Simulation Study on the Self-Organization of Sigmoidal Structure and the Onset of Solar Flares

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Introduction

formation \[\rightarrow\] pre-flare sigmoid \[\rightarrow\] onset of flares \[\rightarrow\] eruption

Questions

- the formation mechanism of sigmoids
- the causal relationship from sigmoids to the onset of flares.

3D MHD Simulation
Mechanism of sigmoid formation

- **kink mode instability**
  - proposed by Rust & Kumar 1996
  - simulations
    - Fan & Gibson 2004, Fan 2005
    - Kliem, Titov & Török 2004, Török & Kliem 2005

**However**, the several observations suggested that the field twist in sigmoids is insufficient for the kink instability. (Leamon et al. 2003, Yamamoto et al. 2005)

- **resistive tearing instability**
  - thin current sheet (reversed-shear layer)
  - self-organization → sigmoid formation
  - double reconnections → flare onset

Helicity Injection Measurement


\[
\left[ \frac{\partial \mathbf{B}}{\partial t} \right]_n = \left[ \nabla \times (\mathbf{V}_t \times \mathbf{B}_n + \mathbf{V}_n \times \mathbf{B}_t) \right]_n
\]

\[
\dot{H} = \int \mathbf{E} \times \mathbf{A}_p \cdot d\mathbf{S}, \quad \mathbf{E} = \nabla \times \mathbf{B}
\]

normalized twist rate \( \Omega = \frac{\dot{H}}{\phi^2} \)

\[(24h) \cdot \Omega \approx O(0.01) << 1\]

much less than one turn twist
Simulation Model (3D MHD)

- Basic equations
  \[ \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} = \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{V}, \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B} - \eta \mathbf{J}) \]
  - zero-\( \beta \) version & finite \( \beta \) version

- Finite difference: 512 X 512 X 1024 (\( \Delta \sim 10^{-3} \))
  - parallelization in terms of MPI library (domain decomposition)

- Boundary Condition
  - line-tide on the bottom, periodic for the axial

- Initial state
  - force-free field with reversed-shear layer

- Anomalous resistivity

\[ \eta = \begin{cases} \eta_0 & (J < J_0) \\ \eta_0 + \eta_1 \frac{J - J_0}{J_0} & (J > J_0) \end{cases} \]

\[ \eta_0 = 10^{-5}, \quad \eta_1 = 5 \times 10^{-4} \]
Time Evolution of Energy

linear growth phase  relaxation phase  eruption phase
Formation of Sigmoidal Structure

Case D

Kinetic Energy

Strong Reversal
Formation of Sigmoidal Structure

- Kinetic Energy

Graph showing the kinetic energy over time.
distribution of $\alpha$ in sigmoid

- $\alpha$ is flattened inside the sigmoid.
- $\alpha$ is limited by eigenvalue.

consistent with Taylor’s relaxation theory
dependency on the initial state
Comparison with Taylor relaxation

LFFF bifurcates into multiple solution, when $\alpha$ is larger than the eigen-value $\alpha_1$. (Taylor, 1986)

$$\nabla \times \mathbf{B} = \alpha_i \mathbf{B}$$

Sigmoidal wavelength is consistent with the Taylor’s minimum energy principle.

Sigmoidal formation can be understood as the self-organization toward the Taylor type state.
Sigmoid to Eruption

tearing mode reconnection → collapsing → double reconnection on T-shape current sheet

explosive growth of energy liberation

CS1 CS2

$L/\delta \approx 21$

$L/\delta \approx 12$
flares from reversed-shear

Maeshiro et al. 2005

TRACE 1600Å

α>0

Hahn et al. 2005

α>0

Maeshiro et al. 2005
Kink Model vs. Reversed-Shear Model

The two models are geometrically different, and the validity of them can be examined by careful observation of continuous evolution of sigmoid.
Conclusions

- The resistive **tearing mode instability** on the reversed-shear layer may cause both the formation of sigmoids and the onset of eruption.

- The sigmoidal formation is consistent with the **self-organization** toward Taylor state.

- The transition from the quasi-steady sigmoid to the sudden onset of eruption can be explained by the arcade **collapsing** and the feed-back of **double reconnections**.

- **Reversed-shear flare model.**