Fractal Structure (Turbulence) and SOC of a Current Sheet in a Solar Flare via Dynamic Magnetic Reconnection

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THE ASTROPHYSICAL JOURNAL LETTERS, 774:L1 (6pp), 2013

THE ROLE OF A FLUX ROPE EJECTION IN A THREE-DIMENSIONAL MAGNETOHYDRODYNAMIC SIMULATION OF A SOLAR FLARE

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Received 2013 March 1; accepted 2013 August 1; published 2013

Plasmoid

5000 km

40 grids
Fermi Acceleration in Plasmoids Interacting with Fast Shocks of Reconnection via Fractal Reconnection

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(Received 16 April 2012; published 30 January 2013)
Motivation of my study

• Magnetic Reconnection is SOC? (current automaton model is ok?)

• What is the origin of Turbulence in solar flares?

• How turbulence/SOC state affects Reconnection mechanism (dynamics, reconnection rate)?
Multiwavelength emissions from a Solar Flare

*Time (minutes) (Kane 1974)*

- **Microwave · Radio** (~3000 MHz)
- **Hα** (~6562 Å)
- **EUV** (10-1030 Å)
- **SXR** <10 keV
- **Non-thermal**
- **HXR** (10-30 keV)
- **HXR** >30 keV

**Energy Release**
- Magnetic Reconnection
- Particle Acceleration

**Loop-top HXR source** (Masuda 1994)

**Emission from loop-footpoint**

**Time-of-flight method** [Aschwanden 1996]
Various scales of Solar Flares

Soft X-rays (\(\sim\) total released energy)

Solar Flares show power-law distributions of peak flux, duration and time interval.

MHD scale free & SOC

[Veronig et al. 2002]
Observations of hard X-rays and Microwave emissions show fractal-like time variability.

Hard X-rays (~ released particle energy)

- Fractal Reconnection (= ensemble of elemental reconnection?)
- Patchy Reconnection (same size of reconnection region)

\[ \Delta t = \frac{L_{\text{acc}}}{c} \]

If \( \Delta t \) is power-law, \( L_{\text{acc}} \) may be also power-law.
Power-laws of UV Footpoint Brightenings

TRACE1600A (C IV 1550A) UV emission

\[ N \propto I^{-1.5} \]

\[ N \propto t_{dur}^{-2.3} \]

\[ N \propto t_{int}^{-1.8} \]

\[ \Delta t = \frac{L_{rec}}{V_A} \]

If \( \Delta t \) is power-law, \( L_{rec} \) may also be power-law.

\[ \rightarrow \text{Evidence of Fractal Reconnection?} \]
Fractal Current Sheet

During this merging process, avalanching system works? No avalanche model.

[Tajima & Shibata 1997]

[Shibata & Tanuma 2001]

Self-similar

Scenario of fast reconnection
Classification of Fast Reconnection in Lab Plasma

- Driver of Fast reconnection
  - Anomalous resistivity
    (Hall effect, Disturbance?, Instability?)
  - 3D effect
  - Non-steady effect
    - Density pile up
    - Current sheet ejection
    - Plasmoid ejection

MRX at PPPL
Null-helicity Pull mode
Hall reconnection
Quadrapole measurement

[Yamada et al. 2006]

[Inomoto et al. 2012 NINS-UT reconnection Workshop]

Faster reconnection by 3D structure change of a current sheet.
Classification of Reconnection in Parm. Regime

- Phase diagram
  - vertical: Lundquist number
  - horizontal: size parameter

- Solar corona
  - multiple X-line hybrid

\[ S = \frac{\mu_0 L_{CS} V_A}{\eta} \quad \lambda = \frac{L}{\rho z} = \frac{L}{\sqrt{(T_i + T_e)m_i} q_i B_{\text{total}}} \]

[Ji & Daughton 2011]
Multiple plasmoids in a Current Sheet

[Loureiro et al. 2009]

[Samtaney et al. 2009]

[Daughton et al. 2009]

[Karlicky and Barta. 2011]

[Tanaka et al. 2010]
Multiple plasmoids in 2D direction

[Barta et al. 2010]

Reconnection in accretion disk (magneto-rotational Instability)

[Hoshino 2012]
Plasmoid and Turbulent current sheet in 3D simulation

[Daughton et al. 2011] PIC simulation
Guide field is very strong.
→ multi fractal analysis [S. Chapman et al. 2012]

[Shimizu et al. 2011] MHD simulation
Guide field is small, patchy reconnection

[Fujimoto & Sydora 2012] PIC simulation
Reconnection generates kinetic turbulence.

[Galsgaard & Nordlund 1996, Vlahos 2004]
Idea of SOC-formed current sheet.
Simulation is very diffusive (small $R_m$)
3D simulation of a Solar Flare and Reconnection current sheet with high resolution

with small guide field (patchy reconnection), low beta plasma ($\beta=0.01$), $R_m \sim 10000$
Numerical Method

- We solved 3D MHD equations and calculated time evolution with multistep implicit scheme (Hu 1989).
- Localized Anomalous resistivity
- Emerging flux as a trigger mechanism (Chen & Shibata 2000)

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} + \frac{1}{\rho} \nabla p - \frac{1}{\rho} \mathbf{j} \times \mathbf{B} &= 0 \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) + \nabla \times (\eta \nabla \times \mathbf{B}) &= 0 \\
\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + (\gamma - 1) T \cdot \nabla \mathbf{v} - \frac{2(\gamma - 1) \eta \mathbf{j} \cdot \mathbf{j}}{\beta_0 \rho} &= 0
\end{align*}
\]

Plasma beta : \( \beta_0 = 0.01 \)

\[\eta = \begin{cases} 
\eta_0 & |v_d| > 2v_c \\
\eta_0 \left( \frac{|v_d|}{v_c} - 1 \right) & v_c < |v_d| < 2v_c \\
0 & |v_d| < v_c
\end{cases}\]

\[v_d = \frac{\mathbf{j}_z}{\rho}\]

* When current density in a current sheet (= relative velocity of ions and electrons) becomes strong, plasma instability in micro-scale generate localized anomalous resistivity.
Extended 3D Model

Initial condition & Perturbation

- Boundary condition: Periodic in y-direction, fixed at z=0, open at others
- Initially P, T, ρ=const, and β~0.01.
- Trigger mechanism by emerging flux (→)

Unit: L0=10^9 cm
Grid: [400x400x400] or [800x800x800]
Emission measure for X-ray images

Snapshot images of a weakly twisted flux rope

\[ \Phi(r = 0) \approx 1.5 \quad \Phi(r) = \frac{LB_\phi(r)}{2\pi r B_z(r)} \]

Upward/downward velocity \( (V_z) \)
Snapshot images of a weakly twisted flux rope

$$\Phi(r=0) \approx 1.5 \quad \Phi(r) = \frac{LB_\phi(r)}{2\pi r B_z(r)}$$

- Symmetric Reconnection & Ribbon Expansion
- Multiple downflows
- Ribbon expansion

Upward/downward velocity ($V_z$)
Snapshot images of a strongly twisted flux rope

\[ \Phi(r = 0) \approx 2.2 \quad \Phi(r) = \frac{LB_\phi(r)}{2\pi r B_z(r)} \]

Upward/downward velocity \((V_z)\)

-4Cs \quad +4Cs

Kink-instability
Snapshot images of a strongly twisted flux rope

\[ \Phi(r = 0) \approx 2.2 \]

Upward/downward velocity \((V_z)\)

Kink-instability
Turbulent structure in 3D current sheet

- 3D reconnection forms turbulent fractal structure in a current sheet.
- Multiple plasmoid ejections enhance E-field, which is favorable for particle acceleration.
Current sheet in 3D

B-field lines (color: B-strength) and current sheet with strong J (pink surface)
Multiple plasmoids are formed in a current sheet.  

3D plasmoid with a finite length.  

Strong E-field is enhanced between plasmoids.
Turbulent structure & Intermittency

Large scale prominence eruption 
& small scale plasmoid ejections increase Reconnection rate
(E=\eta J) and E-field.

Turbulent structure 
\uparrow\downarrow correlated

Intermittency of energy release, E-field (∝ HXR emission)
Intermittent Reconnection in 2D

$t=412$ sec

Electric Field

Velocity $[1.28\times10^7 \text{ cm s}^{-1}]$
The combination of mass pileup and ejection increases effective mass ejection and rec. speed.

\[
\begin{align*}
uL &= 2\delta V_A + L\delta (d\alpha / dt) + 2\delta \alpha V_{eject} \\
u &= \frac{\eta}{\mu_0 \delta'} \quad \text{Pile-up} \\
\text{where pileup factor} \quad \alpha &= \frac{n_{\text{sheet}}}{n_0} \\
\end{align*}
\]

\[
u = \sqrt{\frac{\eta}{\mu_0 L} \left( \frac{2V_A}{L} + d\alpha / dt + \frac{2\alpha V_{eject}}{L} \right)} \\
\text{Pile-up} \quad \text{Ejection}
\]

For simplicity,

\[
\alpha = \frac{n}{n_0} = n_1 (1 + \sin \omega t) \\
v_{eject} = v_1 \{1 + \sin (\omega t + \theta)\}
\]

\[
u^2 = \frac{\eta}{\mu_0 L} \left[ 2V_A + 2\alpha V_1 + 2L\alpha \omega \cos \omega t + 2V_1 \sin \omega t + 2\alpha \sin (\omega t + \theta) + 2\alpha V_1 \sin \omega t \cdot \sin (\omega t + \theta) \right] \\
\text{Ejection}
\]
Critical state of a current sheet

$t=3.0\tau_A$ resistivity

$t=5.0\tau_A$

$t=9.0\tau_A$

$J$ is close to threshold value $J_{\text{thresh}}$ almost everywhere. (=critical state)

Once anomalous resistivity is triggered, it affects the surroundings (=avalanching).
Avalanche model with Scenario of fast reconnection

(i) Current sheet thinning and/or pile up lead to Tearing mode instability. (-> cascading and Fractal formation)

(ii) Instability saturates, and whole system is unstable. J is close to $J_{\text{thres}}$ in smallest current sheets almost everywhere. (=critical state)

(iii) Once anomalous resistivity occur somewhere, surrounding plasmoids start merging each other, and finally ejected outward. (inverse cascade)
Turbulence by Rayleigh-Taylor instability (or interchange/flute instability)

Pressure

Flux rope

RT-instability

Current sheet

Tearing-mode

Current density
Turbulence by Rayleigh-Taylor instability (or interchange/flute instability)

Density distribution and outward Effective gravity generate RT-instability at the surface of a flux rope.

Structure: 1000-2000 km

<table>
<thead>
<tr>
<th>Density</th>
<th>Pressure</th>
<th>Bx -field</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="chart1.png" alt="Density" /></td>
<td><img src="chart2.png" alt="Pressure" /></td>
<td><img src="chart3.png" alt="Bx-field" /></td>
</tr>
</tbody>
</table>

12000 km
Snapshot images of $Jy$

$T=9.0\tau_A$

$T=10.0\tau_A$

$T=11.0\tau_A$

$T=12.0\tau_A$

$T=13.0\tau_A$

$T=14.0\tau_A$

Current sheet

Turbulence at/around a flux rope
Fourier spectrum (Jy) in a current sheet (z=50) tearing-mode

Current sheet

Log-normal

Power-law?

Log-normal

Power-law?

Log-normal

Power-law?
Power-law index varies in time and locations.

Different source of turbulence makes power-law index different.

Fourier spectrum (Jy) in a flux rope (z=20)

Rayleigh-Taylor instability
Summary and Conclusion

• Magnetic Reconnection is SOC? (current automaton model is ok?)

→ It looks like SOC. Fractal/turbulence structure and intermittency are correlated. Further analysis needed.

• What is the origin of Turbulence?

→ Tearing instability (plasmoids) & RT-instability.

• How turbulence/SOC state affects Reconnection mechanism (dynamics, reconnection rate)?

→ Positive feedback by plasmoid ejections (and/or turbulent flows) increase energy release rate.
Time scales related to Solar flares

- **Solar Flare**
  \[ t_{\text{flare}} = 10^2 - 10^4 \text{ sec} \]

- **Magnetic diffusion**
  \[ t_D \approx \frac{L^2}{\eta} \approx 10^{14} \left( \frac{L}{10^9 \text{ cm}} \right)^2 \left( \frac{T}{10^6 \text{ K}} \right)^{\frac{3}{2}} \text{ sec} \]
  Spitzer resistivity: \( \eta = \eta_{\text{Spitzer}} \approx 10^4 \left( \frac{T}{10^6 \text{ K}} \right)^{\frac{3}{2}} \text{ cm}^2 \text{ sec}^{-1} \)

- **Alfven time**
  \[ t_A = \frac{L}{V_A} \approx 10 \left( \frac{L}{10^9 \text{ cm}} \right) \left( \frac{n}{10^9 \text{ cm}^{-3}} \right)^{\frac{1}{2}} \left( \frac{B}{10 \text{ G}} \right)^{-1} \text{ sec} \]

- **Mag. Reynolds num.**
  \[ R_m = \frac{t_D}{t_A} = \frac{L V_A}{\eta} \approx 10^{13} \left( \frac{L}{10^9 \text{ cm}} \right) \left( \frac{T}{10^6 \text{ K}} \right)^{\frac{3}{2}} \left( \frac{B}{10 \text{ G}} \right) \left( \frac{n}{10^9 \text{ cm}^{-3}} \right)^{-\frac{1}{2}} \]

- **Thermal conduction**
  \[ t_{\text{cond}} = \frac{3nkL^2}{\kappa T^{5/2}} \approx 1.4 \left( \frac{n}{10^9 \text{ cm}^{-3}} \right) \left( \frac{L}{10^9 \text{ cm}} \right)^2 \left( \frac{T}{10^7 \text{ K}} \right)^{-\frac{5}{2}} \text{ sec} \]

- **Radiation cooling**
  \[ t_{\text{rad}} = \frac{3kT}{nQ(T)} \approx 4 \times 10^4 \left( \frac{n}{10^9 \text{ cm}^{-3}} \right)^{-1} \left( \frac{T}{10^7 \text{ K}} \right)^{\frac{3}{2}} \text{ sec} \]
Plasmoid-induced reconnection model

(1) To store energy by inhibiting reconnection

Plasmoid inhibits reconnection
Energy is stored
When plasmoid is ejected, energy is released suddenly

(2) To induce strong inflow into reconnection region

\[ v_{in} = \frac{w_p}{L_{in}} v_p \]
Comparison between Type III burst (electron beam) and E-field enhancement in the simulation.

- Simulation show intermittent time variability of E-field enhancement in the turbulent current sheet, as observed in Type III burst. Each of them corresponds to a small plasmoid ejection.