

Research Updates

Maitri

Objective:

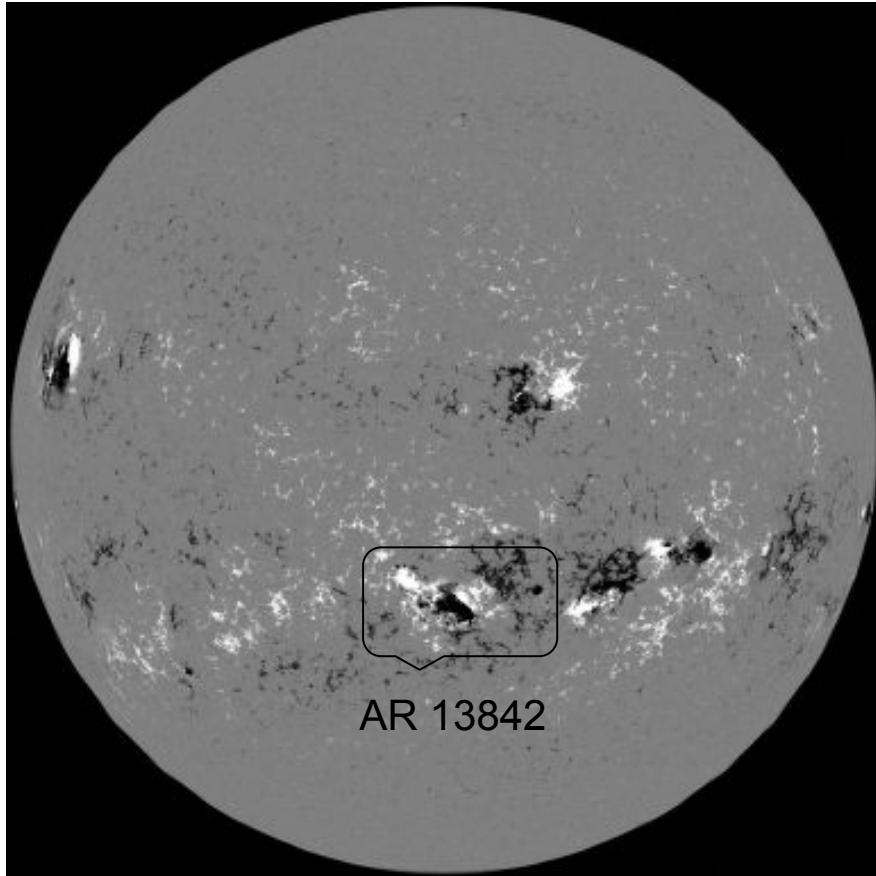
- Analyze the critical conditions that led to the X9.0 flare on Oct 3, 2024.

Methodology:

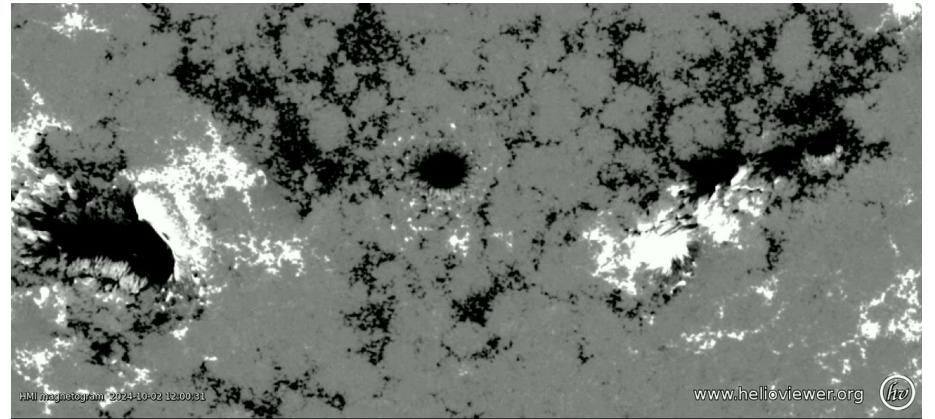
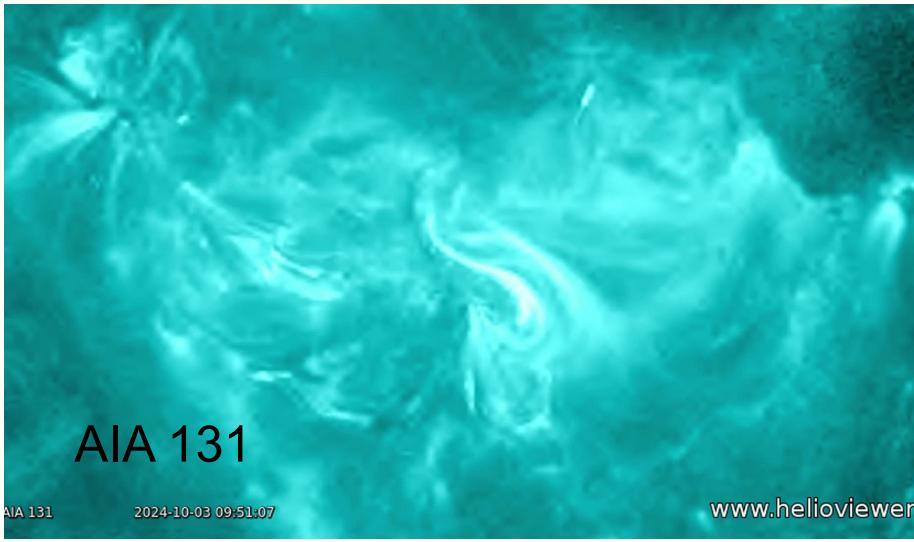
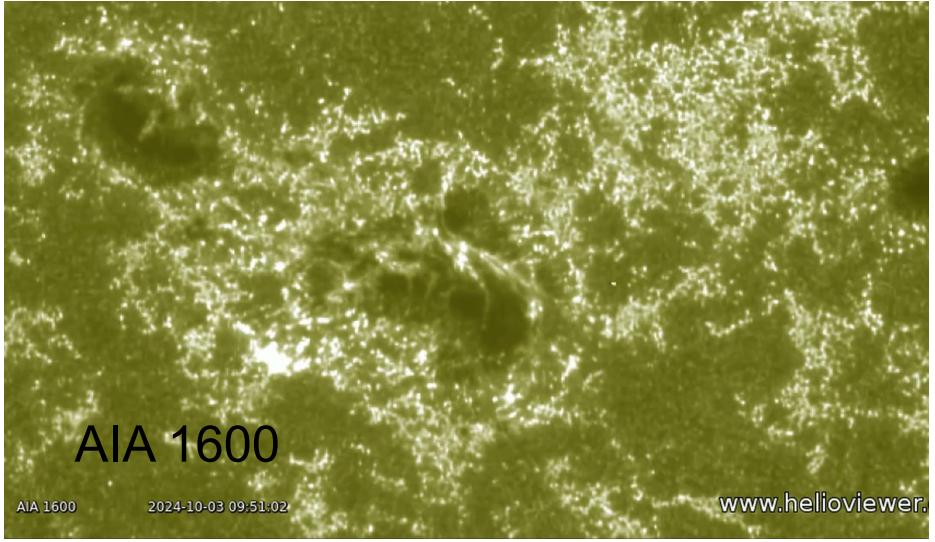
- Generate multiple NLFFF using HMI data at different times.
- Compare these NLFFF in terms of the decay index and magnetic twist number.
- Run MHD simulations to check if an eruption occurs using NLFFF as the initial condition.
- Identify key differences through NLFFF and MHD simulations.

Expected Outcome:

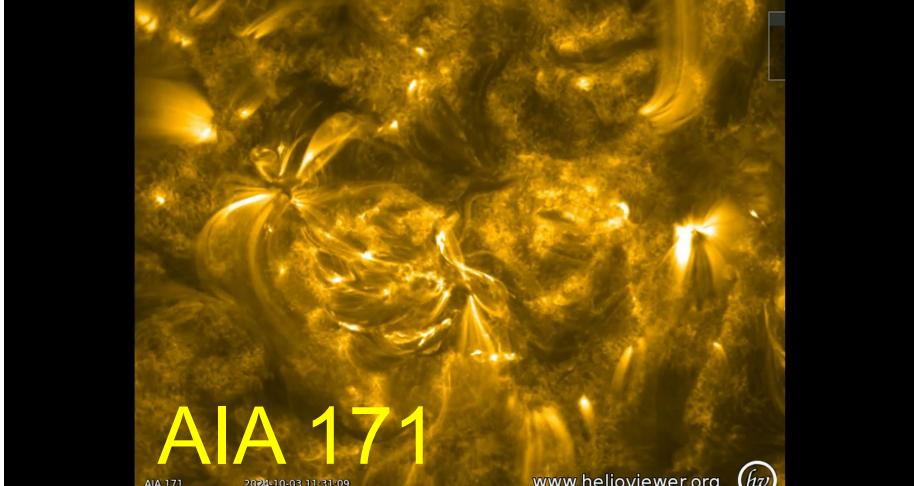
- Identify the critical physical conditions responsible for X9.0 flare initiation.



AR : 13842
Flare: 3 october 2024
Start: 12:08 UTC
End: 12:27 UTC

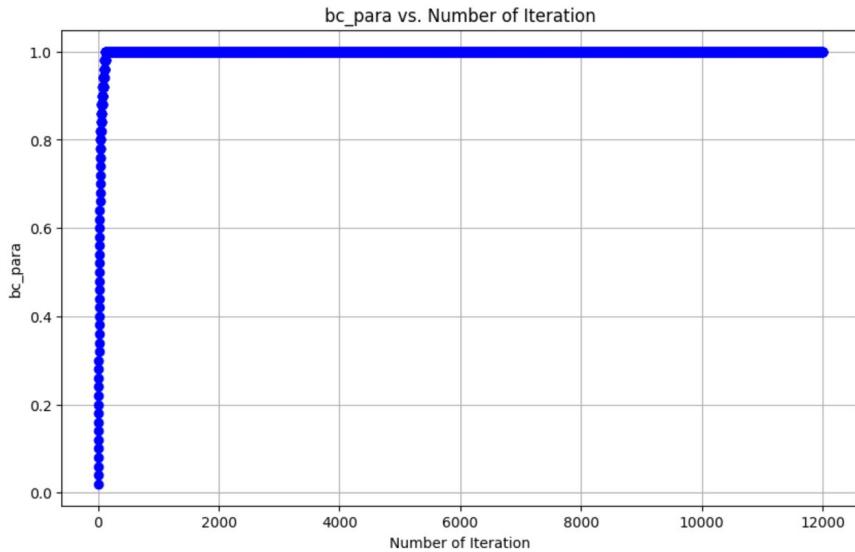


HMI Magnetogram



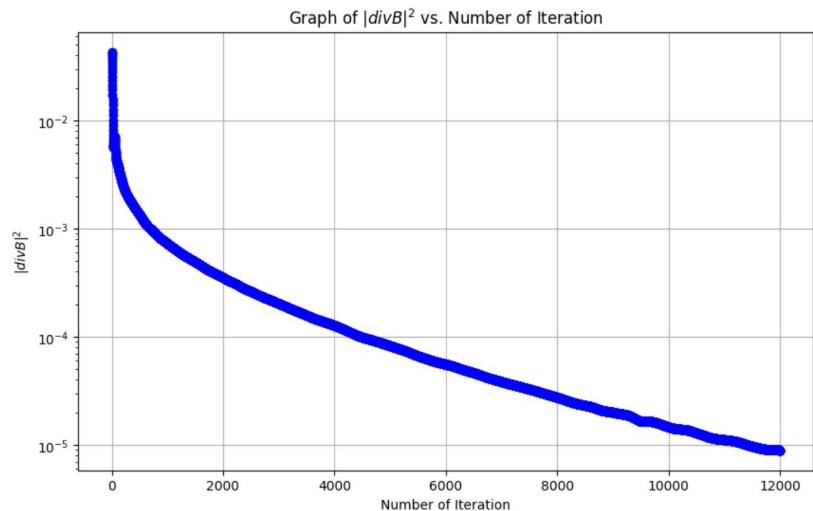
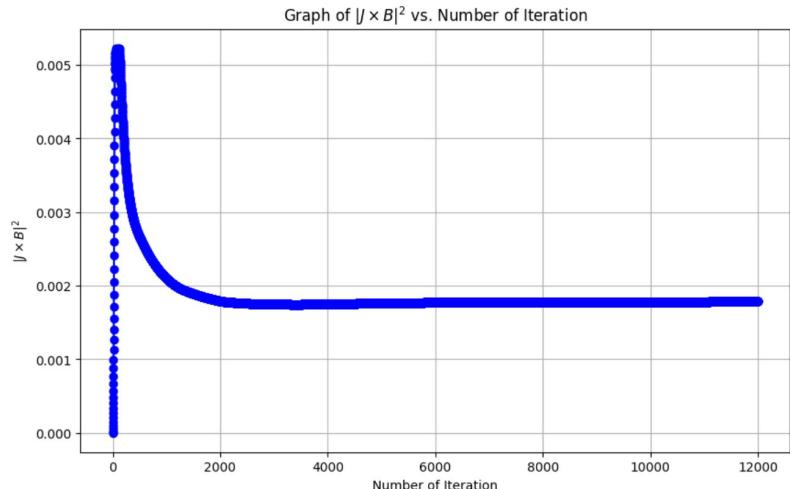
Plots for Lorentz force, divB and Gamma

For 2 Oct 10:36 –



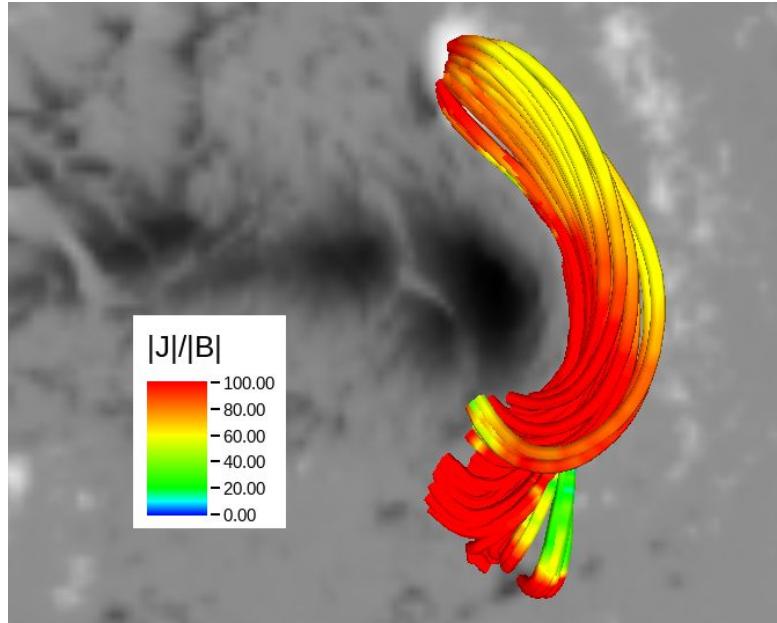
$$B_{bc} = \zeta B_{obs} + (1-\zeta)B_{pot}$$

ζ is Gamma coefficient, $0 < \zeta < 1$

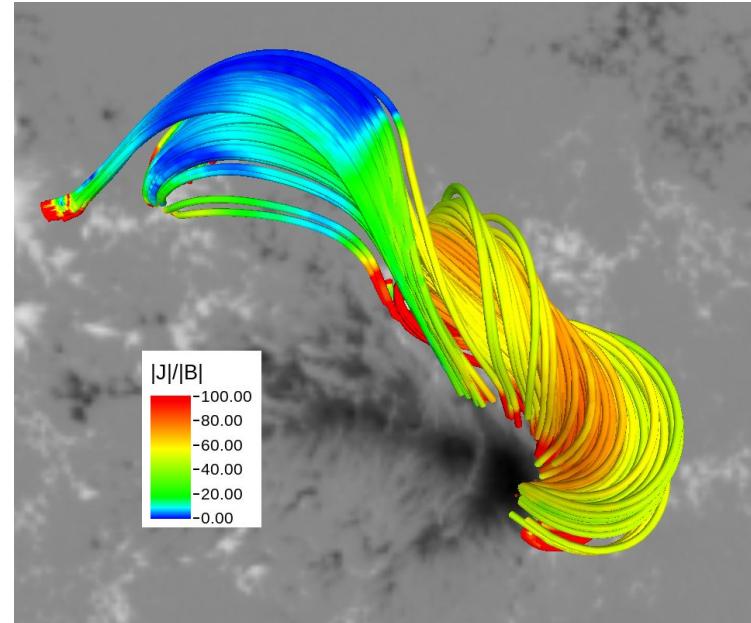


Visualization of $|J|/|B|$

**NLFFF on 2oct 10:36 UT
(26 hours before)**



**NLFFF on 3oct 10:48 UT
(1.5 hours before)**



Why NLFFF extrapolation ?

We Can't Directly Observe Coronal Fields

- Even the most advanced solar satellites cannot directly observe the 3D magnetic field in the corona.
- They provide only vector magnetic field data (B_x, B_y, B_z) on the photosphere (the Sun's surface).
- So, we must extrapolate the coronal field using a numerical models based on these surface measurements.

The Force-Free Approximation

Since the plasma beta ($\beta = \text{gas pressure, gravity} / \text{magnetic pressure}$) in the corona is very low ($\approx 0.1\text{--}0.01$), magnetic forces dominate over pressure forces.

This allows us to use the force-free field approximation ; $\nabla \times \mathbf{B} = \alpha(r) \mathbf{B}$ and $\mathbf{B} \cdot \nabla \alpha(r) = 0$

1. Potential field: $\alpha = 0 \rightarrow$ No currents, minimum energy state.
2. Linear force-free field (LFFF): constant $\alpha \rightarrow$ Slightly higher energy
3. Nonlinear force-free field (NLFFF): α varies with position

Potential field as an initial condition for NLFFF calculation

- The NLFFF equation is nonlinear, meaning small errors can blow up fast.
- The potential field is easy to calculate, uniquely defined, and always **divergence-free ($\nabla \cdot \mathbf{B} = 0$)**.
- Potential field extrapolated from the normal component (B_z) of the magnetic field on all the boundaries, which is used as an initial condition in the NLFFF calculation.

Zero Beta MHD equations:

$$\rho = |\mathbf{B}|,$$

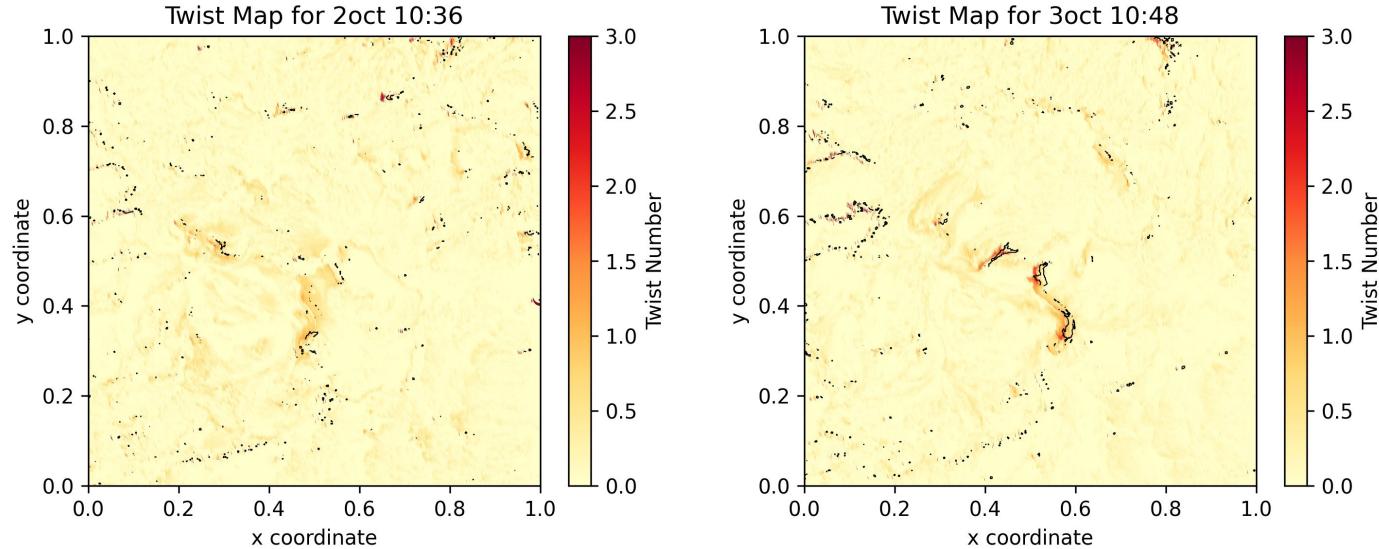
$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v} \cdot \nabla) \mathbf{v} + \frac{1}{\rho} \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{v},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} - \nabla \phi,$$

$$\mathbf{J} = \nabla \times \mathbf{B},$$

$$\frac{\partial \phi}{\partial t} + c_h^2 \nabla \cdot \mathbf{B} = -\frac{c_h^2}{c_p^2} \phi,$$

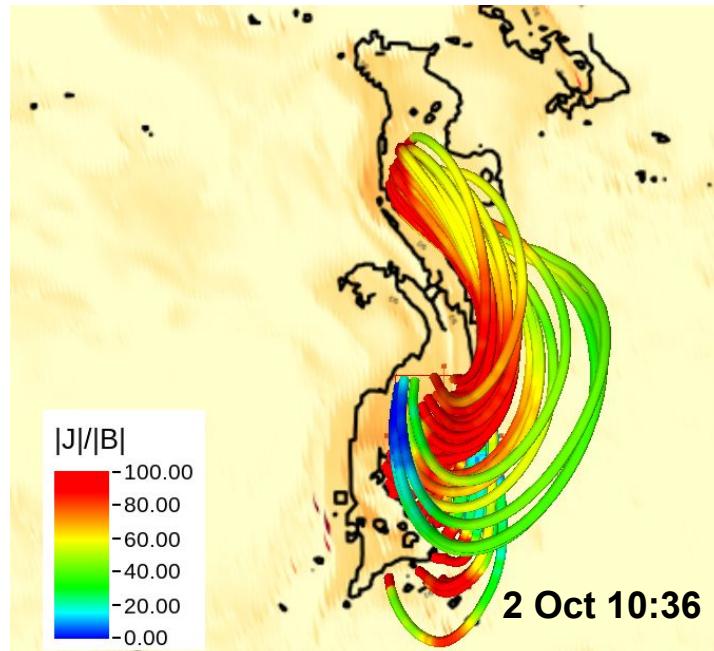
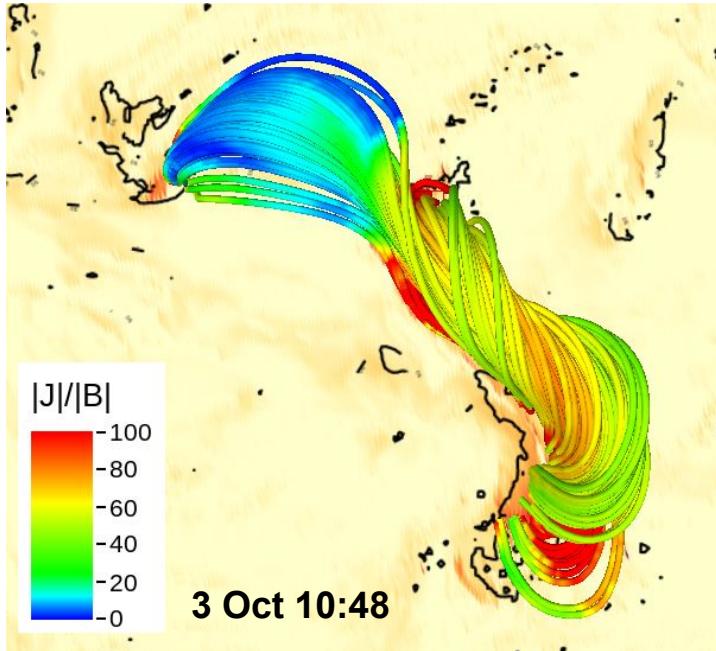
Twist Map:



- To assess the non-potentiality of NLFFF in pre-flare state, I calculate the twist of magnetic field lines.

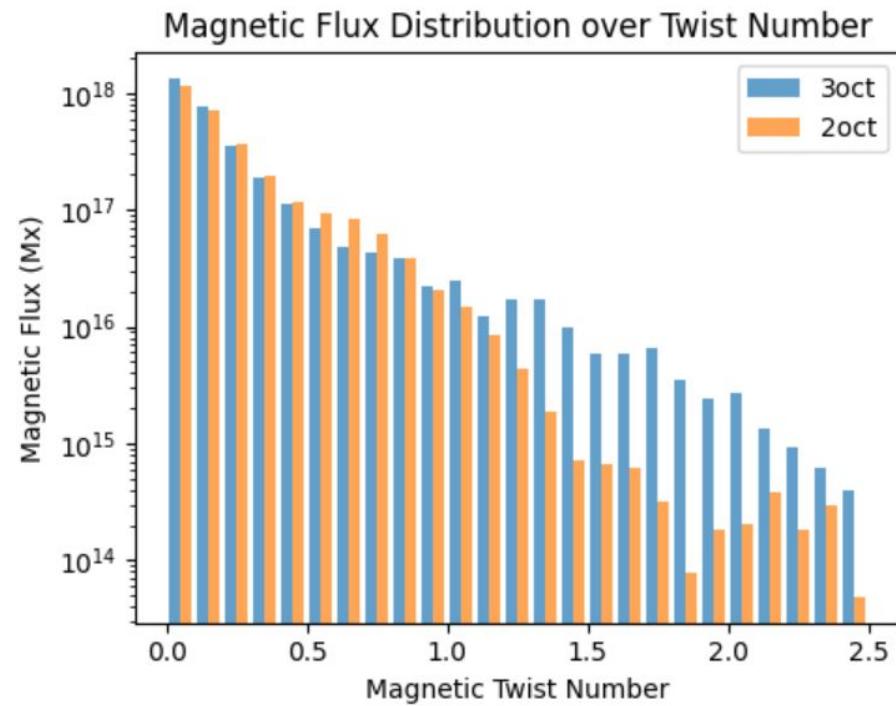
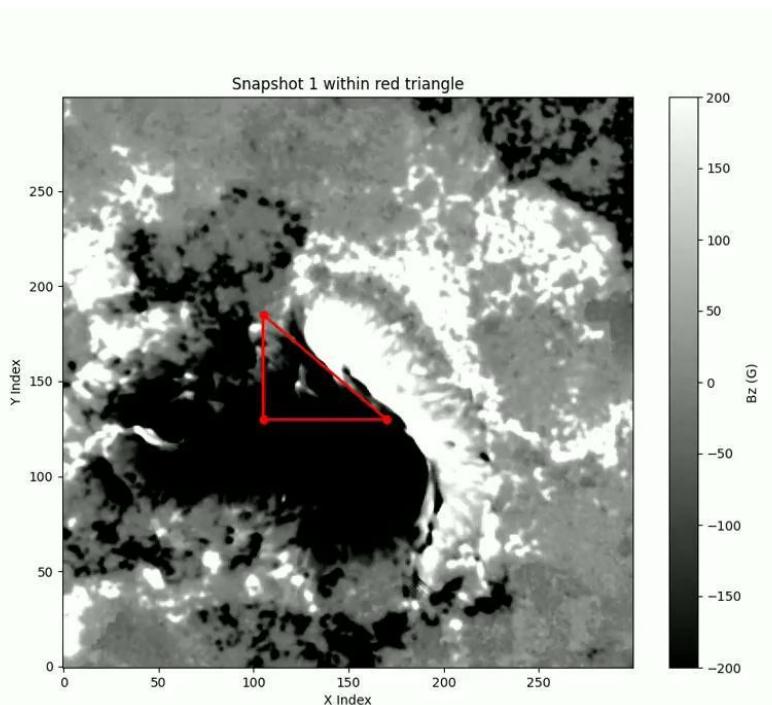
$$T_w = \frac{1}{4\pi} \int \frac{\mathbf{J} \cdot \mathbf{B}}{|\mathbf{B}|^2} dl,$$

- Tw represents the local twisting between two infinitesimally close field lines.
- Higher twist indicates stronger current, energy and more twisted, stressed field lines.
- Positive helicity is predominant in the active region.



- Field lines in NLFFF where $T_w > 0.5$.
- The S-shaped sigmoidal structure indicates a dominant positive helicity.

Flux emergence for 3oct 00UT-12:48UT



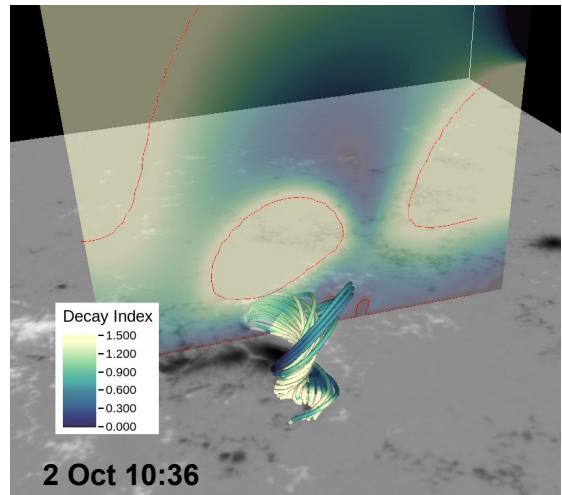
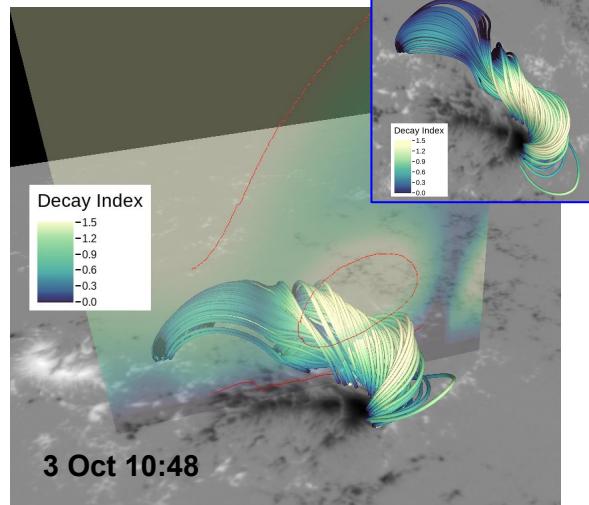
Decay Index

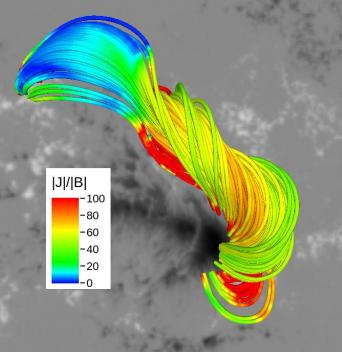
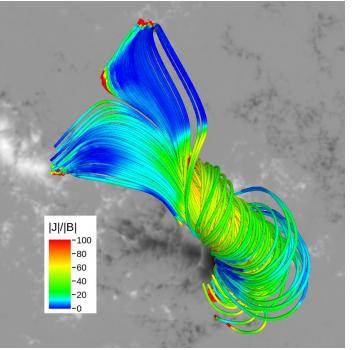
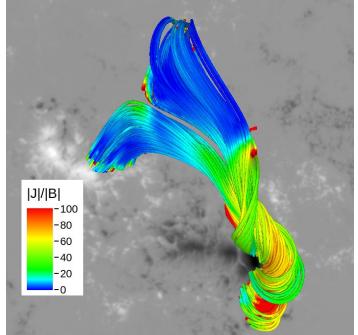
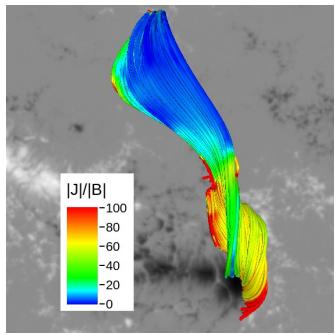
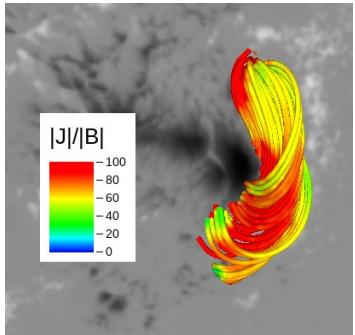
- I calculated the decay index to discuss the stability of the Torus Instability.

$$n = -\frac{d \ln |\mathbf{B}_{\text{ex}}|}{d \ln z}$$

- The figure(3oct 10:48) shows that the top of the twisted field lines have reached a critical height of the TI; $n=1.5$.
- If \mathbf{B}_{ex} weakens too fast with height, it can't hold the MFR down, and an eruption can happen. → Torus Instability.

● **Next Goal:** To fully understand the stability and critical condition, I will conduct the MHD simulation that can capture the time evolution of the magnetic field from flare initiation to eruption.





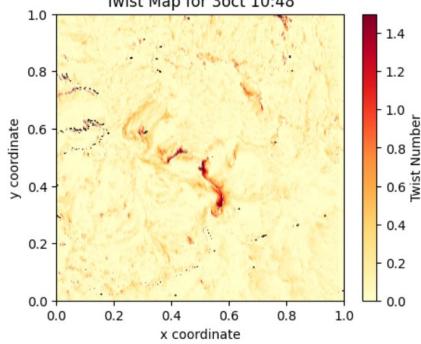
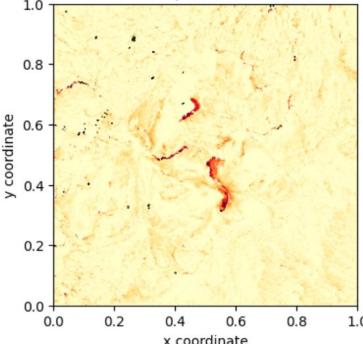
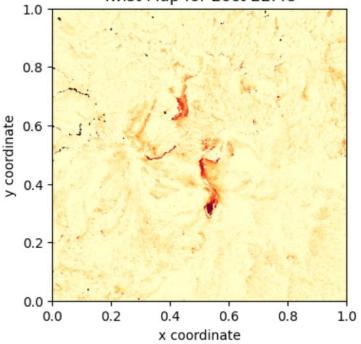
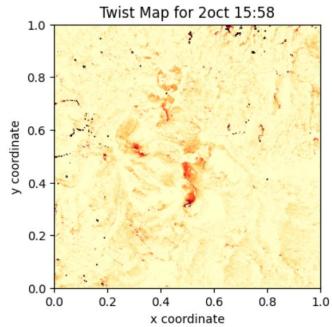
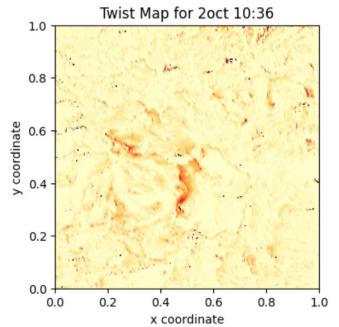
NLFFF on 20ct 10:36 UT
(26 hours before)

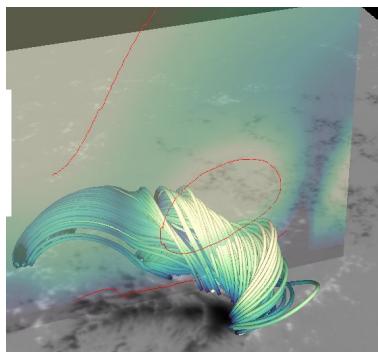
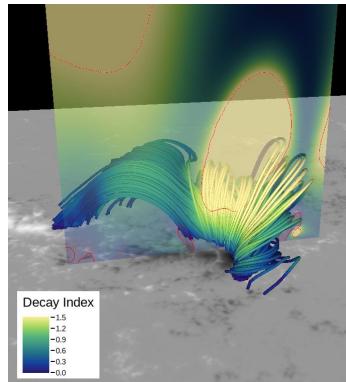
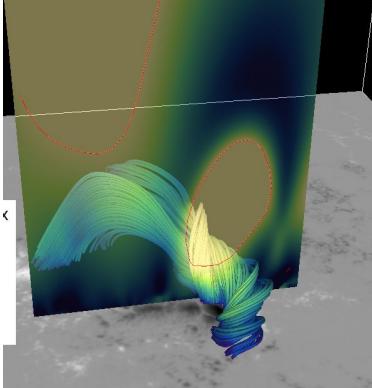
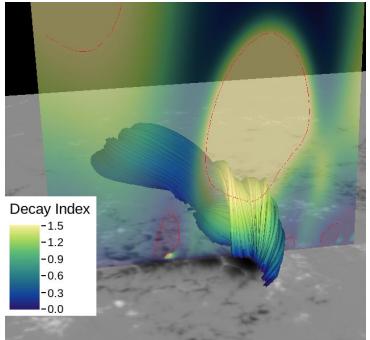
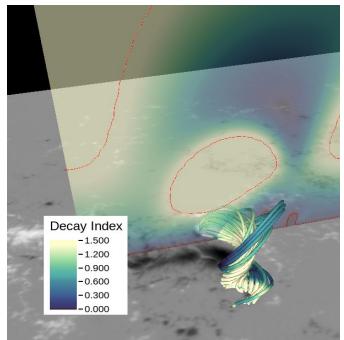
NLFFF on 20ct 15:58 UT
(19 hours before)

NLFFF on 20ct 22:48 UT
(14 hours before)

NLFFF on 30ct 04:48 UT
(7.5 hours before)

NLFFF on 30ct 10:48 UT
(1.5 hours before)





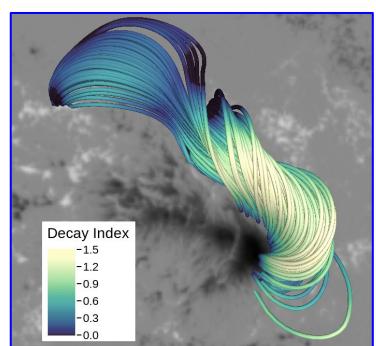
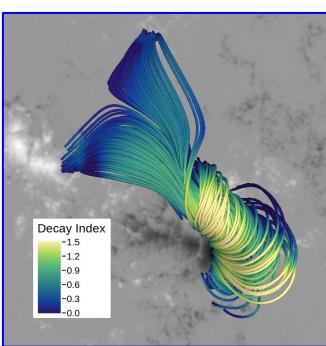
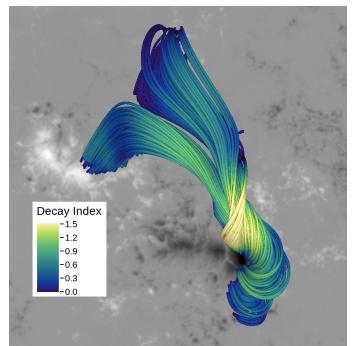
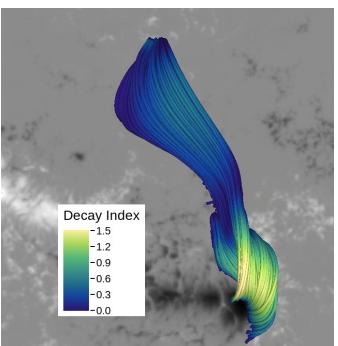
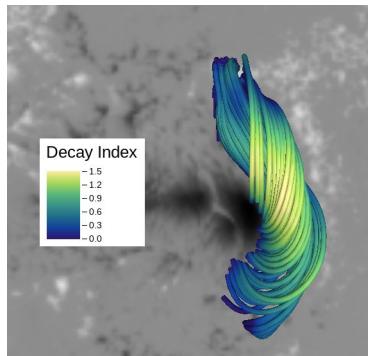
NLFFF on 20ct 10:36 UT
(26 hours before)

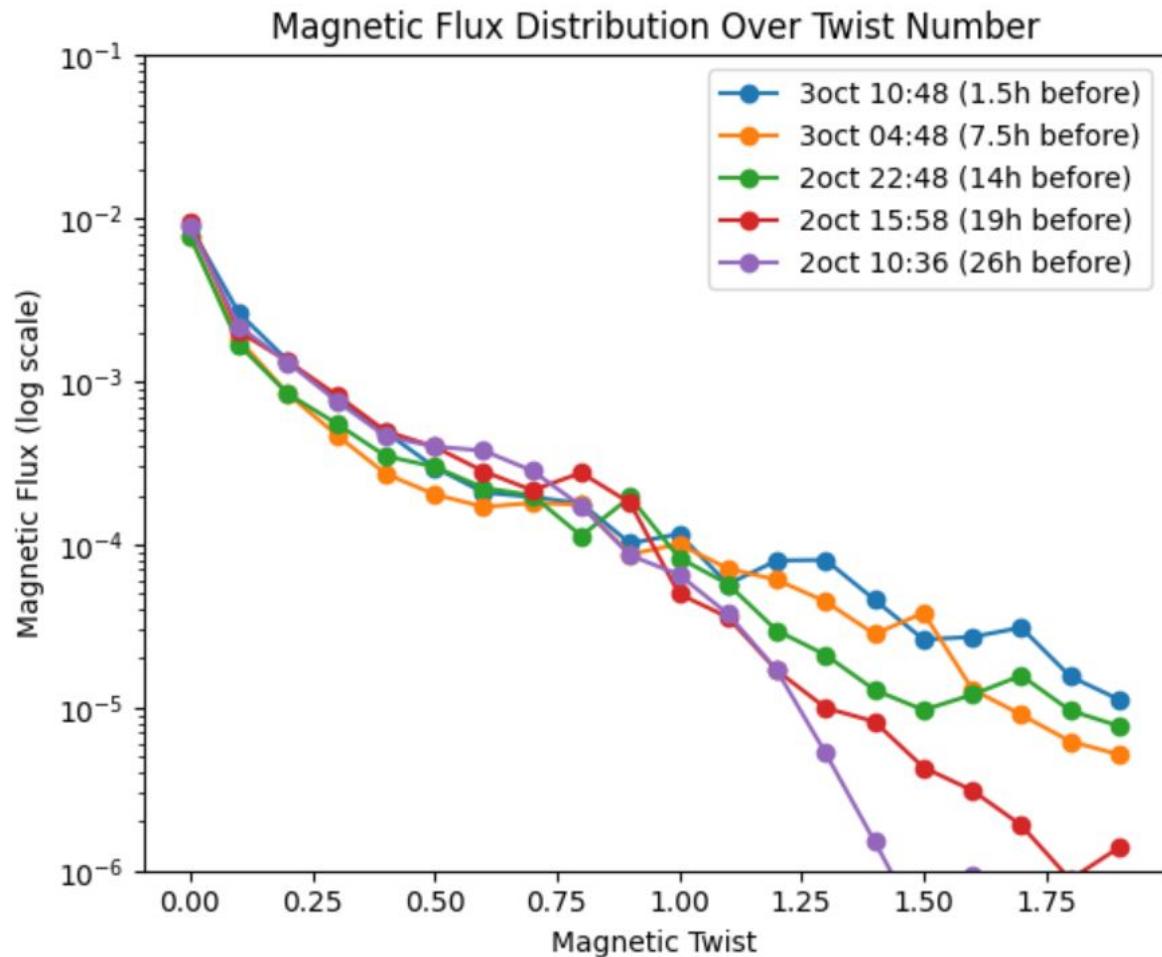
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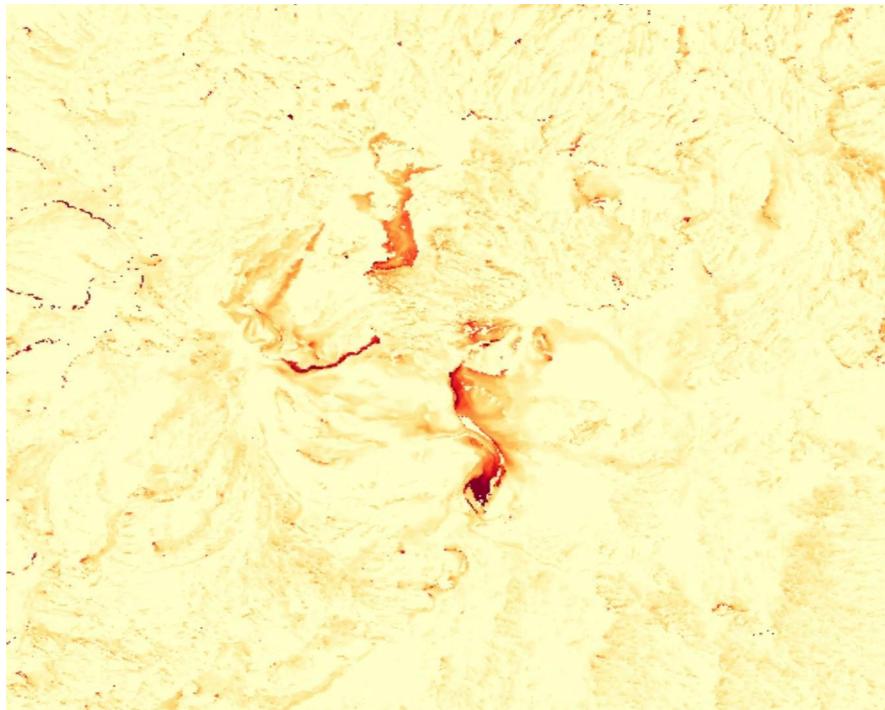
NLFFF on 30ct 04:48 UT
(7.5 hours before)

NLFFF on 30ct 10:48 UT
(1.5 hours before)



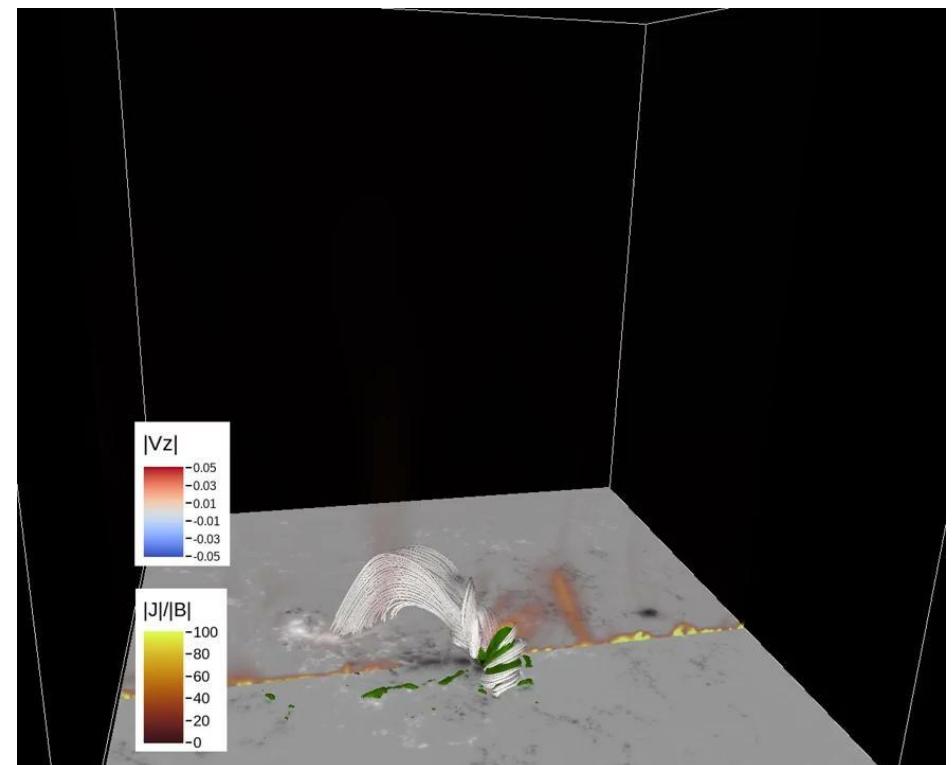


Time evolution of twist - before 14 hours

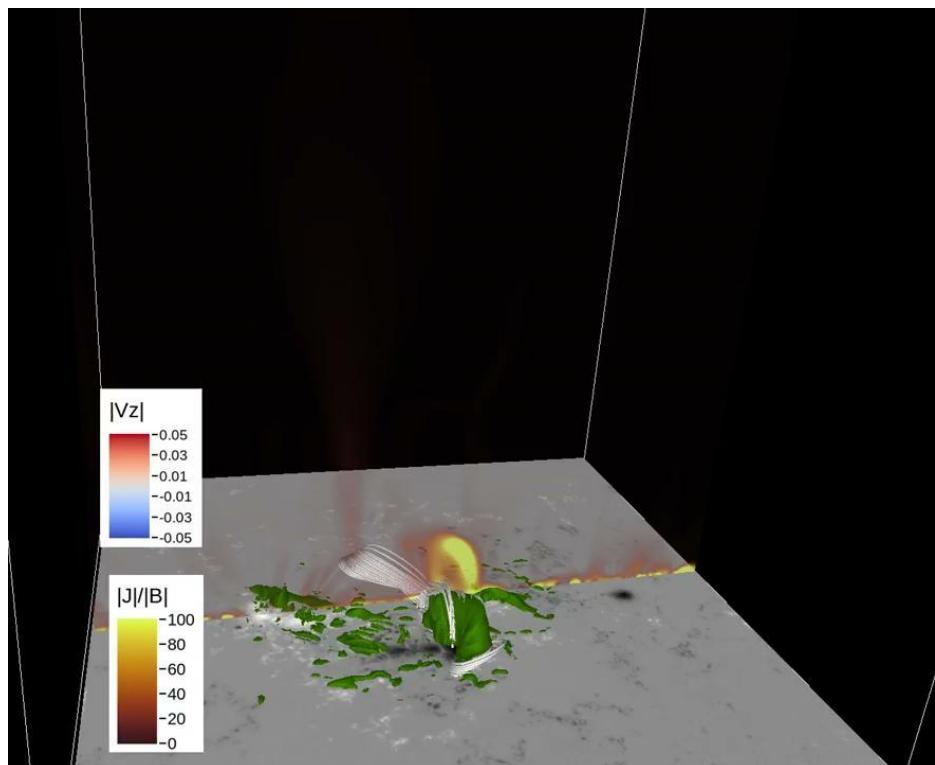


Only field lines from outer-upper region
are shifting to circular ribbon

Simulation 14 hours before

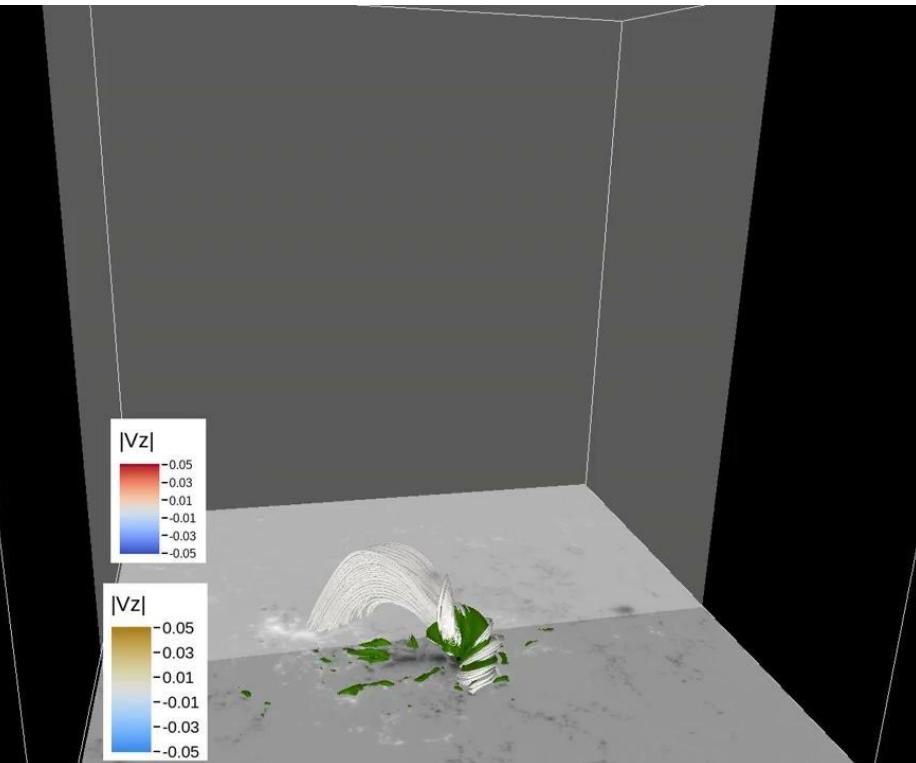


Simulation 19 hours before

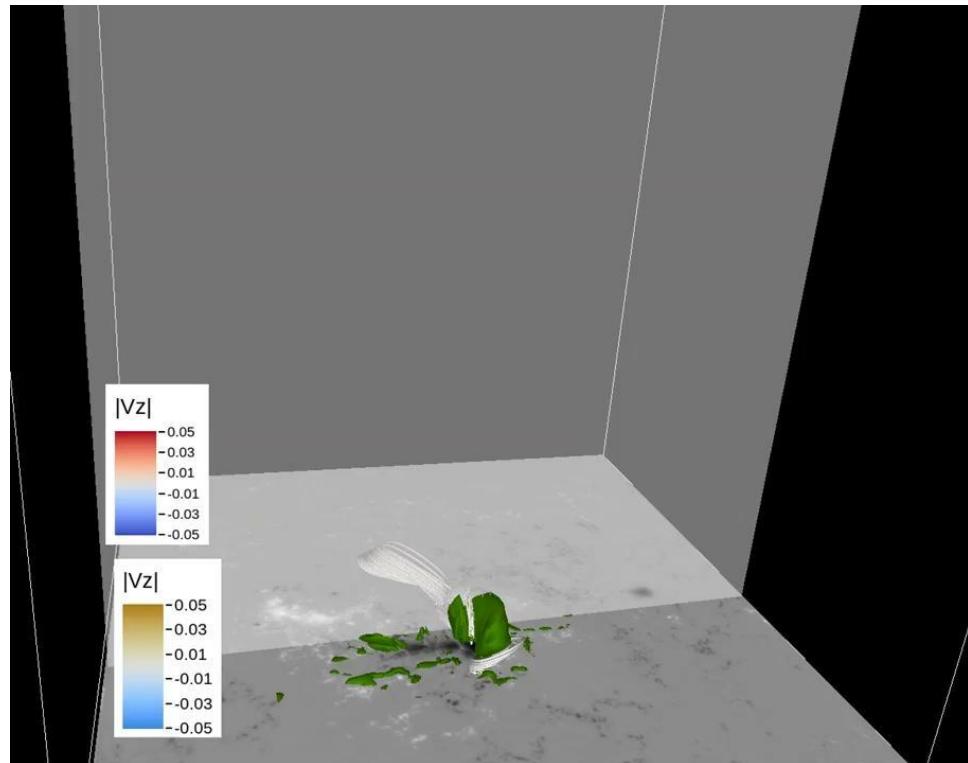


Only field lines from outer-upper region are shifting to circular ribbon

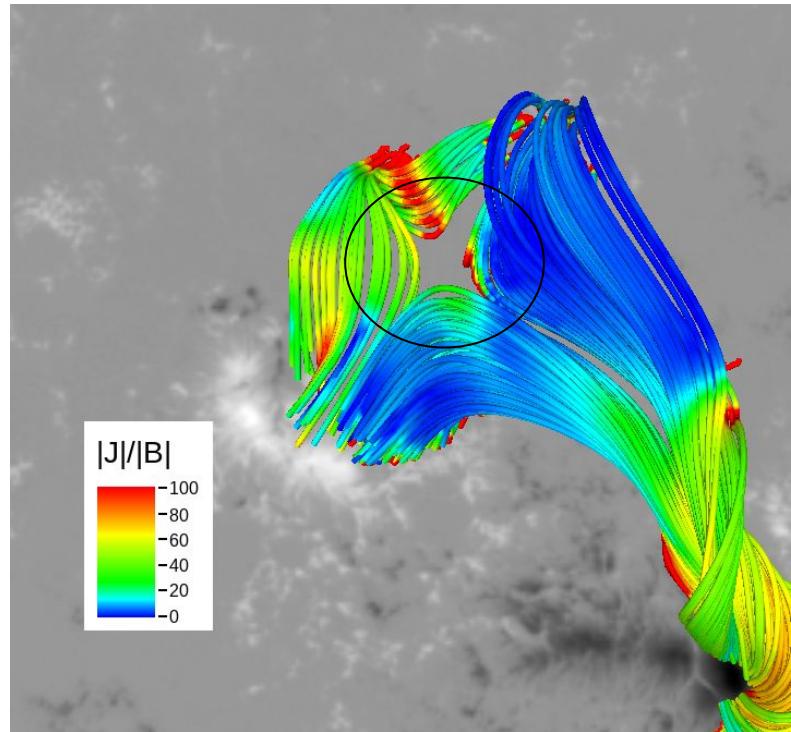
Simulation 14 hours before with Vz slice



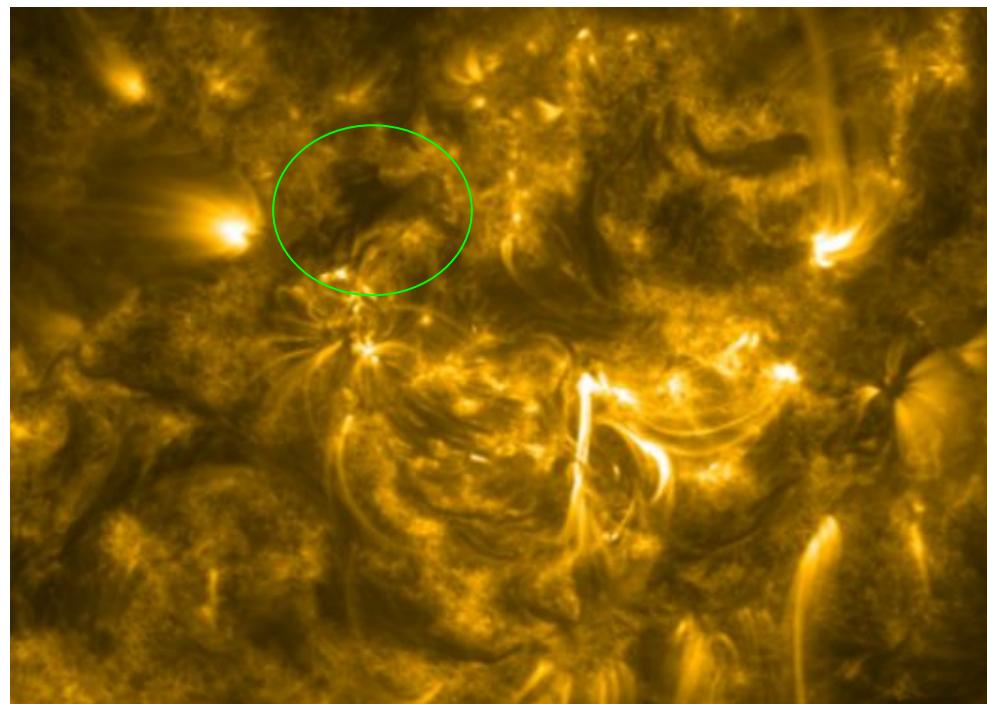
Simulation 19 hours before with Vz slice



Separatrix structure has null point 14 hours before

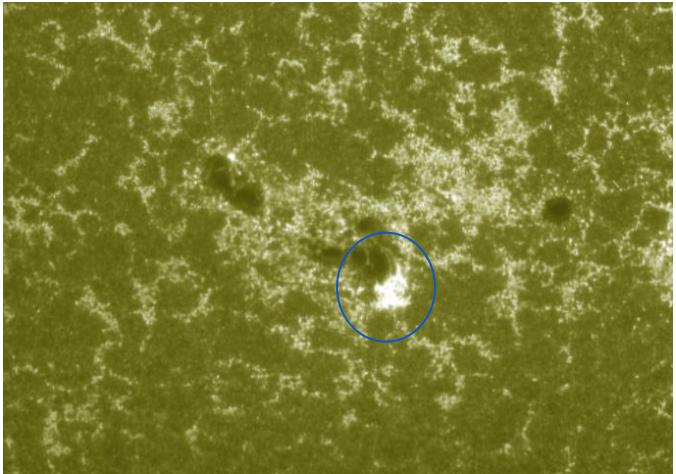


Simulation Result

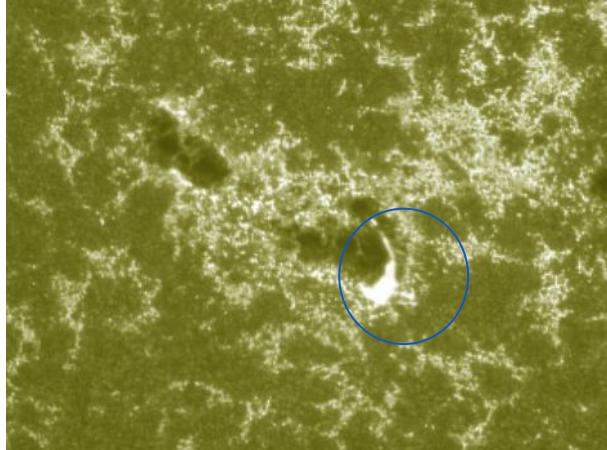


Observational Result

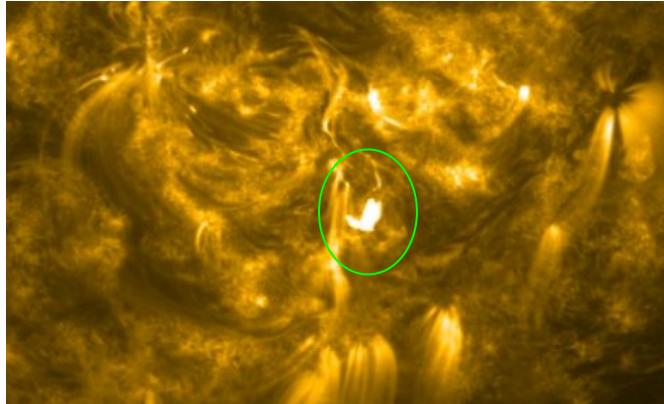
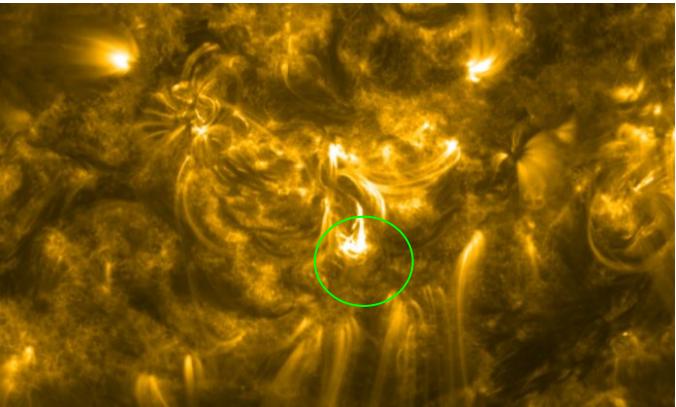
Brightening comparison between AIA 1600 and AIA 131



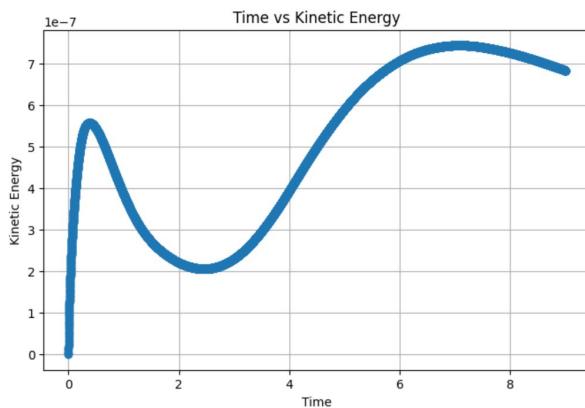
→ 2oct 23:04UT



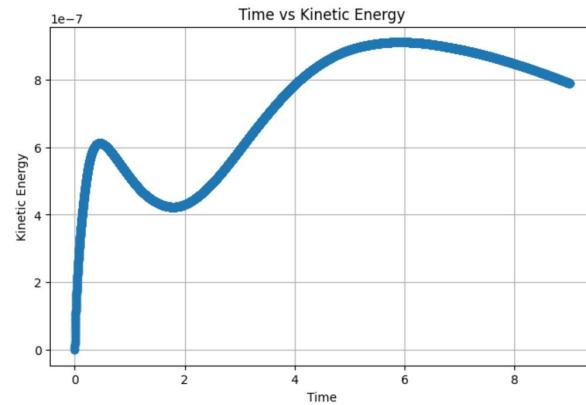
→ 2oct 18:29UT



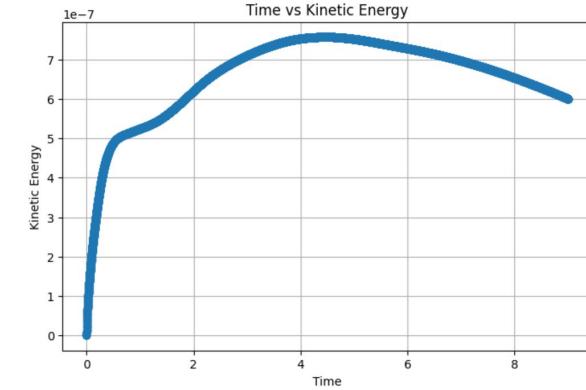
$$v_i = 7.5 \times 10^{-4} \text{ and } \eta_i = 1 \times 10^{-5}$$



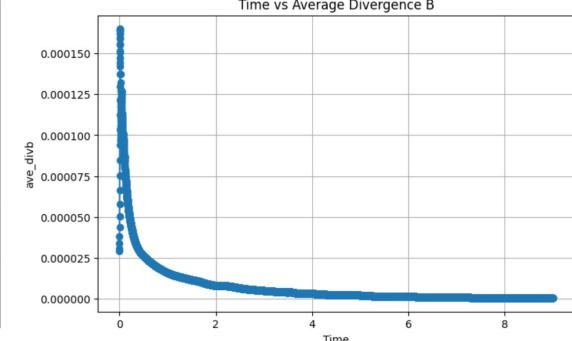
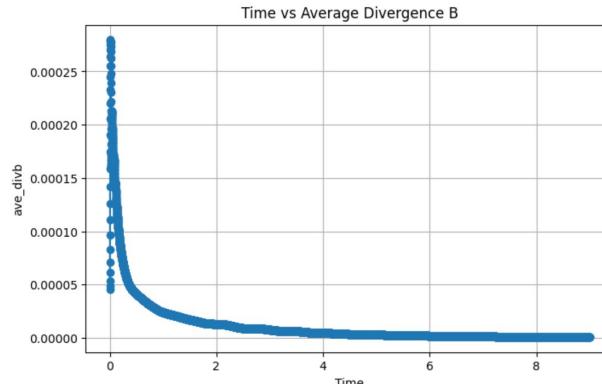
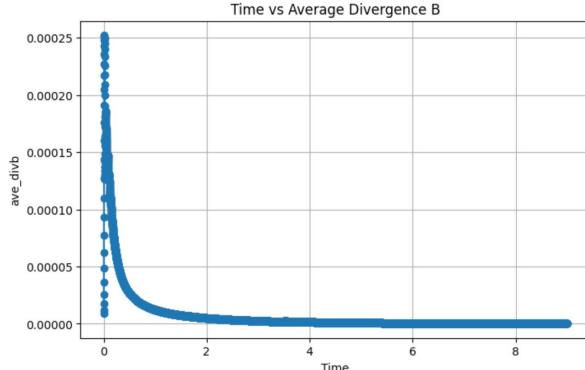
26 hours before

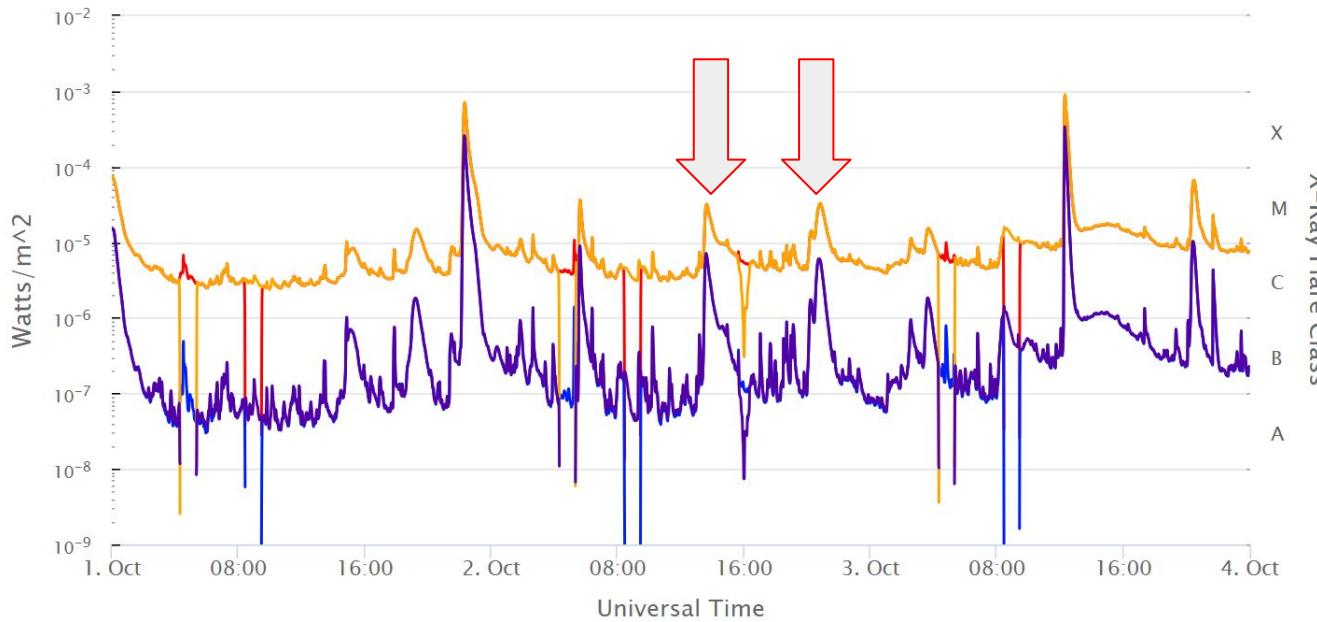


19 hours before



14 hours before



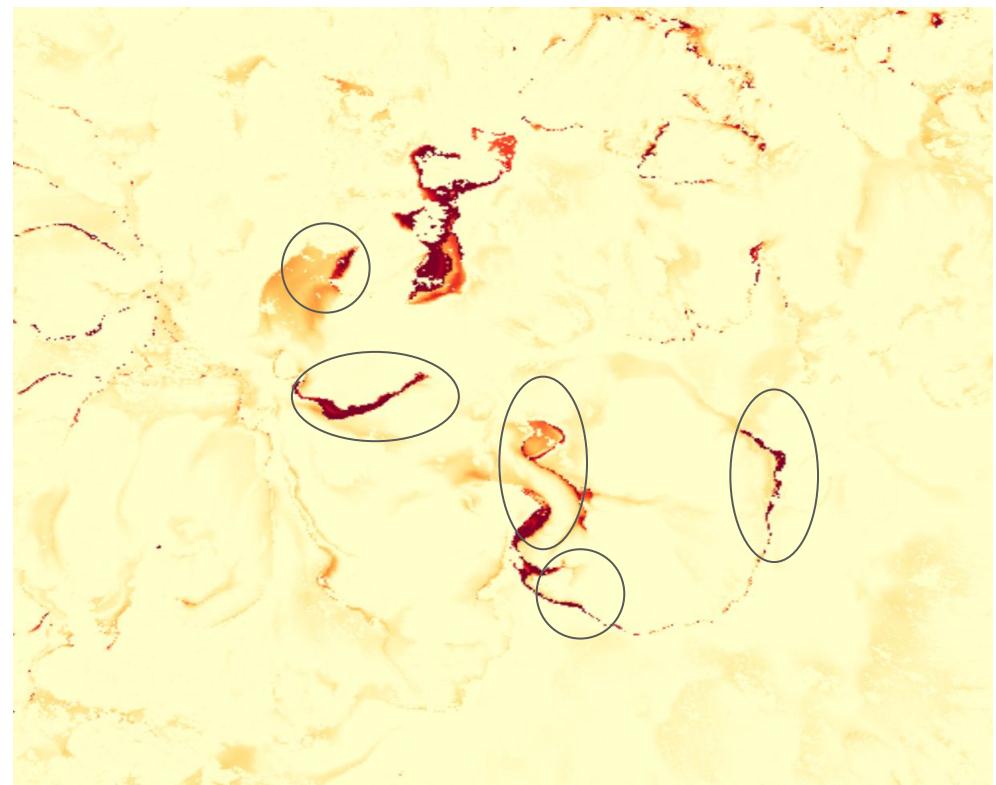
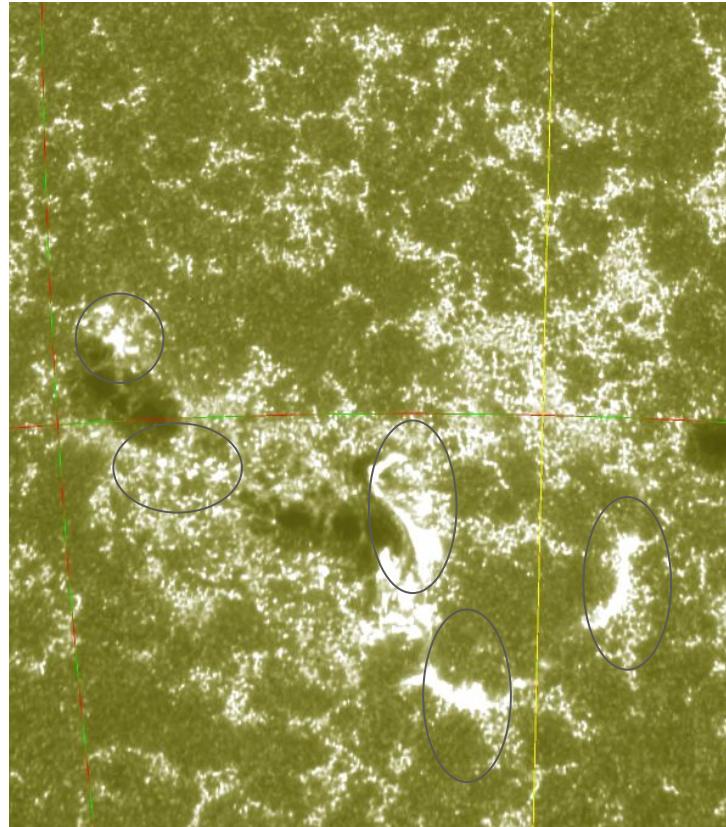


M class flare between 2oct - 3oct

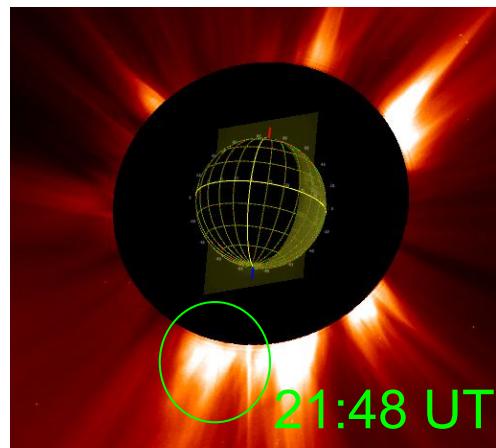
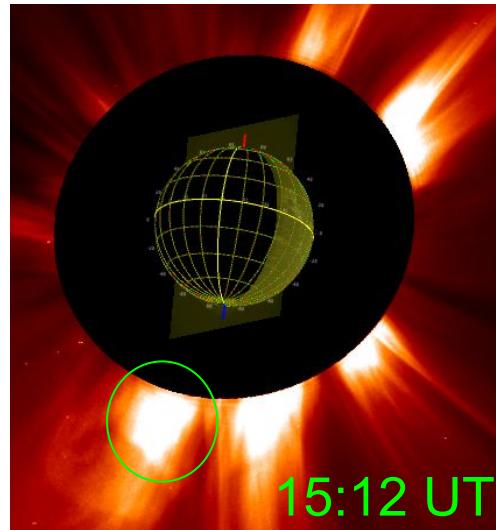
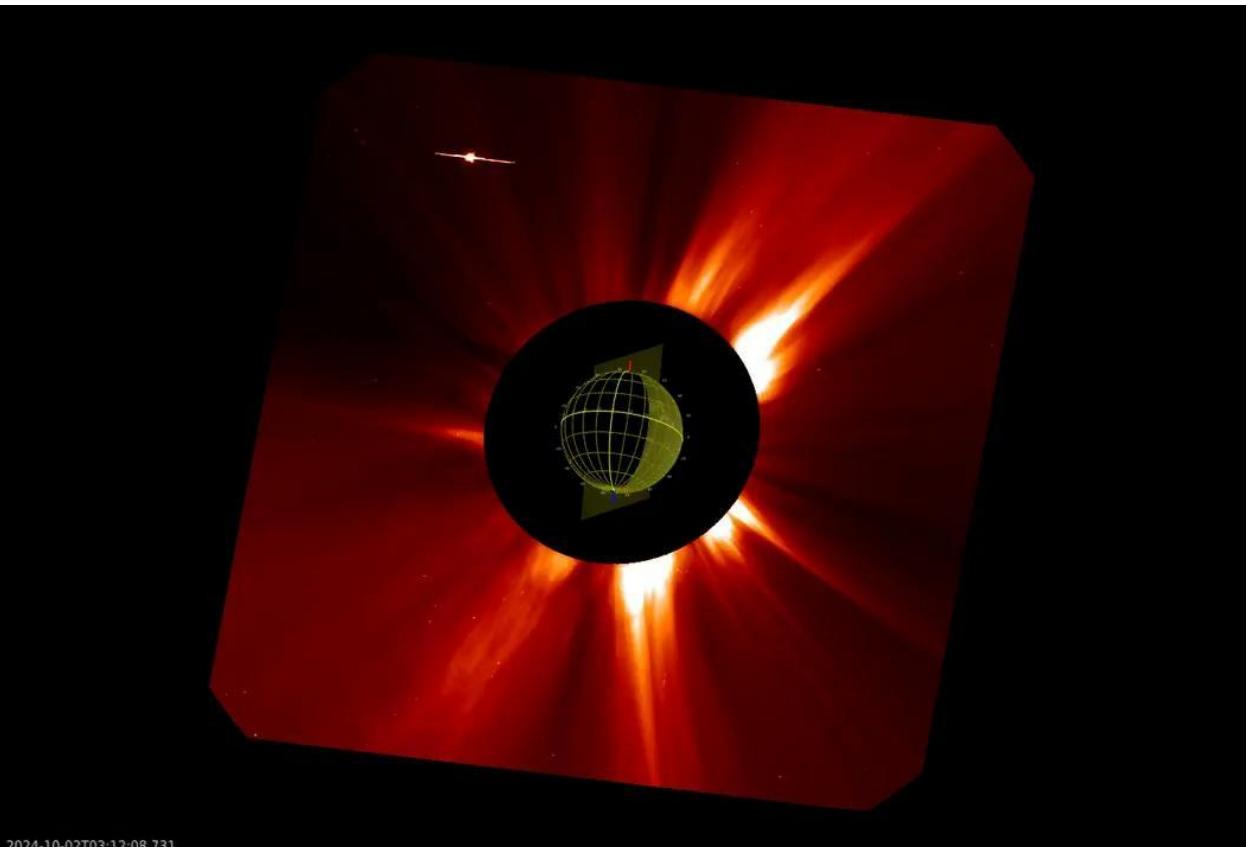
- 1) 2oct - 13:50 UT (21.2 hours before)
- 2) 2oct - 20:54 UT (15.5 hours before)

2 oct - 20:09UT

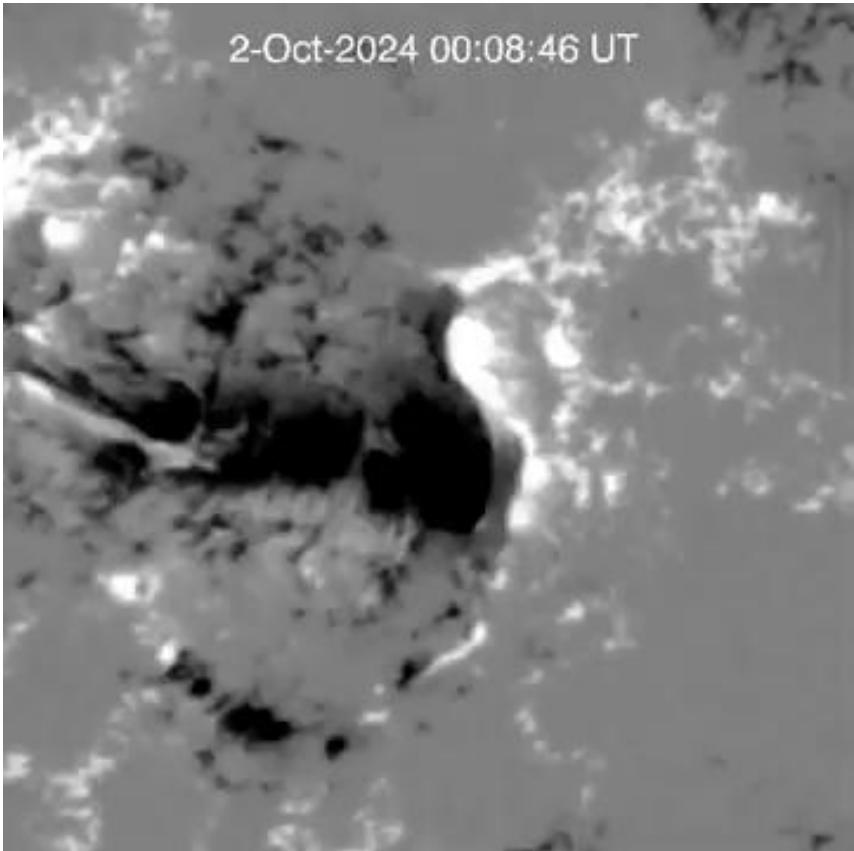
Brightening of AIA 1600 and footpoints of flare ribbon



CMEs on 2oct



Flux cancellation on 2 oct



Oct 2:

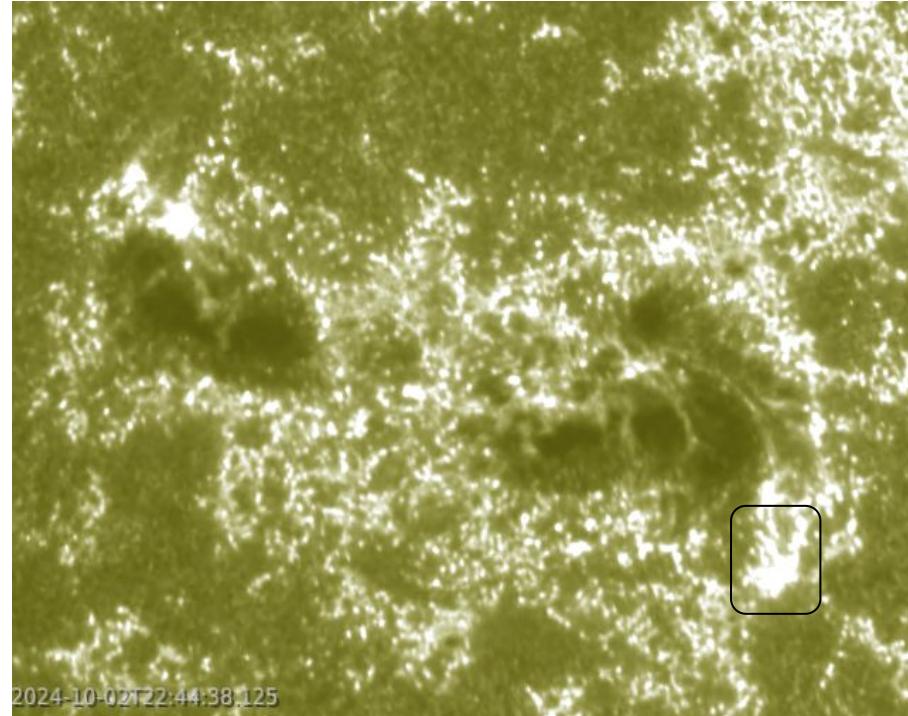
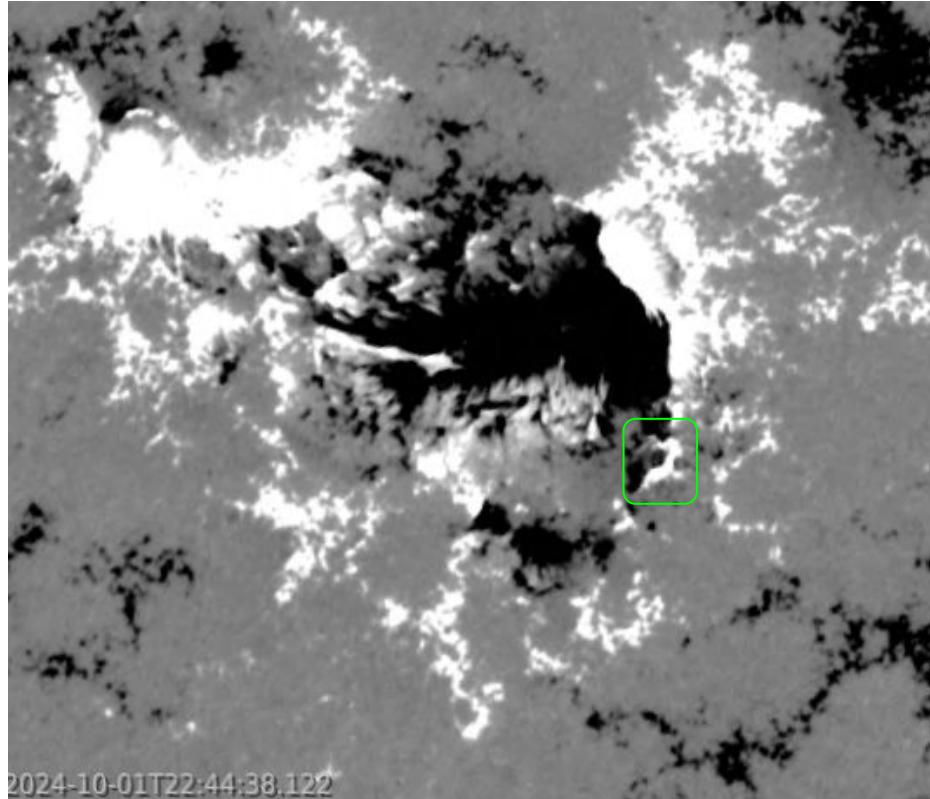
- 02:44 UT to 05:40 UT,
- 04:02 UT to 12:49 UT,
- 22:05 UT to 02:38 UT oct 3,

Oct 3:

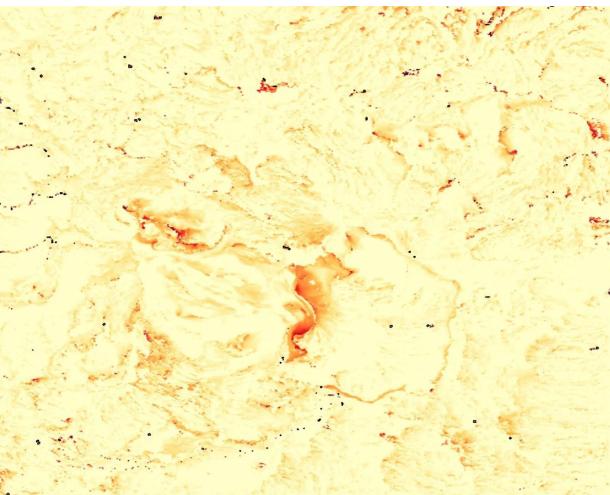
- 02:57 UT to 06:51 UT,
- 08:09 UT to 12:02 UT,
- 10:45 UT to 12:02 UT.

Reference:<https://iopscience.iop.org/article/10.3847/2041-8213/add32c>

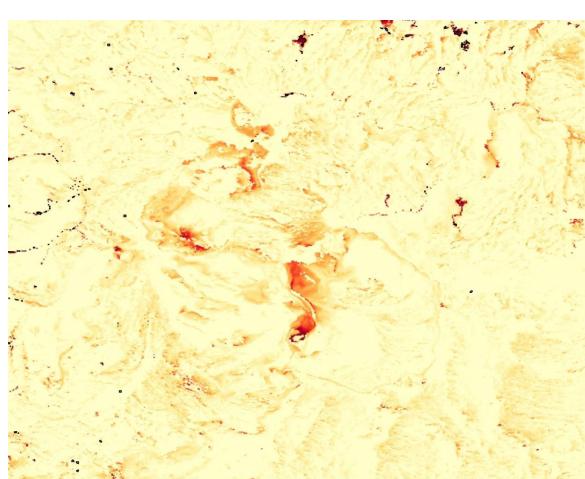
Flux cancellation at 22:44UT



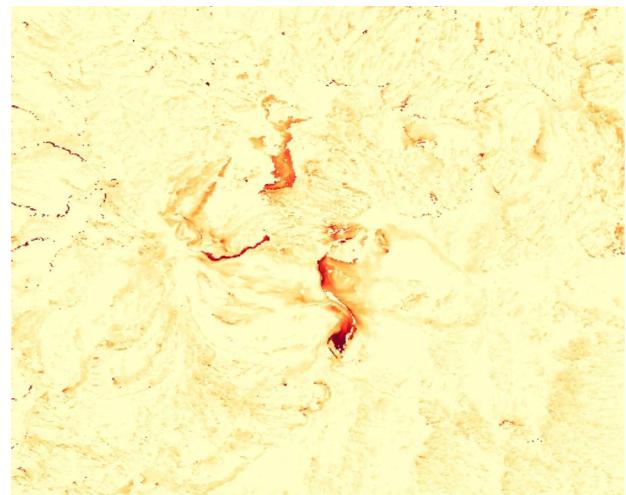
Time evolution of twist



26 hours before



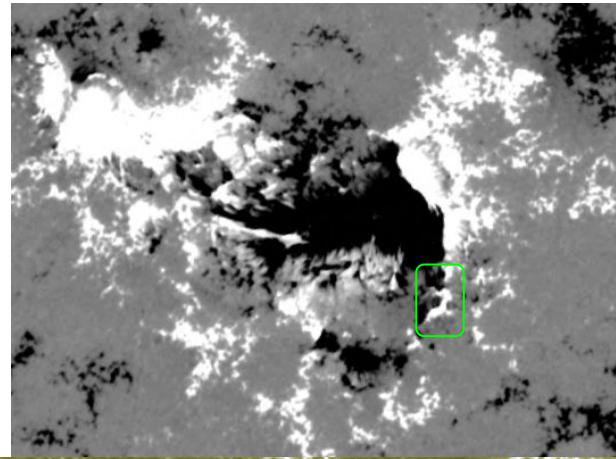
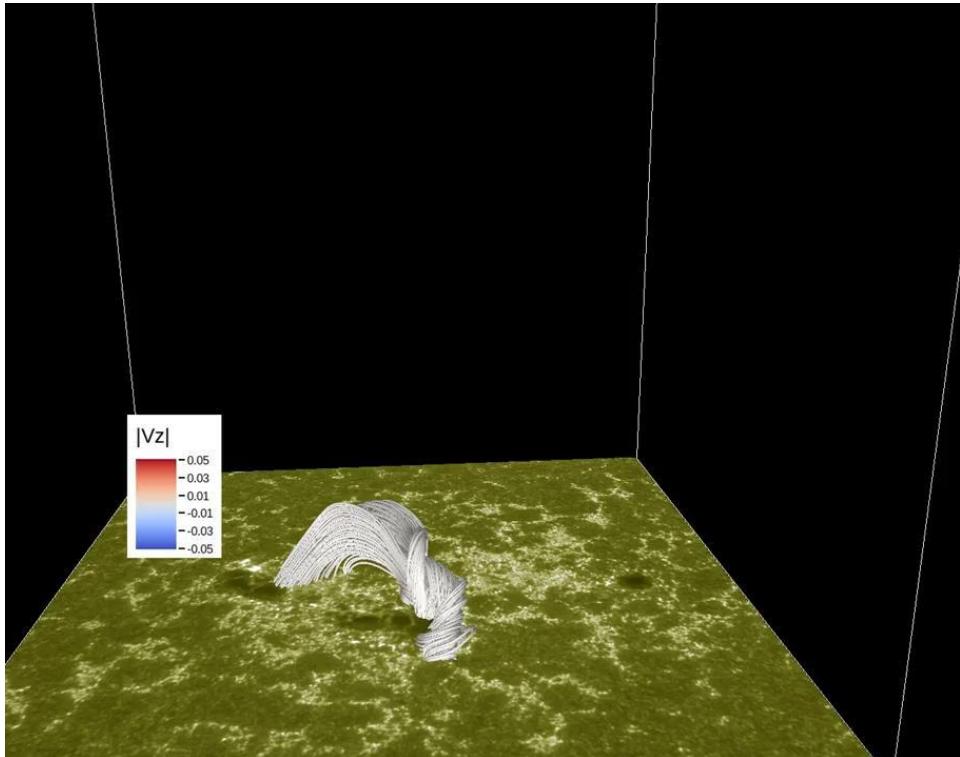
19 hours before



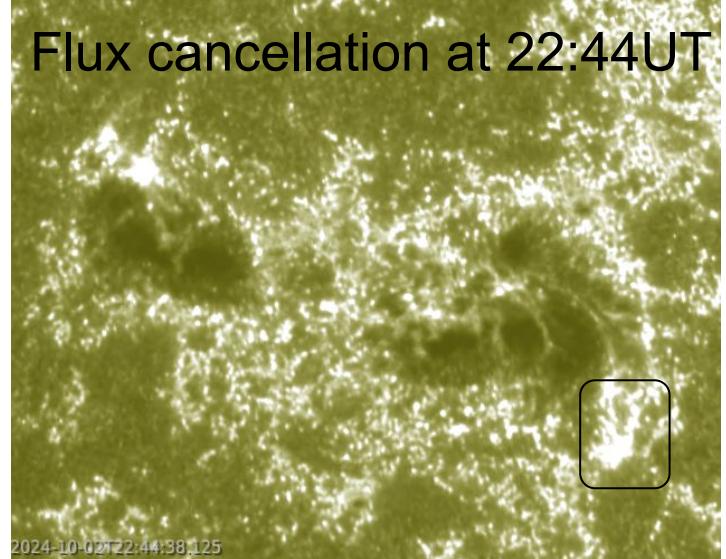
14 hours before

Simulation 14 hours before

$v_i = 1 \times 10^{-4}$ and $\eta_j = 1 \times 10^{-5}$

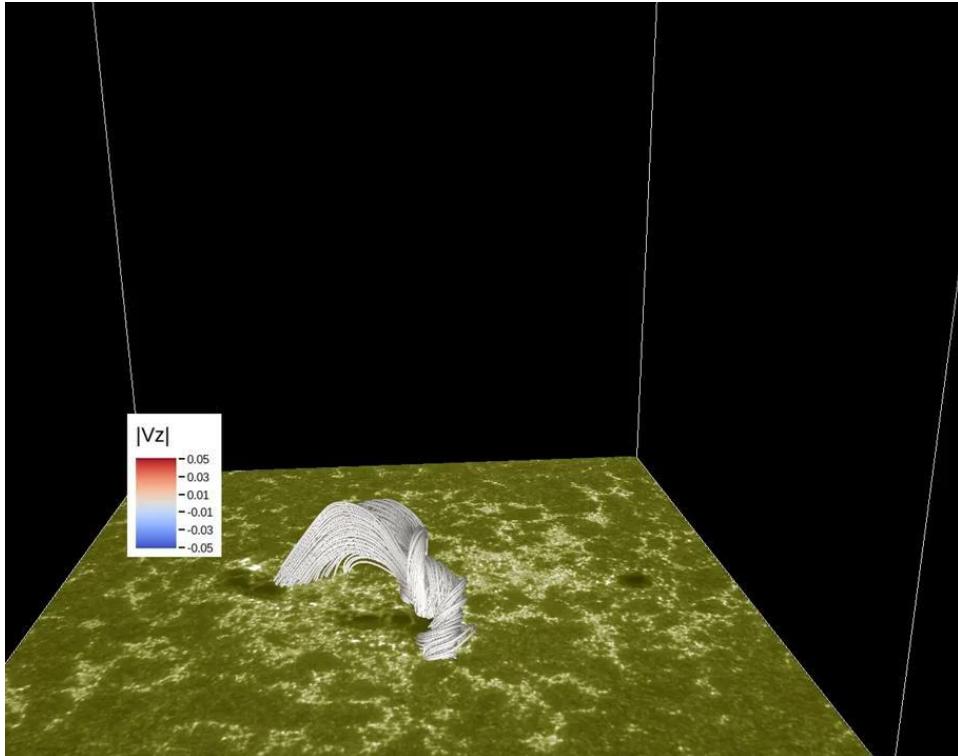


Flux cancellation at 22:44UT



Simulation 14 hours before

$v_i = 1 \times 10^{-4}$ and $\eta_j = 1 \times 10^{-5}$



Twist Difference Map: 2 Oct 15:58UT - 22:48UT

