Numerical Study of X-Ray Jets in Coronal Hole

M. Yamada, E. Belova, J. Latham*,

Princeton Plasma Physics Laboratory, Princeton University
Theory Seminar
February 2, 2021

X-Ray Jets – Anemone Configuration


https://www.britannica.com
Plasma jets with X ray emissions are observed when an inner dome configuration is tilted with respect to outer open field lines.

Spheromak tilt is proposed as an eruption mechanism

A model was proposed in 2019 for “spheromak formation and tilt”
Basic Concept

**A storage and release mechanism for solar flare eruption**

- We consider a dome-shaped magnetic configuration: spheromak
- How does a spheromak which emerges slowly from the sun’s surface suddenly become unstable against an MHD instability?
- The effects of line-tying on an elongated spheromak stability are presented
- We conclude that magnetic reconnection occurs near the top of a half-sphere configuration to generate plasma jets with X-rays
Spheromak tilt: Line-Tying Improves Stability

Spheromak tilt: Oblate v. Prolate

Oblate

Prolate

Tilt unstable

Line-tying should help stabilize tilt mode

Modeling of spheromak line-tied to the sun surface
Calculation by HYM code (E. Belova)
Summary

- We have verified that a spheromak can exist in a stable form with line-tied state to a single conducting surface.
- Marginal amount of line-tying will stabilize spheromak (more line-tying needed for elongated spheromak).
- Magnetic reconnection on bottom of spheromak is necessary to detach flux for spheromak formation and for the tilt.
- In the final stage, magnetic reconnection occurs at the top of inner dome and ejects a plasma jet to the open field.
Numerical Study of Plasma Jets Formation in the Coronal Hole

E. Belova, M. Yamada (PPPL), J. Latham* (University of Michigan)

*Latham et al, Physics of Plasmas 28, 012901 (2021); https://doi.org/10.1063/5.0025136
Anemone jets are explained by magnetic reconnection

- X-ray anemone jet is a coronal jet, ejected from an “anemone-type” active region.
- Both observations and numerical simulations indicate that the eruptions leading to the generation of X-ray jets results from magnetic reconnection in the corona.
- Magnetic structure can be stable to a long time before the eruption. Mechanism leading to eruption/reconnection is unknown.
- Several possible scenarios had been studied in numerical simulations:
  - Flux emergence and reconnection,
  - Plasma footprint motion.

Coronal jets parameters: \( L \sim 10^4 - 10^5 \text{km}, \) \( V \sim V_A \sim 300 \text{ km/s}, \) life-time \( \sim 10 - 100 \ t_A \)
Flux emergence/reconnection scenario

Yokoyma and Shibata [PASJ 1996] (2D simulations of coronal jets)

- Flux emergence is due to magnetic buoyancy instability (Parker instability) [Parker 1966].
- Flux emergence and reconnection can lead to an anemone shape at footpoint of the x-ray jet.
- Issues: continuous reconnection; 2D picture - does not produce circular pattern in 3D?
Foot-print circular motion mechanism

- Simulations start with ‘flux emergence’—like 2D configuration.
- Due to circular motion at the base, magnetic field lines twist leading to kinking and the reconnection.
- This mechanism does produce magnetic configuration similar to the dome-shaped (anemone) configuration, but several full rotations are needed to drive the reconnection—not very realistic.

Meyer et al. ApJ 2019 (0.6 and 4 full rotations at the base)
Can anemone magnetic structure be a spheromak?

- Confined plasma can relax into Taylor-state spheromak with \( \nabla \times \mathbf{B} = \lambda \mathbf{B} \) – is that relevant for astrophysics/solar physics?
- Unconfined spheromak will expand indefinitely in the absence of external field.
- In the ambient magnetic field, spheromak will be unstable to tilt instability. It will tilt (on few \( t_A \) time scale) and reconnect.
  - Tilt instability occurs because the magnetic moment of a spheromak is anti-aligned with an external magnetic field.
- Tilt instability can be reduced by line-tying [Finn, Reiman, PF1982; Hooper, Phys. Plasma 2009]. Can it be stabilized by line-tying alone?

Tilt stabilization by line-tying

- 3D MHD simulations used to study the $n=1$ tilt mode for a spheromak line-tied to a conducting surface.
- Initial conditions: low $\beta$ ($\sim 0.02$) GS solution with $RB_\varphi \sim \psi^\sigma$
- Stability depends mostly on two parameters:
  - elongation $\varepsilon = L/R$ (changed by changing $\sigma$),
  - fraction of line-tied internal flux $\chi = \psi_{\text{tied}}/\psi_0$.
- For stabilization conducting surface needs to be placed very close to spheromak crossing the separatrix.
- Stability thresholds are found using linearized simulations using HYM code.
Larger elongations require stronger line-tying for stability

- Simulation box size was increased until the converged results were obtained.
- Spheromak can be stable to tilt if line-tying is sufficiently strong.
- For spheromak with large elongation more line-tying is required for stability:
  - for $\varepsilon = L/R \leq 2$, $\chi^* \approx 0.15-0.2$,
  - for $\varepsilon = 2.75$, $\chi^* \approx 0.8$.
- Results are consistent with previous studies of spheromak stability [Finn PF 1981; Bondeson PF 1981; Finn PF1982; Hooper, PoP 2009].

Growth rate of the n=1 tilt mode vs line-tying parameter, $\chi$, for spheromaks with 4 different elongations [Latham et al. PoP 2021].
Tilt stability – elongation vs line-tying

- Spheromak can remain stable due to line tying to the conducting surface (solar surface) until the increase of spheromak elongation and/or reduction of the fraction of its line-tied flux will make it unstable to the tilt instability.
- Elongation can increase due to flux emergence, but that would change line-tied fraction.
- Approximate relation between $\chi$ and $\varepsilon$ as spheromak grows through line-tied flux injection can be obtained: $\chi(\varepsilon) = 1 - a/\varepsilon$ (a=const).
- Another possibility for crossing the stability threshold is the reduction of line-tying (through reconnection on the bottom).

Line-tying stability threshold, $\chi^*$, vs elongation (red). Relation $\chi(\varepsilon) = 1 - a/\varepsilon$ is shown in blue. [Latham et al. PoP 2021]
Nonlinear evolution of the tilt leads to top reconnection

- Nonlinear simulations of tilt unstable spheromak show formation of current sheet at the top, where magnetic field of tilted spheromak opposes the background magnetic field.
- Left half of the spheromak, which tilts upwards, flows into the current sheet and forces the reconnection.
- Two models of resistivity were used: 1) uniform with $S \sim 10^4$, and 2) anomalous resistivity model as in [Yokoyama PASJ 1996; Sato and Hayashi PF 1979].

Contour plots of toroidal current and vector plots of (a) magnetic field and (b) velocity at different times. Tilting motion is clockwise.
Tilting motion pushes spheromak field vs external field

Contour plots of toroidal current and vector plots of (a) magnetic field and (b) velocity. Tilting motion is clockwise. Solar surface is modelled as a dense cold plasma with n = 10^3 \( n_{\text{corona}} \).
Later stages of instability show outflows with $v \sim v_A$

Vector plots of plasma flow; lines are integrated ($B_z$, $B_R$) streamlines. Tilting motion is clockwise. Contour plot of velocity normalized to $V_A$ show outflow velocities up to $V \approx V_A$. 

0.0  4.4E-01  8.8E-01  1.3E+0
Summary

• It has been demonstrated that a spheromak can exist in a stable form when line-tied to a single conducting surface (solar surface).

• Marginal amount of line-tying will stabilize the tilt instability in an oblate spheromak (more line-tying needed for very elongated spheromak).

• Stable spheromak can be destabilized due to 1) elongation, 2) flux emergence or 3) reduction of line-tying (flux detachment via reconnection at the bottom).

• In the tilt unstable spheromak, magnetic reconnection occurs at the top of dome leading to ejection of a plasma jet.