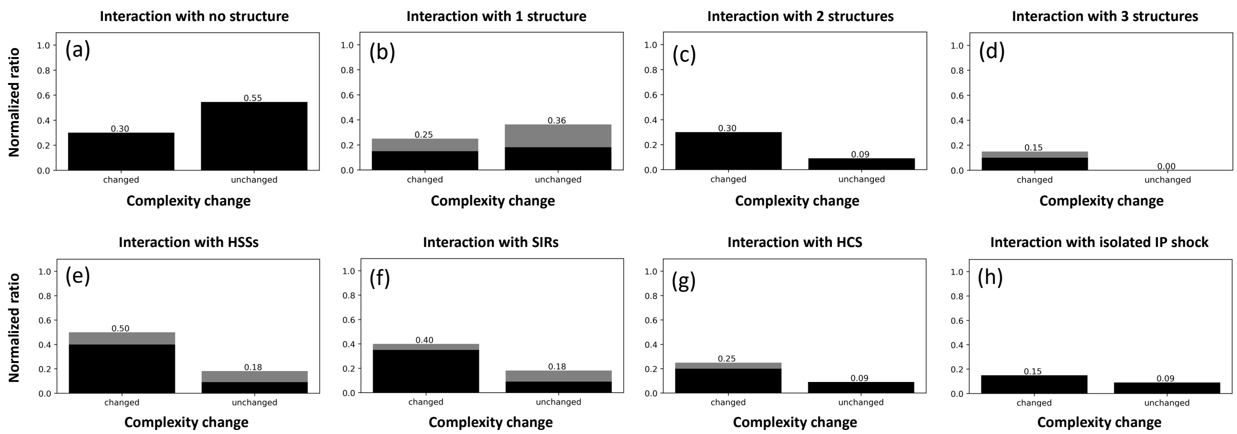

Figure 3: Summary of the frequency of ICME magnetic complexity changes as a function of the number of interactions that the ICME underwent during propagation (panels a to d), and of the type of interacting solar wind structure (panels e to h). Certain and probable interactions are indicated in black and gray, respectively. Adapted from [Scolini et al. 2022b].

and composition data are of utmost importance to decipher the fundamental nature of ICME complexity changes. By observational gaps we mean a lack of spacecraft measurements (all or just some types) along specific radial, longitudinal, and latitudinal locations of interest. Currently, the largest obstacle to advancing our studies of ICME complexity evolution is the lack of a full suite of in situ plasma and magnetic field data at small enough spatial separations but also covering a large distance range (and therefore likely needing to involve a large number of spacecraft) from the Sun to 1 au to unambiguously detect complexity changes and determine their causes.

In general, gaps in the aforementioned data products available may: 1) lead to higher uncertainties in the identification of ICME boundaries [e.g. Cane & Richardson 2003; Riley et al. 2004; Jian et al. 2006; Al-Haddad et al. 2013; Winslow et al. 2015; Good & Forsyth 2016; Davies et al. 2021]; 2) prevent a detailed investigation of the physical phenomena (e.g. magnetic reconnection, forces, conversion/transfer of energy between ICME substructures, generation/propagation of plasma waves — see Manchester et al. 2017 for reference) involved in complexity changes observed within ICMEs [e.g. Winslow et al. 2016; Farrugia et al. 2020]; 3) complicate the interpretation of ICME kinematics/propagation [e.g. Hess & Zhang 2014; Lugaz et al. 2020]; 4) complicate the identification of large-scale structures interacting with ICMEs [e.g. Scolini et al. 2021]; 5) complicate the identification of complexity changes that may have occurred due to the lack of the same type of observations at multiple spacecraft locations [e.g. Scolini et al. 2022b].

Unfortunately, the limited number of spacecraft able to cross individual ICME structures [Lugaz et al. 2018] has prevented the spatial (i.e. longitudinal and latitudinal) characterization of the magnetic complexity distribution within MEs and its evolution with heliocentric distance. This is true both at 1 au, where a maximum of three spacecraft crossing individual ICME structures along different radial directions has been achieved only in the early phases of the STEREO mission [Farrugia et al. 2011; Kilpua et al. 2011; Ruffenach et al. 2012], and also in the inner and outer heliosphere, where measurements are typically rare and single-spacecraft. Exploiting the ability to simulate spacecraft swarms in global heliospheric simulations, an exploratory numerical investigation by Scolini et al. [2022a] estimated the minimum number of spacecraft that would be required to characterize the spatial distribution of magnetic complexity within MEs and its evolution with heliocentric distance, depending on the ICME propagation scenario (i.e. whether there were interactions with other large-scale solar

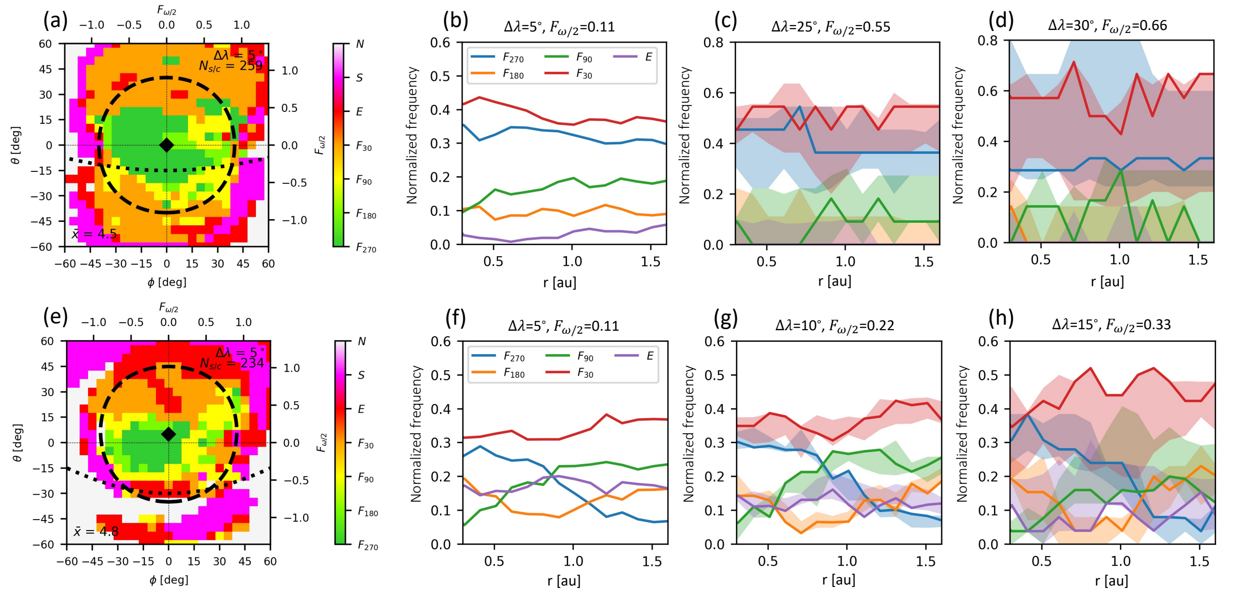

Figure 4: ICME magnetic complexity from spacecraft swarms in global heliospheric simulations. Top row: ICME not interacting with any other large-scale interplanetary structure. Bottom row: ICME interacting with a HSS/SIR. Panels a, e show the spatial distribution of magnetic complexity at 1 au, based on the classification scheme proposed by Scolini et al. [2021] and adapted from Nieves-Chinchilla et al. [2018]. Panels b–d and f–h show the evolution of magnetic complexity with radial distance determined from spacecraft swarms with different angular separations. Adapted from Scolini et al. [2022a].

wind structures). Selected results are provided in Figure 4, which show the spatial distribution of ICME magnetic complexity detected at 1 au and also show the ICME's radial evolution as observed by spacecraft swarms with different angular separations. Such an investigation revealed that globally, the ICME magnetic complexity requires a minimum of ∼10 spacecraft crossings at each heliocentric distance to be fully characterized (shown in panels b, c in Figure 4). With less spacecraft crossings available (panel d in Figure 4), the complexity determined based on in situ data may not be indicative of the actual complexity of the ICME structure as a whole. Interactions with other large-scale solar wind structures such as SIRs and HSSs increase the minimum number of spacecraft crossings required by a factor of 4 to 10, bringing it up to a minimum of 50 to 65 spacecraft (panels f, g in Figure 4).

The simulations by Scolini et al. [2022a] also suggest that ICMEs may retain a lower complexity level along their magnetic axis. In this respect, future missions composed of spacecraft swarms orbiting in the ecliptic plane may characterize the complexity evolution of low-inclination ICME flux ropes [i.e. having their magnetic axes approximately aligned with the ecliptic plane; Kilpua et al. 2017] near the ecliptic plane with as little as ∼6 spacecraft crossings, rising to ∼9 in case of interaction with HSSs and SIRs. At the same time, the characterization of their global complexity requires crossings along both the axial and perpendicular directions, i.e. in and off the ecliptic plane. Whether high-inclination ICME flux ropes manifest a similar magnetic complexity evolution in response to interactions remains an issue open to future investigations.

4 Open questions and recommendations

As described above, although a number of recent studies have investigated complexity changes in ICMEs with multi-spacecraft measurements and simulations, many open questions remain. It is important to highlight that most studies on this topic so far have addressed magnetic complexity changes only, not viewing ICME complexity from a holistic standpoint (i.e., looking at both large-scale magnetic configuration changes as well as changes in the plasma characteristics and composition). A holistic view is necessary, however, in order to fully test the hypothesis that ICME complexity generally increases with increasing heliocentric distance. The main limitation to such comprehensive studies is the lack of plasma and magnetic field measurements of the same ICMEs at various radial and longitudinal locations in the inner heliosphere.

Compelling open questions in this area, from a fundamental science perspective, are:

- In general, does the overall complexity of individual ICMEs (including magnetic configuration and plasma characteristics in the different ICME substructures) increase with heliocentric distance in the inner heliosphere? Or is it more common for the ICME internal structure to simplify as it evolves (i.e., relaxes through for e.g. Taylor relaxation)? Alternatively, is it more likely that different ICME substructures behave differently from each other, i.e., ICME complexity increases in some parts while it decreases in others?
- What are all possible drivers of ICME complexity changes during propagation? Also, what is the main driver?
- To what extent are ICMEs coherent and how does this affect their complexity evolution?
- How do instabilities/small-scale processes contribute to global ICME complexity changes?
- To what degree, if at all, does the presence of a shock/sheath protect the ICME ME from large-scale and comprehensive complexity changes?
- How does ICME–ICME interaction affect the individual ICME's complexity?
- How do ICMEs of different complexity levels affect the global heliospheric magnetic field and contribute to the heliospheric flux budget?
- Can we leverage proxy observations to gain information about ICME complexity?

In order to be able to answer the above stated questions, our recommendations for the Heliophyiscs 2024 Decadal Survey Committee are:

1. More comprehensive in situ ICME measurements are needed from the Sun to 1 au at multiple heliocentric distances. This would entail having magnetic field, solar wind plasma, and suprathermal electron measurements at many locations radially outwards from the Sun. Current standard time resolution of magnetometers and plasma and electron spectrometers at a continuous duty cycle should be sufficient for these studies. Initially, for the Heliophysics 2024 Decadal Survey, we recommend pathfinder mission(s) combined with simulations allowing for the exploration of the parameter space, while for the following Decadal Survey, a dedicated flagship mission building on these findings would be necessary to substantially advance our understanding of ICME evolution.
2. Options should be explored on the optimal spacecraft configuration in terms of radial, longitudinal, and latitudinal spacing through simulations to achieve the necessary spatial resolution in the data needed to fully explore ICME complexity evolution in the inner heliosphere.
3. Once the data are available, more comprehensive/holistic studies of ICME complexity evolution are needed, integrating the results from many vantage points.

Exploratory investigations using global heliospheric simulations are already showing us how spacecraft swarms can be best used to investigate the physical origin, evolution, and spatial distribution of magnetic complexity within ICMEs. In the future, we stress that simulations need to be able to resolve more physics (e.g. achieving more accurate characterizations of small-scale phenomena such as magnetic reconnection and shock–ICME interactions), and be able to include more realistic descriptions of the global internal magnetic configuration of MEs, including alterations arising from their early evolution in the solar corona, in order to be able to test such numerical simulations against real ICME events.

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