Redefining Flux Ropes in Heliophysics

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ABSTRACT

Magnetic flux ropes manifest as twisted bundles of magnetic field lines. They carry significant amounts of solar mass in the heliosphere. This paper underlines the need to advance on the fundamental understanding of heliospheric flux ropes and provides the motivation to significantly improve the status quo of flux rope research through the novel and requisite approaches. It briefly discusses the current understanding of flux rope formation and evolution, and summarizes the strategies that have been undertaken to understand the dynamics of heliospheric structures. The challenges and recommendations put forward to address them are expected to broaden the in-depth knowledge of our nearest star, its dynamics, and its role in its region of influence, the heliosphere.

Keywords: Sun, heliosphere, magnetic field, flux rope, coronal mass ejection, solar wind

1 INTRODUCTION

This 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 and Howard, 2012), streamer blow-outs (SBOs, Vourlidas and Webb, 2018; Nitta et al., 2021), density blobs generated due to magnetic reconnection at the tip of helmet streamer within the heliospheric plasma sheet (HPS, Lavraud et al., 2020; Réville et al., 2022), small structures called “plasmoids” or “blobs” observed in 2D by heliospheric imagers (e.g. Khabarova et al., 2021; Pezzi et al., 2021), in solar flares (e.g. Kumar and Cho, 2013), small magnetic structures observed by in-situ instrumentation (e.g. Moldwin et al., 2000; Cartwright and Moldwin, 2010a; Chen et al., 2020; Liu et al., 2021; Chen and Hu, 2022), **as substructures of a larger structure (see for instance, Chen et al., 2023)** and magnetospheric flux transfer events (FTEs, Russell and Elphic, 1978; Slavin et al., 2012; Murphy et al., 2020). FRs contribute greatly to the transport of energy, mass, and helicity from the Sun through 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 (e.g. Linton and Moldwin, 2009). 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 has matured, the idealized FR concept (i.e. that of a circularly-symmetric, force-free, twisted flux tube) has become insufficient to accurately describe the structures often found in the heliosphere, which are not always static or in equilibrium but ubiquitous in Heliophysics.

In this 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. For example, the interpretation of remote-sensing and in-situ observations often suggests complex distortions of FRs that are ambiguous and open to debate, and current models are not equipped to reproduce and simulate such complexities. In our opinion, 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. On the basis of current challenges in FR research, we also envision strategies and future venues to be addressed in the upcoming years.

2 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 models that are focused on CME eruption include a FR as an essential part of the process. 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 sheared arcade that triggers magnetic reconnection in its wake (resistive magnetohydrodynamic instability, e.g. Antiochos et al., 1999). The nature of the pre-eruptive configuration of solar eruptions has been extensively debated (see the reviews of 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, which result from the buoyant rise of magnetic plasma from the convection zone into the overlying atmosphere (e.g. Lites, 2009; Cheung and Isobe, 2014; Pontin and Priest, 2022). It is currently believed that the combination of photospheric plasma flows and magnetic reconnection above polarity inversion lines (see for instance, van Ballegooijen and Martens, 1989; Jiang et al., 2021) leading to flux rope formation, also during flux emergence, is the most common mechanism.

After observations of SBOs, 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. Sheeley et al., 2009; Sanchez-Diaz et al., 2017; Khabarova et al., 2021). Although there is supporting evidences that support each of the different aforementioned mechanisms, there are no conclusive findings and this prevents us from fully understanding the formation of different FRs.

The FRs originating further away from the Sun in the heliosphere mainly result from the solar wind's evolution. This corresponds to magnetic reconnection in the 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 and Hu, 2018). Daughton et al. (2011) showed that for the most common type of reconnection layer with a finite guide field, the three-dimensional evolution is dominated by the formation and interactions of flux ropes.

Several studies have correlated small FRs with interplanetary shock waves, particle energization, and stream interaction regions (SIRs/CIRs) (see for instance, Feng et al., 2007; Cartwright and Moldwin, 2010b; Zank et al., 2014; le Roux et al., 2015; Zheng and Hu, 2018). 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 generation is still inconclusive.

In the ideal FR built in the laboratory, an axial current density induces the helical magnetic field topology. However, a non-idealized and more realistic heliospheric FR could be described by more complex internal current density distributions which, perhaps, impact the way the structure evolves. Therefore, does the formation mechanism determine the internal magnetic structure and impact the subsequent evolutionary processes?

3 FLUX ROPE EVOLUTIONARY PROCESSES

In the heliosphere, FRs are not static. They may continuously evolve through expansion, rotation, deflection, erosion, and distortion (e.g. Manchester et al., 2017; Kilpua et al., 2019; Luhmann et al., 2020). 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., 2022a; Rodríguez-García et al., 2022; Good et al., 2019), the expansion with the deflection (Nieves-Chinchilla et al., 2012, 2013), and they result in local significant changes within the global structures (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 the Lorentz force (e.g. Vršnak, 2008; Kay and 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, leading to FR deformation such as the "pancaking effect" (e.g., Cargill et al., 1996; Owens et al., 2006; Savani et al., 2010; Davies et al., 2021). However, the question of whether the global structure of FRs can be distorted or not is still open in the Heliophysics community. The interpretation of the remote-sensing and in-situ observations that suggest complex distortions are ambiguous and open to debate (Owens, 2020). It is also important to highlight the importance of varied solar wind background structure that can distort longitudinally the coherent flux rope and significantly affect it local parameters probed at different places. Also the interaction between structures can temporally changes even relatively quickly the flux rope properties (Kilpua et al., 2019) and, on top of that, there are just a few physics-driven FR models flexible enough to advance such investigations (Hidalgo, 2003; Hidalgo and Nieves-Chinchilla, 2012; Nieves-Chinchilla et al., 2022a; Weiss et al., 2022).

The deflection or rotation effects are related to the change of the global orientation of a FR in the heliosphere, but their 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 appears to be an internal magnetic instability (see for instance, Lynch et al., 2009; Florido-Llinas et al., 2020). Currently, running MHD simulation can be computational expensive in time and resources and prevent us of testing different assumptions and conditions.

Finally, the erosion effect might significantly contribute to CME evolution. This well-known observed effect at the front, and sometimes also at the back, of the in-situ observations of FRs is due to magnetic reconnection of the FR magnetic field with the ambient interplanetary magnetic field. This may impact the FR's magnetic flux, twist, helicity, and cross-sectional area by "peeling off" its outer layers (Ruffenach et al., 2012; Pal et al., 2020, 2021; Pezzi et al., 2021; Pal et al., 2022a; Pal, 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 or in the boundaries (see e.g. Feng et al., 2011; Hwang et al., 2020).

In this section, we have focused on the open challenges of large-scale FRs in the heliosphere associated with CMEs, however all of these challenges can be extrapolated to other FRs in the heliosphere such as small-scale FRs or FTEs, for instance. In any case, we lack of a current effort to understand of the physical characteristics of the FR internal structures, the changes as they evolve in the heliosphere, and the way the innate FR features connect to the matured structure's features. Above all, there is a need to investigate how does the temporal and spatial evolution impact the stability, equilibrium, morphology, and entity of FRs.

4 THE CHALLENGE OF PUZZLING OUT FLUX ROPES IN THE HELIOSPHERE

To study the FRs' internal structure and evolution at any point of the heliosphere, it is customary to assemble observations from different assets in space, connect them with different models and data-analysis techniques, and elaborate on a scenario that reasonably describes their source region and the impact of the evolution in their structure. Figure 1 illustrates an exercise of connecting the remote and local in-situ measurements of a FR at its source and in the inner heliosphere (see also Palmerio et al., 2018).

However, the unavailability of enough multi-point observations often misleads us in interpreting the global structure of FRs. We use different models and data-analysis techniques to bridge the gap resulting from the lack of observations with the caveat that these models can differ significantly from each other and can lead to different conclusions. For example, most models that use white-light observations (coronagraphs and heliospheric imagers) to study FR evolution fit static geometrical structures to match the morphology of a CME in simultaneous images (Thernisien et al., 2006; Rodríguez-García et al., 2022). These models do not include magnetic field information, and require multi-view points to (very often poorly) reproduce the 3D structure of the FR (see the discussion in Nieves-Chinchilla et al., 2022a). Furthermore, they do not provide thorough information about the evolutionary physical processes.

On the other hand, physical models that include magnetic field estimations (i.e. FR fitting models) are designed to match local in-situ measurements and rely on, in the best of the scenarios, single/few-point observations with smaller spatial and varied temporal separations (e.g. Palmerio et al., 2021; Weiss et al., 2021; Pal et al., 2022b). Contemporary FR fitting approaches are not necessarily guaranteed to work well on larger scale separations (e.g. Weiss et al., 2021) as the simplifications in these models can break down. However, it is not well understood if by increasing the number of local FR measurement points, the FR reconstruction capabilities will improve unless the appropriate modeling techniques are developed in lock step.

The aforementioned aspects prevent us from reaching a comprehensive understanding of FRs in the heliosphere. The ultimate challenge is to develop a model that is able to consistently respond to the wealth of observations and the evolution of these structures. In our perspective, we believe that to address this challenge, in addition of increasing space-based observations, the community should also make an effort to develop fundamental physics to explore the diversity of FR in the heliosphere as well as to develop new techniques and approaches to further evaluate the stability, dynamics and interaction with the surrounding environment.

5 PROPOSED STRATEGIES

Here we summarize the challenges that result from the discussion in the previous sections and strategies to address those challenges. The goal of this perpective article is to raise awareness in the scientific community for the importance of magnetic FRs as a fundamental and ubiquitous magnetic structure in Heliophysics.

5.1 Challenges That Have Arisen From Studies

The primary question that challenges our current understanding of FRs in the heliosphere is:

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

To address this main issue, in the coming years we, as a community, should aim to answer the following questions:

- Does the FR formation mechanism determine its internal magnetic structure and the impact of its subsequent evolution?
- How does the temporal and spatial evolution impact the stability, equilibrium, morphology, and entity of FRs?
- Can all FRs be understood via a single model?

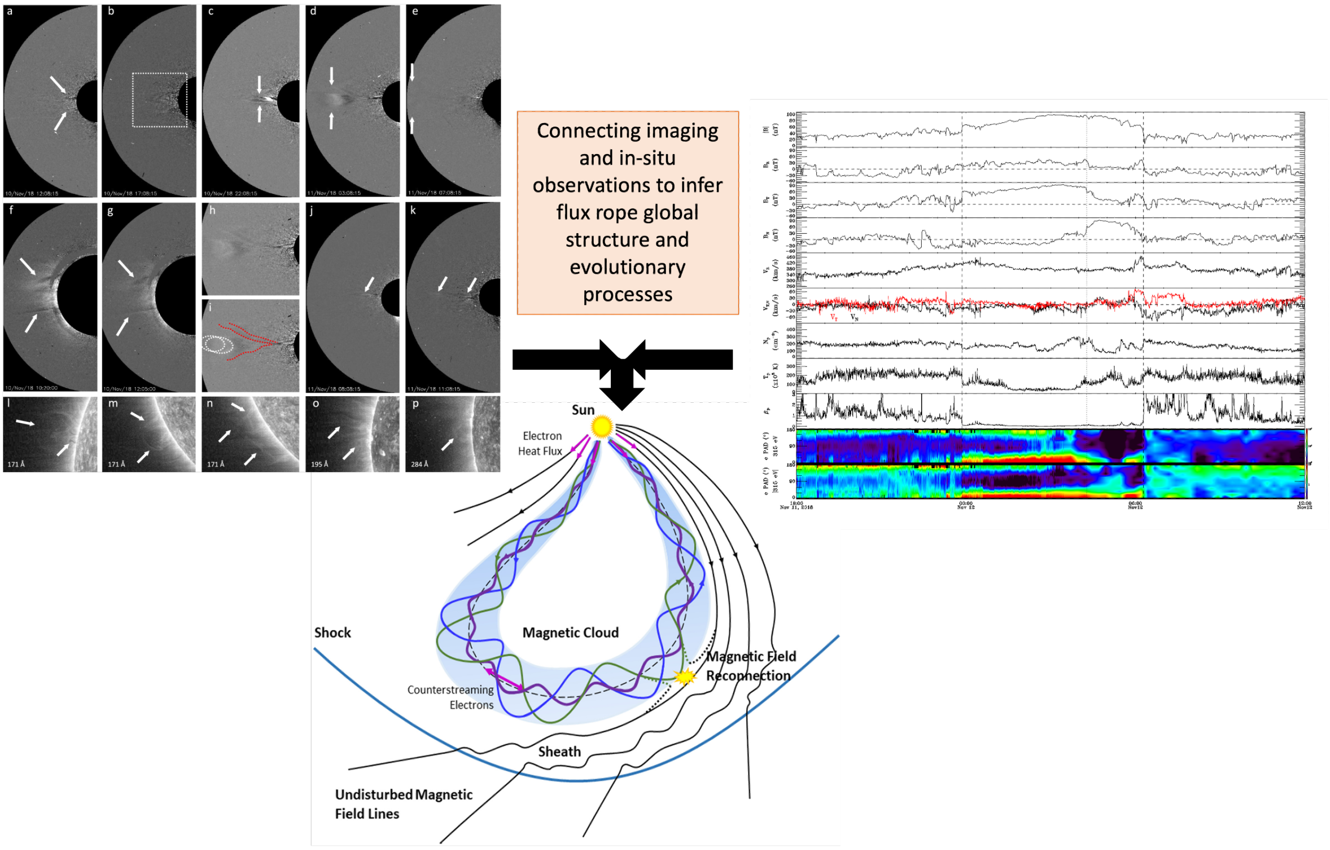

Figure 1. Example featuring the process of connecting the remote-sensing observations (from STEREO/EUVI and STEREO/COR2 & COR1) of a FR (left) and its local in-situ measurements (right) to infer the global internal structure and heliospheric evolution (middle). The images are reproduced from Nieves-Chinchilla et al. (2020) and Wang et al. (2018).

5.2 Strategies to Address the Challenges

- **Future Missions**

  As for any research in Space Physics, space assets tailored to solve specific problems are required. Here, we enumerate the most relevant instrumentation needed to tackle the pending fundamental questions regarding FRs. However, one of the pending tasks is to integrate the current observations into a single meta-data base. Thus, as the Heliophysics fleet of spacecraft grows, the upcoming observations will be seamlessly integrated.

  Constellations of spacecraft should bring the opportunity to develop techniques and approaches to the problem from different perspectives. An example of this is the novel approach developed by Ayora Mexia (2022) to evaluate the internal magnetic field current density distribution within the FRs. 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.

  In the case of 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 observations is of vital priority in this regard. Moreover, tracking and understanding the continuous evolution of solar FRs in the interplanetary medium as they propagate towards Earth, requires L4/L5 remote sensing instrumentation with improved detection capabilities (e.g. Bemporad, 2021).

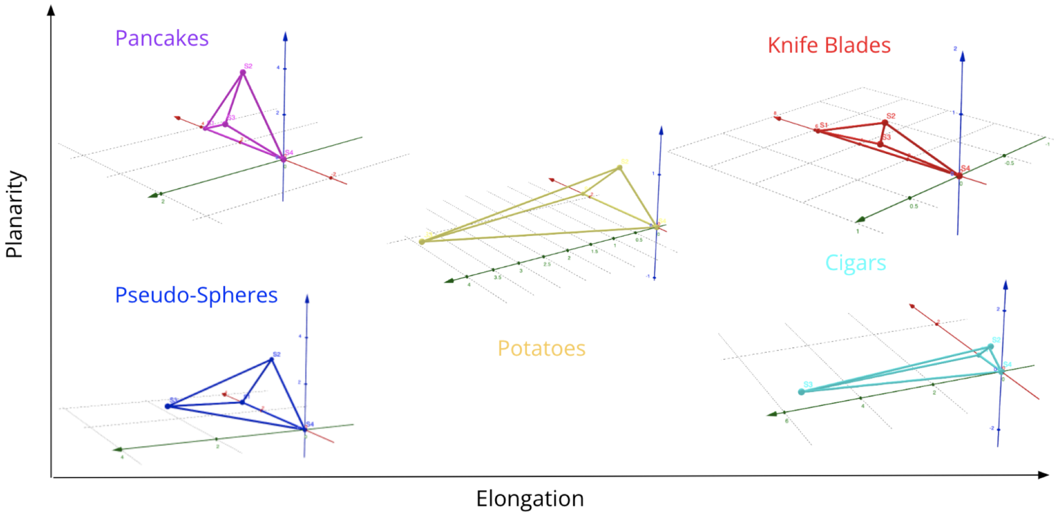

Figure 2. Exploring the efficiency of the curl-meter technique using five different types of tetrahedra as a function of elongation and planarity. According to Ayora Mexia (2022), the pseudo-sphere is the best constellation formation to obtain the internal current density distribution within a FR.

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 in turn may lead us to uncover their origin. Multi-point observations will help in validating the model results meant for reconstructing complex FR structures and thereby leading to improvements in the models.

- **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 remote-sensing and in-situ 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 instrumental focus. As mentioned above one of the pending tasks in the Heliophysics community is to integrate the current observations into a single meta-data base enabling the focus on the scientific problem without the burden of the inter-calibration of instrumentation. **Efforts in this direction has been made by the community, see for instance `https://parker.gsfc.nasa.gov/icme_lists.html` or `http://fluxrope.info/`, where the first link attempts to provide a catalog of events and reconstructions based on a circular-cylindrical (CC) and elliptical-cylindrical (EC) model (see Nieves-Chinchilla et al., 2016; Nieves-Chinchilla et al., 2018). The last link systematically collects the small FRs observed in by different missions using an automatic method based on the Grad-Shafranov reconstruction technique (see Hu and Sonnerup, 2002; Hu et al., 2018; Hu, 2021; Hu et al., 2022, for more information)** The next step will be the development of visualization tools that will allow tackling the multidimensional problem and connecting with modeling in an integrated fashion. Working in this direction may be also connected with artificial intelligence techniques.
- **Artificial Intelligence and Machine Learning**
  There has been a recent increase in machine learning applications in space weather, with the community identifying three key usages (Camporeale et al., 2018): (i) automatically identifying events/features that are traditionally time-consuming and error-prone via manual selection; (ii) methods to study

causality and cluster similar events with the aim of deepening our physical understanding; and (iii) 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 FRs, we should continue the work to leverage the combination of machine learning techniques with both measured data and synthetic 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 of FRs, while also validating physics-based models. Using a convolutional neural network, dos Santos et al. (2020) created a binary classifier that learned to predict if a FR 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 FRs. Nguyen et al. (2018) have explored machine learning techniques for automated identification of CMEs in situ and Reiss et al. (2021) used machine learning to predict the minimum Bz value as a FR was sweeping past a spacecraft. This recent research demonstrates the potential for an integrated machine learning workflow to autonomously identify and classify FR 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 FR morphology and internal distribution of the plasma and magnetic field (see examples in 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 FR interaction with the space environment. We recommend developing specific programs that support this goal including long-term studies to develop FR models and fundamental investigations to analyze the effects of evolutionary processes from the theoretical perspective. We also recommend the coordination with laboratory plasma physics to test advances in the laboratory (see e.g. Gekelman et al., 2020; Zweibel and Yamada, 2016)

As a final remark, we emphasize that improving our understanding of heliospheric FRs using technologies and modeling techniques would not only have an impact on fundamental physics understanding and on deep-space exploration, but also result in a significant societal benefit by enhancing the predictability of adverse space weather conditions.

CONFLICT OF INTEREST STATEMENT

AN and NA were employed by ADNET Systems, Inc. LFGdS was employed by Shell Global Slutions (US) Inc. EP was employed by Predictive Science Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

TNC was responsible for the organization of this article and contributed to all sections. All authors were involved in the preparation of the final manuscript. All authors revised the manuscript before submission. (Nieves-Chinchilla et al., 2022b)

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