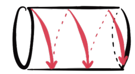
Magnetic flux ropes can become **kink unstable** during their interplanetary journey due to **different factors** and, as a result, start to **rotate.**

Magnetic Flux Ropes (MFRs)

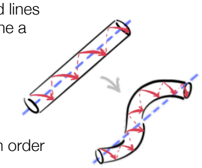
Collections of magnetic field lines wrapped around an internal main axis in a twisting way.



Why study them? MFRs frequently appear in the heliosphere as part of coronal mass ejections (CMEs), large eruptions of magnetized plasma that can severely impact telecommunications and space systems.

Kink Instability

Plasma instability that occurs when the twist of the magnetic field lines in a flux rope exceeds a critical threshold, making the axis become a helix itself.

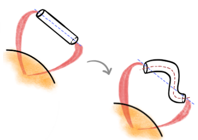


Why study it? The kink instability could be causing rotations of magnetic flux ropes in the heliosphere. Studies show that it can also play an important role during their eruption at the Sun, as well as in laboratory plasmas, where it needs to be avoided in order to allow the fusion reactions to take place.

Rotations

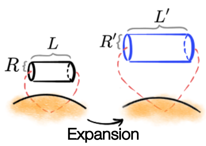
The **accumulation of poloidal magnetic flux** during the first stages of the evolution of a CME could modify the internal twist distribution and physical parameters of the MFR.

If the critical thresholds found through this stability analysis are exceeded, it could drive the onset of kink instabilities, which would be seen as **rotations in the lower-middle corona** in remote sensing coronagraphs.



Expansion

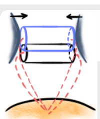
The results for the CC model, and the study of how its parameters change during the MFR evolution, imply that different **expansion regimes** can have a stabilizing or destabilizing effect. More specifically:



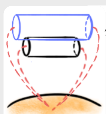
CC model parameters after expansion:

$$\begin{cases} \tau' = \tau \\ \tilde{C}'_{nm} = \frac{L'}{L}\frac{R}{R'}\tilde{C}_{nm} \end{cases}$$

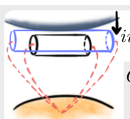
Comparing each mode of expansion with the results of the stability analysis, it is concluded:



$i)\ \frac{L'}{L} < \frac{R'}{R}$; $\tilde{C}'_{nm} < \tilde{C}_{nm}$ — Destabilizing effect



$ii)\ \frac{L'}{L} = \frac{R'}{R}$; $\tilde{C}'_{nm} = \tilde{C}_{nm}$ — No change



$iii)\ \frac{L'}{L} > \frac{R'}{R}$; $\tilde{C}'_{nm} > \tilde{C}_{nm}$ — Stabilizing effect

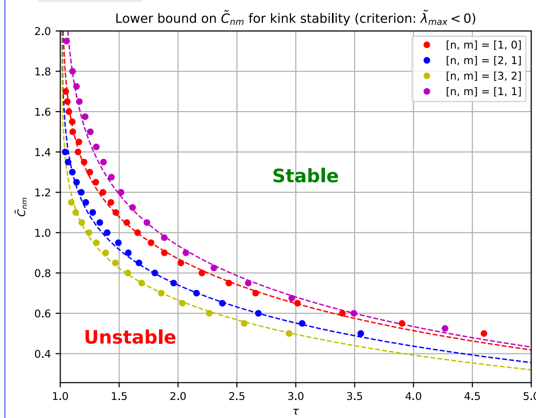
Magnetic Forces

The study of the **misalignment** between the current density and the magnetic field of each MFR model suggests that the distribution of magnetic forces within the structure could have a relevant relation to the onset of the instability, for example:

- MFRs with forces in **opposite directions** within them are less kink stable.
- MFRs with **inward** forces around the **boundary** are more kink stable.

Results

CC model:

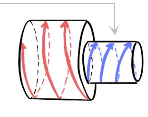


Lundquist model: Stable for $\alpha < \alpha_{crit} = 3.2$

GH model: Stable for $q < q_{crit} = 1.2$

Future Research

- Modify the equations of the numerical method to consider **other boundary conditions** and possible interactions.
- Analyze the stability of other MFR models with **different twist profiles** and magnetic forces distributions, and the full **nonlinear instability evolution**.
- Further study the formation and properties of the kink stable **reversed chirality scenario**, in which there is a change of the field lines chirality.
- Check the conclusions drawn from this analysis with **observational data**, looking for signatures of rotations and studying the possibility of the occurrence of a kink instability as discussed in this work.



Methodology

MFR Cylindrical Models Under Study:

Circular-cylindrical (CC) analytical model

- Parameters $\tau, \tilde{C}_{nm}$
- Nieves-Chinchilla et al. (2016)
- No constraints on forces
- $[n, m] = [1,0], [2,1], [3,2], [1,1]$

$$\begin{cases} B_y = B_y^0\left(1 - \frac{1}{\tau}\bar{r}^{n+1}\right) \\ B_\varphi = \frac{B_y^0}{\tau\tilde{C}_{nm}}\bar{r}^{m+1} \end{cases}$$

Lundquist model

- Parameter α
- Force-free

$$\begin{cases} B_y = B_y^0 J_0(\alpha\bar{r}) \\ B_\varphi = B_y^0 J_1(\alpha\bar{r}) \end{cases}$$

Gold-Hoyle (GH) model

- Parameter q
- Force-free

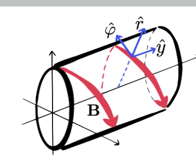
$$\begin{cases} B_y = \frac{B_y^0}{1+q^2\bar{r}^2} \\ B_\varphi = \frac{q\bar{r}B_y^0}{1+q^2\bar{r}^2} \end{cases}$$

- Cylindrical coordinates (r, y, φ) are used
- B_y^0 is the magnetic field magnitude at the axis
- $\bar{r}$ is the normalized radial coordinate
- J_0, J_1 are Bessel functions

Linear Stability Analysis:

Assumptions:

- Cylindrically symmetric magnetic field
- Small displacement perturbation applied to the system
- Linearized equations of motion
- MFR boundary is free to move, no external magnetic field
- Normal mode approach



Equations: (based on Linton et al. (1996))

- **Euler-Lagrange equation:** gives the perturbation that minimizes the energy of the system
- **Free boundary condition:** determines the allowed frequencies of the system evolution over time, for any perturbation with a specific wavenumber (spatial periodicity)

Stability criterion:

The system is kink stable if, and only if, the perturbations that solve the Euler-Lagrange equation and satisfy the boundary condition, do not grow exponentially with time, for any wavenumber.

Kink Stability Code:

A numerical method has been developed in Python to do the linear stability analysis.

- It can be applied to **any** cylindrical MFR model
- It provides the following information:
  - **Critical threshold** of the parameters to develop the instability
  - **Growth rate** of the instability
  - **Shape** of the instability
  - Minimum and maximum **wavenumbers** of the instability

Analysis of the Helical Kink Instability of Differently Twisted Magnetic Flux Ropes

Check out the article for full details:

journal link

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