Magnetic Reconnection in Solar and Laboratory Plasmas

C. Z. Cheng (陳秋榮)
National Cheng Kung University (國立成功大學)

Collaborators:
Y. Ono, University of Tokyo, Japan
G. S. Choe, Kyung Hee University, Korea
Y. H. Yang, National Central University

at National Astronomical Observatory of China, Sept. 11, 2013
Solar Storms

- When the sun’s magnetic field is most tangled, energy builds and explodes as solar storms.
- Solar storms release energy via solar flares and clouds of plasma – coronal mass ejections (CMEs).
- Solar flares emit high energy electrons and ions, and radiations (from radio waves to EUV to X-ray to $\gamma$-ray), reaching Earth in $\sim 8$ minutes with energy of $\sim 10^{32}$ ergs ($\sim 200$ billion Hiroshima bombs) in 100-1000 seconds.
- CMEs reach Earth in 1-3 days, smashing Earth with 1-10 billion tons of plasma at 1-5 million miles an hour, growing into a cloud tens of millions of miles wide.
- CME moves through slower solar wind, creating shock waves that can accelerate charged particles to ultra-high energy.
- CME and flare are two manifestations of the same physical process! For every CME there is a flare associated with it.
A Long Duration Flare Observed by Yokoh

(Yokoh SXT, emission energy ~ 1 keV, Tsuneta et al. 1992)
Yohkoh Observations suggest Magnetic Reconnection Model of Flares

Yokoh SXR flare

Solar surface (photosphere)
Flares are related to CMEs (movie provided by NASA)
Magnetic Reconnection Model of Solar Flares and Coronal Mass Ejections

Coronal mass ejection, Plasmoid ejection, Filament ejection

Prominence, Filament, Flux Rope

Looptop HXR; e⁻ acceleration

Soft X-ray EUV Hα

Filament ejection

2-ribbon expansion

Hα two-ribbon
2002/02/20
Solar Flare

• Impulsive release of non-thermal emission (HXR) during SXR rise phase!
• Electrons are impulsively accelerated to 100s of keV.

$1\text{ eV} \approx 11,600 \text{ }^\circ\text{K}$

$\Rightarrow$ How and where are particles accelerated?
Large solar flares are the most powerful explosions in the solar system:

- Up to ~ \(10^{32} - 10^{33}\) ergs released in 10 - \(10^3\) s
- Electrons are accelerated up to ~ 100s of MeV
  - Flare accelerated electrons (\(~20 - 100\) keV) contain ~ 10 - 50% of total energy release
- Ions are accelerated up to ~ 10s of GeV
  - In large flares > ~ 1 MeV ions contain comparable energy

→ Particle acceleration is related to flare energy release.
→ When, where and how are particles accelerated from ~ 100 eV to MeV energy?
→ How large and where is the electric field?
Acceleration of CME Motion is related to Impulsive Flare HXR Emission

Nov. 24, 2000 X1.8 flare-CME event


- Good agreement between observation (blue curves) and MHD simulation results (black curves) on flux rope motion (in acceleration phase).
- Impulsively fast magnetic reconnection during flare rise phase
- Peak reconnection electric field at X-line in current sheet is $E_{\text{max}} \sim 1$ kV/m for X-class flares, can accelerate electrons to 100 keV - 1 MeV energy to produce HXR emission.
CME and Flare Emission

Filament (flux rope) eruption during flare rise phase → two-ribbon emission (with two separating & expanding ribbons)

2000 September 12
← Coronal Mass Ejection
(from http://cdaw.gsfc.nasa.gov/)

Filament (flux rope) eruption & 2 expanding ribbons
Estimate of Reconnection Rate from Expansion of Two-Ribbons

For 2-1/2D field
\[ \mathbf{B} = \hat{e}_z \times \nabla \psi(x, y, t) + B_z(x, y, t)\hat{e}_z \]
\[ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \]

Reconnection electric field at X-line is related to the change of magnetic flux on solar surface:
\[ E_{rec} = -\frac{\partial \psi}{\partial t} = -\frac{1}{L} \frac{\partial}{\partial t} \int \mathbf{B}_n \cdot d\mathbf{a} \]
\[ \approx B_n v_\perp \]
\[ d\mathbf{a} \] is area of ribbons;
\[ \mathbf{B}_n \] is normal component of magnetic field on photosphere;
\[ v_\perp \] is outward expansion velocity of ribbon emission edge.

Outside reconnection region
\[ \mathbf{E} + \mathbf{V} \times \mathbf{B} \approx 0 \]
Ribbon 1

Ribbon 2

M1.0 flare on 2000 September 12

Halpha at 11:51:58 UT

Magnetogram at 09:39:30 UT

Electric field (V/cm)

Flux rate (Mx/s)
Reconnection Rate vs. CME Acceleration

Sept. 12, 2000 M1.0 flare event

- Peak reconnection rate and acceleration:
  \( E_{\text{rec}} \sim 50 \text{ V/m} \)
  \( a \sim 0.4 \text{ km/s}^2 \)

- \( E_{\text{rec}} / a \)


CME Acceleration / Reconnection Rate


<table>
<thead>
<tr>
<th>Event (magnitude)</th>
<th>2000/09/12 (M1.0)</th>
<th>2001/10/19 (X1.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max CME acceleration (km/s²)</td>
<td>0.2 - 0.4</td>
<td>2.</td>
</tr>
<tr>
<td>Duration of acceleration (min)</td>
<td>&gt; 120</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>Mean and Max. velocity (km/s)</td>
<td>1550 &amp; 1700</td>
<td>900 &amp; 1450</td>
</tr>
<tr>
<td>Max. magnetic field (Gauss)</td>
<td>200</td>
<td>1200</td>
</tr>
<tr>
<td>Max. electric field (V/m)</td>
<td>50</td>
<td>580</td>
</tr>
<tr>
<td>Duration of reconnection (min)</td>
<td>&gt; 120</td>
<td>~ 30</td>
</tr>
</tbody>
</table>
Reconnection Electric Field in 2003/10/29 X10 flare obtained from TRACE 1600 A ribbons

\[ E = \frac{1}{L} \frac{\partial}{\partial t} \int \vec{B} \cdot d\vec{a} \]

\( a \): newly brightened areas swept by ribbons at each time

\( B \): normal component of magnetic field in the photosphere

\( L \): characteristic length of newly brightened areas

The RHESSI 50-100 keV lightcurve \( (F_{\text{HXR}}) \) is also shown here for comparison.
2003/10/29 X10 flare
Comparison on Peak Reconnection E-field with Different Studies

Estimates of peak electric field inside reconnecting current sheet from various studies:

<table>
<thead>
<tr>
<th></th>
<th>Peak $E$ (kV/m)</th>
<th>Formula</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xu et al. (2004)</td>
<td>4.5</td>
<td>$V_\perp B_n$</td>
<td>Near-Infrared</td>
</tr>
<tr>
<td>Jing et al. (2005)</td>
<td>3.8</td>
<td>$V_\perp B_n$</td>
<td>H$_\alpha$</td>
</tr>
<tr>
<td>Krucker et al. (2005)</td>
<td>6.7</td>
<td>$V_\perp B_n$</td>
<td>RHESSI HXR</td>
</tr>
<tr>
<td>Liu &amp; Wang (2009)</td>
<td>1.7</td>
<td>$\frac{1}{L} \frac{\partial}{\partial t} \int \vec{B} \cdot d\vec{a}$</td>
<td>H$_\alpha$</td>
</tr>
<tr>
<td>Yang et al. (2011)</td>
<td>6.0</td>
<td>$V_\perp B_n$</td>
<td>RHESSI HXR</td>
</tr>
<tr>
<td>Yang et al. (2011)</td>
<td>2.6</td>
<td>$\frac{1}{L} \frac{\partial}{\partial t} \int \vec{B} \cdot d\vec{a}$</td>
<td>TRACE UV</td>
</tr>
</tbody>
</table>

Mm and Submm Emission in Solar Flares

• Provide information of energy spectrum of accelerated electrons
  – important to constraint flare models
• High energy (> 10 keV) electrons
  – bremsstrahlung $\rightarrow$ Hard X-rays/γ-rays
  – (gyro) synchrotron (continuum) emission $\rightarrow$
    mm/submm-waves ($f \sim \gamma^3 f_{ce}$)
• Thermal bremsstrahlung of the hot flare plasma $\rightarrow$ EUV and soft X-rays
Magnetic Reconnection:  
Particle Acceleration & Flare Emissions

Magnetic Reconnection  
- Particle acceleration

Looptop HXR  
In reconnection current sheet

Thermal Energy Release

Soft X-rays
Microwaves
mm/submm Emission

Hard X-rays  
Gamma-rays  
EUV Lines  
H$_\alpha$

Corona
Transition Zone
Chromosphere
Photosphere
Impulsive Micro/mm Wave Emission during Solar Flare Impulsive HXR Phase


KOSMA Observation
April 12, 2001 X2.0 flare

April 12, 2001 X2.0 flare

1) $H_\alpha$ image
2) Yohkoh SXT (dotted) & HXT 53-93 keV (solid contours)
3) Magnetic neutral line (MDI/SOHO)
4) Half power sources at 230 & 345 GHz

KOSMA
Pointing accuracy ~ 25 arcsec
HPBW:
117 arcsec at 230 GHz
88 arcsec at 345 GHz

Luthi et al., Astronomy & Astrophysics, 415, 1123-1132, March 2004
### From the Sun to the stars

from Maggio et al. 2007 Simbol-X Workshop

<table>
<thead>
<tr>
<th></th>
<th><strong>Sun</strong></th>
<th><strong>Active stars</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X-ray luminosities</strong></td>
<td>$L_x/L_{bol} \sim 10^{-6}$ (quiescent)</td>
<td>$L_x/L_{bol} \sim 10^{-3}$ (quiescent)</td>
</tr>
<tr>
<td></td>
<td>$L_x/L_{bol} \sim 10^{-5}$ (large flares)</td>
<td>$L_x/L_{bol} \sim 10^{-1}$ (large flares)</td>
</tr>
<tr>
<td><strong>Occurrence of large flares</strong></td>
<td>1 every 10 days (at max of solar cycle)</td>
<td>A few per day (no magnetic cycle?)</td>
</tr>
<tr>
<td><strong>Flare time scales</strong></td>
<td>up to a few hours</td>
<td>up to a few days</td>
</tr>
<tr>
<td><strong>Coronal plasma temperature</strong></td>
<td>$\approx 10^6$ K (quiescent)</td>
<td>$\approx 10^7$ K (quiescent)</td>
</tr>
<tr>
<td></td>
<td>$\approx 10^7$ K (flaring)</td>
<td>$\approx 10^8$ K (flaring)</td>
</tr>
<tr>
<td></td>
<td>???</td>
<td>???</td>
</tr>
</tbody>
</table>
Stellar Soft X-ray vs. Radio Emission

- Correlation over 8 dec, including full range of solar flares
- Thermal and non-thermal emission appear linked
- Are stellar coronae heated by continuous flaring activity?
- Do stellar flares have similar mechanism as solar flares?

Benz & Güdel 1994
ALMA has the combination of angular resolution, sensitivity and frequency coverage necessary to address adequately many solar and stellar flare science objectives:

- **Receivers:** 10 bands: 0.3-9 mm (31-950 GHz)
- **High angular resolution:** 0.2” l (mm) / baseline (km); best resolution is 0.005 arcsec
- **FOV:** > 50” for large flares; at 1mm, 12m telescope has 20” primary beam.
- **High-sensitivity:** to remove Sun’s thermal emission (dual-polarization 8 GHz bandwidth spectral-line and continuum measurements between all antennas using 2 digital correlators)
- **Lowest possible receiver noise:** use superconducting mixers to minimize noise contribution
- **Calibration of atmospheric phase distortion:** use special purpose water vapor radiometers
- **Provide interferometric and total power astronomical information**
Experimental Study of Plasmoid Ejection as a Fast Magnetic Reconnection Mechanism

Yasushi Ono, Yoshinori Hayashi, Michiaki Inomoto, Takuma Yamada, C. Z. Cheng
and TS Group, Graduate School of Frontier Sciences, University of Tokyo

Pull Merging: Parallel Sheet current tends to form a plasmoid with closed surface.

Diagram showing the process of plasmoid ejection with various labels such as Thickness, Reconnection, X-point, Current Sheet, and Outflow.
Experimental Study of Plasmoid Ejection as a Fast Magnetic Reconnection Mechanism

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Pull Merging: Parallel Sheet current tends to form a plasmoid with closed surface.
1) Reconnection Heating Experiment
2) Upscaled Exp. R~0.5m of TS-3
3) Internal Coils
4) 2D Measurement of B, Tₐ, (Tₑ, nₑ)
   R=0.50-0.55m
   B₀=0.3-1kG
   Tₐ=10-100eV
   Tₑ=10-30eV
   nₑ=0.5-5×10¹⁹ m⁻³
TS-4 Plasma Merging

Data Set Name: f8410013

psi [Wb]: Contour Spacing 0.0010

jt [MA/m^2]:

-0.1500
0.1500

Left: 15.15
Right: 15.66
Fluxcor: 14.89 [mWb]
Rate: 98.3

Time 400.00 [usec]
High external inflow causes current sheet to eject a plasmoid, increasing reconnection speed impulsively.

(a) High Inflow Case

Poloidal flux contours with toroidal current density $j_t$ (red and blue colors) under high inflow condition.
A variety of plasmoids are ejected from the current sheet. A large plasmoid ejection leads to a large increase in rec. speed.

(a) High Inflow Case

(b) Low Inflow Case

Graph showing the change in electric field $E$ over time $t$ for Small-size and Large-size cases.
The reconnecting electric field $E_t$ and $\eta$ increased and reached their peak values when the plasmoid acceleration $dV/dt$ is maximum at about $t\sim 27\mu\text{sec}$.

The plasmoid ejection makes the sheet thinner than $\rho_i$, increasing $\eta$ anomalously.
Summary and Conclusion

• We have shown an impulsively fast magnetic reconnection mechanism by the acceleration of plasmoid/flux rope ejection for both solar flare-CME observations and laboratory plasma merging experiments.

• The reconnection rate correlates with the acceleration of plasmoid/flux rope velocity, which suggests that the reconnection rate is controlled by the acceleration of plasmoid/flux rope ejection.

• Reconnection electric field reaches ~O(1) kV/m for X-class flares.

• Electrons are accelerated along field lines in current sheet and near separatrix, and then stream down to photosphere to produce hard X-ray emission.