What is a Heliospheric Flux Rope?

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Synopsis

This white paper underlines the lack of fundamental understanding of heliospheric flux ropes and provides the motivation to significantly improve the status quo of flux rope research through novel and requisite approaches. The recommendations put forward in this paper will broaden the in-depth knowledge of our nearest star, its dynamics, and its role in its sphere of influence, the heliosphere.

1 Current State of Knowledge and Challenges

This white paper addresses the need to investigate the fundamental solar and heliospheric magnetic structures known as *flux ropes* (FRs). FRs are commonly associated with coronal mass ejections [CMEs, Webb & Howard 2012], streamer blow-outs [SBOs, Vourlidas & Webb 2018] within the heliospheric current sheet [HCS, Lavraud et al. 2020], small structures called "plasmoids" or "blobs" observed in 2D by heliospheric imagers [e.g. Khabarova et al. 2021] and in solar flares [e.g. Kumar & Cho 2013], magnetic structures observed by in-situ instrumentations [e.g. Moldwin et al. 2000], or magnetospheric Flux Transfer Events [FTEs, Russell & Elphic 1978; Slavin et al. 2012]. FRs dominate the transport of energy, mass, and helicity from the Sun to the heliosphere and from the heliosphere to the planets' local environment. They are characterized by an organized bundle of magnetic field lines, twisting around a common axis, confining plasma, and dragging away a large part of the Sun's or a planet's atmosphere. **Considering the diversity of FRs described above, a question still remains: are all these structures alike in terms of morphology, magnetic and plasma properties, and dynamics?**

The FR concept was borrowed from the laboratory plasma physics experiments in the 1950–60s to confine and reach a stable plasma equilibrium to produce thermonuclear fusion power [e.g. Lundquist 1950]. Helical magnetic field structures were produced by induced toroidal current densities in laboratory devices, such as Tokamaks, to determine their stability. However, as the Heliophysics discipline matured, the idealized FR concept has become obsolete to accurately describe the structures often found in the heliosphere, which are not always static or in equilibrium.

In this white paper, we will discuss some of the issues that prevent us from advancing our understanding of the origin of these structures and the physical processes associated with their evolution. The challenges that we present here range from data returned by space-based observatories to more theoretical approaches, but also encompass the development of more robust plasma physics laboratory experiments.

1.1 Flux Rope Formation

Despite countless observations, both remote and in situ, that account for the existence of FRs, we have only a vague idea of their formation. Most FR models that are focused on CME eruption include a FR as an essential part of the process and the phenomenon. However, there is a long-standing debate about whether these FRs exist in the corona before the eruption and later become unstable [ideal or magnetohydrodynamic instability, e.g. Török et al. 2004] or whether the FR forms as a consequence of the take-off of an unstable filament (sheared arcade) that triggers magnetic reconnection (resistive magnetohydrodynamic instability) in its wake [e.g. Antiochos et al. 1999]. The nature of the pre-eruptive configuration of solar eruptions has been extensively debated [see Klimchuk 2001; Forbes et al. 2006; Green et al. 2018; Patsourakos et al. 2020]. Episodes of magnetic flux emergence can be regarded as the manifestation of twisted magnetic flux tubes rising through the solar surface, that result from the buoyant rise of magnetic plasma from the convection zone into the overlying atmosphere [e.g. Lites 2009; Cheung & Isobe 2014]. It is currently believed that the combination of photospheric plasma flows and magnetic reconnection above the polarity inversion lines [van Ballegooijen & Martens 1989] leading to flux rope formation, also during flux emergence, is the most common mechanism.

After observations of streamer blowouts, it has been proposed that FRs can also be created later in the corona through reconnection processes [Lynch et al. 2016]. The same mechanism seems to be responsible for the formation of small FRs or blobs and plasmoids [e.g. Khabarova et al. 2021]. Although there is supporting evidence for the aforementioned mechanisms, there are also contradictory findings that prevent us from fully understanding the formation of different FRs.

The FRs originating away from the Sun in the heliosphere mainly result from the solar wind's evolution. This corresponds to magnetic reconnection in the heliospheric current sheet (HCS) [e.g. Eastwood et al. 2002; Moldwin et al. 2000; Lavraud et al. 2020] and discontinuities produced by the action of turbulence in the solar wind [e.g. Zheng & Hu 2018]. All these structures are again formed by the same magnetic reconnection process [e.g. Daughton et al. 2011].

Several studies have correlated small FRs with interplanetary shock waves, particle energizations, and stream interaction regions (SIRs/CIRs) [see for instance, Feng et al. 2007; Cartwright & Moldwin 2010; Zank et al. 2014; le Roux et al. 2015; Hu et al. 2018]. Also, they are sometimes believed to be associated with magnetic reconnection and magnetohidrodynamic turbulence. Thus, although the origin of large-scale FRs possesses well-defined observational signatures and unambiguously corresponds to CMEs and similar solar events, identification of the procedures involved in small-scale FR generations are still inconclusive.

In the ideal FR built in the laboratory, an axial current density induces the helical magnetic field topology. However, an unidealized and more realistic heliospheric FR could be described by more complex internal current density distributions with, perhaps, impact in the way the structure will evolve. Therefore, **does the formation mechanism determine the internal magnetic structure and future impact of the evolutionary processes?**

1.2 Flux Rope Evolutionary Processes

Later, in the heliosphere, FRs are not static. They continuously evolve, expanding, rotating, deflecting, eroding, or distorting [Manchester et al. 2017]. The physical processes associated with these effects are clearly related to the interaction with the local environment but disentangling them is not an easy task. Most of the processes are coupled; for instance, the erosion with the distortion [Nieves-Chinchilla et al. 2022], expansion with deflection [Nieves-Chinchilla et al. 2012, 2013], but also the impact of local changes within the global structure [Owens 2020].

In the current state of the field, studies on the early evolution of FRs originating from the Sun estimate that the expansion and acceleration are probably due to Lorentz force [e.g. Vršnak 2008; Kay & Nieves-Chinchilla 2021] but the range of influence of the different forces are not yet well defined.

In the interplanetary medium, the evolution of FRs is mostly dominated by interactions with the ambient solar wind. The MHD/aerodynamic drag [e.g. Vršnak et al. 2004, 2008, 2013] affects FR kinematics and overall dynamics. It is also believed that with increasing heliocentric distance [e.g., Leitner et al. 2007; Gulisano et al. 2012], the FR radial expansion weakens which leads to FR deformation such as the "pancaking effect" [e.g., Cargill et al. 1996; Owens et al. 2006]. However, the question of whether a FR can be distorted or not is still open in our community. The interpretation of the remote-sensing and in situ observations that suggest complex distortions are ambiguous and open to debate. On top of that, there are just a few physics-driven FR models flexible enough to advance such investigations [Hidalgo 2003; Hidalgo & Nieves-Chinchilla 2012; Nieves-Chinchilla et al. 2022; Weiss et al. 2022].

The deflection or rotation effects are related to the change of global orientation of a flux-rope in the heliosphere but the physical cause may be completely different. [e.g. Vourlidas et al. 2011; Nieves-Chinchilla et al. 2012]. While the deflection is mostly driven by the force imbalance with the solar wind [Wang et al. 2004; Kay et al. 2017; Sahade et al. 2020], the rotation seems to be an internal magnetic instability [see for instance, Lynch et al. 2009; Florido-Llinas et al. 2020]. Currently, we don't have the resources to test these assumptions because of the lack of computational resources.

Finally, the erosion effect might significantly contribute to the CME evolution. This well-known observed effect at the front, and sometimes also at the back, of the in-situ observations of the FR is basically a magnetic reconnection of the magnetic field with the ambient interplanetary magnetic field. This may impact FR's magnetic flux, twist, helicity, and cross-sectional area by "peeling off" its outer layers [Ruffenach et al. 2012; Pal et al. 2021, 2022; Rodríguez-García et al. 2022]. Magnetic reconnection is also associated with the internal changes of the FR, being a possible cause of internal complexity.

In summary, we lack an understanding of the physical characteristics of the FR internal structure and changes as they evolve in heliosphere and in what way the innate features connect to the matured structure features. Basically, we need to answer the question **how does the temporal and spatial evolution impact the stability, equilibrium, morphology, and entity of flux-ropes?**

1.3 Puzzle Out Flux Ropes in the Heliosphere

To study the FRs' internal structure and evolution at any point of the heliosphere, we assembled observations from different assets in the space, connect them with models and techniques, and look to create a scenario that describes the source region and the impact of the evolution in the structure. Figure 1 illustrates an exercise, connecting FR observations at their sources and heliosphere through modeling.

However, the unavailability of enough multi-point observations misleads us in interpreting the global structure of FRs. We use different models and techniques to bridge the gap resulting from the lack of observations. Each of them has different nature and are developed using a specific set of data. Thus, most models that use white light observations (coronagraphs and heliospheric imagers) to study FR evolution fit static geometrical structures to match the morphology of images at different times [Thernisien et al. 2006; Rodríguez-García et al. 2022]. These models do not include magnetic field information, and require multiview points to (very often poorly) reproduce the three dimensional structure of the FR [see the discussion in Nieves-Chinchilla et al. 2022]. These models do not provide a thorough information about the evolutionary physical processes. On the other hand, physical models that include magnetic field estimations are designed to match local in-situ measurements and rely on, in the best of the scenarios, single/few-point observations with a spatial and temporal separation [Weiss et al. 2021; Pal et al. 2022]. All of these prevent us from a comprehensive understanding of FRs in the heliosphere. Improving the number of local FR measurement points will definitely improve the models' FR reconstruction capabilities. Therefore, the lack of knowledge on FRs' global nature raises the questions – **Can all FR be understood by an unique model? Is there a unique FR model valid for all observations?**

2 Challenges That Have Arisen From Studies

Here we summarize the challenges that came out from the discussion in the previous sections. The primary question that challenges our current understanding of the flux ropes in the heliosphere:

Are all flux ropes in the heliosphere alike in terms of morphology, magnetic and plasma properties, and dynamics?

To address this main question, in the coming years we should be able to answer the following questions:

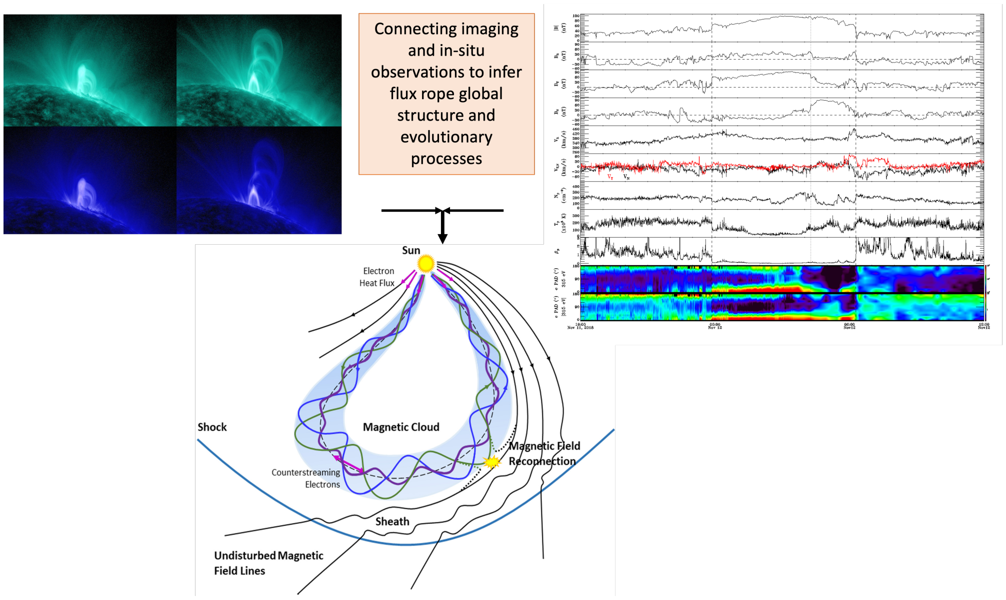

Figure 1: Example featuring the process of connecting the imaging (SDO/AIA) of an emerging FR (left) and its local in situ measurements (right) to infer its global internal structure and heliospheric evolution (middle). The images are reproduced from Nieves-Chinchilla et al. [2020] and Wang et al. [2018].

- Does the formation mechanism determine the internal magnetic structure and future impact of the evolutionary processes?
- How does the temporal and spatial evolution impact the stability, equilibrium, morphology, and entity of flux-ropes?
- Can all flux ropes be understood by an unique model?.

3 Strategies to Address the Challenges

Active in-situ and imaging observations available for more than a decade may help in addressing the challenges by enabling use of a statistical approach where machine learning methodology can be of great help. The statistical analysis over different phases of solar cycles will lead the understanding the dependencies of FR behavioral changes on their launch environment.

- **Data Assimilation and Visualization**
  In order to decipher the internal structure and evolution of complex FRs, we need to enable the human mind to synthesize and make sense of the existing in-situ and remote measurements by bringing clarity to how and where diverse observations connect. 1D, 2D, and multi-point observations from a variety of missions may all hold a piece of the story but are separated in space, time, and instrument focus. Visualization tools that centralize the goal of relating these disparate measured data will bring insight into the evolution of these structures. Including varied FR simulations as an additional part of such a visualization suite will extend our understanding of the measured data as well as the interplay of forces at work throughout the global 3D heliospheric configuration. A well-designed visualization tool is essential in putting the myriad pieces of the puzzle together.
- **Future Missions**
  To shed light on the formation and early evolution of FRs, it is crucial to improve remote sensing capabilities at low coronal heights. Upcoming new instrumentation that would enable filling the prevailing gap between 1.3 and 2.2 solar radii for uninterrupted coronal

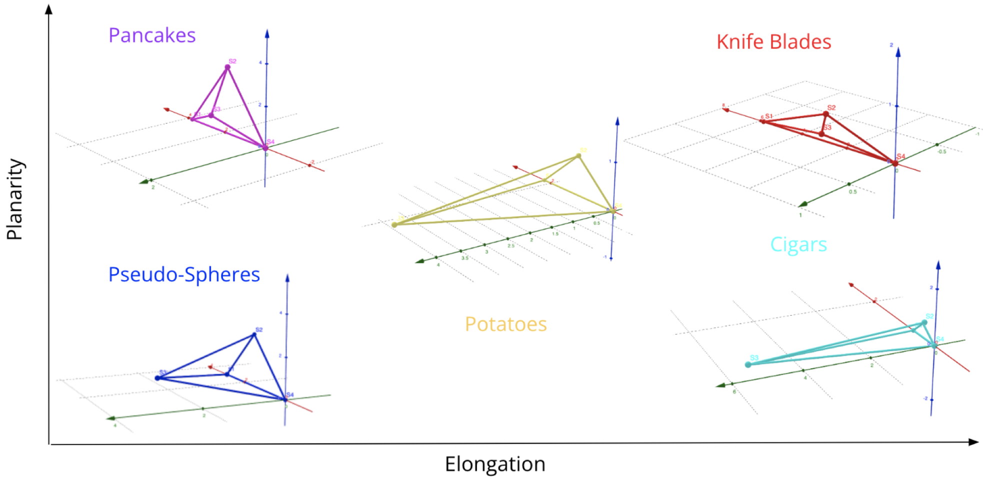

Figure 2: Exploring the efficiency of the curl-meter technique using five different types of tetrahedra as a function of Elongation and Planarity. According with [Ayora Mexia 2022] the pseudo-sphere is the best constellation formation to obtain the internal current density distribution within a flux rope.

observations is of vital priority in this regard. Moreover, tracking and understanding the continuous evolution of solar flux ropes in the interplanetary medium as they propagate towards Earth, requires L4/L5 remote sensing instrumentation with improved detection capabilities.

Using joint measurements from recently launched space missions and pre-existing satellites would allow probing for FRs in a large extent of the heliosphere may help in better understanding the in situ evolution of FRs and their full three-dimensional distribution from a purely observational point of view. With the new additional satellites, several unknown facts regarding heliospheric variability have already been explored (references). Multiple probing of FRs at different heliocentric distances and at different latitudes and longitudes may be used for classifying the large and small-scale FRs' spatial and temporal behavior and their evolution which further may lead us to uncover the origin of the FRs. Multipoint observations will help in validating the model results meant for reconstructing complex FR structures and thereby leading to improvements in the models.

Constellations of spacecraft will also bring the opportunity to develop techniques and approach the problem from different perspectives. For instance, Figure 2 illustrates the different spacecraft constellation formation to implement the curl-meter technique and to obtain the internal current density distribution within a FR. [Ayora Mexia 2022].

- **Artificial Intelligence and Machine Learning**

  Machine learning is a subfield of artificial intelligence devoted to building algorithms that 'learn' by leveraging data to improve performance on tasks. Portions of machine learning are closely related to computational statistics in which computers learn to make improved predictions from observed patterns and correlations in data. There has been a recent increase in machine learning applications in space weather with the community identifying three key usages [Camporeale et al. 2018]:

  1. Automatically identifying events/features that are traditionally time-consuming and error prone via manual selection.
  2. Methods to study causality and cluster similar events with the aim of deepening our physical understanding.
  3. Techniques to forecast space weather events from solar images, solar wind, and

geospace in situ data.

Because there are only sparse sets of measured data from within identified flux ropes, we should continue the work to leverage the combination of machine learning techniques with both measured data and data from simulated flux rope models. Early results have shown a tantalizing glimpse of how this synergy of methods can inform our understanding of the structure and evolution flux ropes while also validating the physics-based models. Using a convolutional neural network, dos Santos et al. [2020] created a binary classifier that learned to predict if a flux rope was or was not present in a given interval of solar wind data. Narock et al. [2022] subsequently used a related deep neural network to predict the orientation of the identified flux ropes. Nguyen et al. [2018] have explored machine learning techniques for automated identification of ICMEs and Reiss et al. [2021] used machine learning to predict the minimum Bz value as a flux rope was sweeping past a spacecraft. This recent research demonstrates the potential for an integrated machine learning workflow to autonomously identify and classify flux rope events alleviating much of the tedious and time consuming manual component.

- **Exploring New Flux Rope Models by Developing More Theory and Laboratory Research** Currently we lack a comprehensive understanding of realistic flux rope morphology and internal distribution of the plasma and magnetic field [see examples Weiss et al. 2022]. As we evolve in this knowledge we need more physics-driven models, numerical and analytical, to connect observations and understand the physical processes associated with the interaction with the space environment. We recommend developing specific programs that support this goal including long-term studies to develop flux rope models and fundamental investigations to analyze the effects of evolutionary processes from the theoretical perspective. We also recommend coordination with laboratory plasma physics to test the advances in the laboratory [see for instance Gekelman et al. 2020; Zweibel & Yamada 2016]

In summary, improving our understanding of heliospheric flux ropes using technologies and modeling techniques would have an impact on deep space exploration and result in a significant societal benefit by enhancing the predictability of adverse space weather conditions.

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