Plasma Heating and Asymmetric Magnetic Reconnection During Solar Eruptions

Nick Murphy

Harvard-Smithsonian Center for Astrophysics

Collaborators: Paul Cassak, Kelly Korreck, Jun Lin, Mari Paz Miralles, Mitsuo Oka, Crystal Pope, John Raymond, Kathy Reeves, Dan Seaton, Chengcai Shen, Carl Sovinec, Aad van Ballegooijen, David Webb, & Trae Winter

Naval Research Laboratory
April 6, 2012
Understanding astrophysical phenomena requires knowledge of the energy budget.

White light coronagraphs give kinetic energies of CMEs.

The Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO lets us study the thermal energy content of CMEs.

Ionization/recombination timescales are comparable to the CME propagation timescale.

We perform a time-dependent ionization analysis to constrain plasma heating requirements during a CME on 2000 June 28.

We also perform simulations of asymmetric reconnection in flare/CME current sheets.
  - Two competing reconnection sites
  - Line-tied asymmetric reconnection
Open Questions

- What are the key characteristics of plasma heating in CMEs?
  - How much are CMEs heated?
  - What causes the heating?
- How does asymmetry modify the reconnection process?
  - Where does the energy go?
  - What are the observational signatures?
We identify six features seen by UVCS in MLSO/MK4 polarization brightness and LASCO white light images.
UVCS observed Ly α, Ly β, C III, O V, O VI, C II, and N III emission during this event.

Blob F appears as a diagonal shear flow feature in UVCS with weak Ly α and Ly β emission.
We use a 1-D time-dependent ionization code to track ejecta between the flare site and UVCS slit

- We run a grid of models with different initial densities, initial temperatures, and heating rates (e.g., Akmal et al. 2001)
- The final density is derived from UVCS observations using:
  - The density sensitive $[\text{O} \, \text{v}]/\text{O} \, \text{v}$ line ratio
  - Radiative pumping of the $\text{O} \, \text{vi}$ doublet (Raymond & Ciaravella 2004)
- Assume homologous expansion
- Multiple heating parameterizations
  - An exponential wave heating model (Allen et al. 1998; AHH)
  - Expanding flux rope model by Kumar & Rust (1996; KR)
  - Heating proportional to $n$ or $n^2$
- The models consistent with UVCS observations give the allowed range of heating rates
- See Murphy, Raymond, & Korreck (ApJ, 2011)
Allowed temperature histories for blob F
Cumulative heating energy, kinetic energy, and potential energy in units of $10^{14}$ erg g$^{-1}$

<table>
<thead>
<tr>
<th>Blob</th>
<th>$Q_{AHH}$</th>
<th>$Q \propto n$</th>
<th>$Q \propto n^2$</th>
<th>$Q_{KR}$</th>
<th>K.E.</th>
<th>P.E.</th>
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<tr>
<td>A</td>
<td>6–35</td>
<td>7–46</td>
<td>22–42</td>
<td>7–127</td>
<td>136 ($&gt;29$)</td>
<td>7.4</td>
</tr>
<tr>
<td>B</td>
<td>0.3–37</td>
<td>1.4–86</td>
<td>18–117</td>
<td>7–379</td>
<td>164 ($&gt;27$)</td>
<td>7.9</td>
</tr>
<tr>
<td>C</td>
<td>0.2–36</td>
<td>0.6–87</td>
<td>12–112</td>
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<td>164 ($&gt;27$)</td>
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<tr>
<td>D</td>
<td>0.2–61</td>
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<td>16.9</td>
<td>—</td>
<td>56.6</td>
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For blobs A and E, the cumulative heating energy is less than or comparable to the kinetic energy.
Cumulative heating energy, kinetic energy, and potential energy in units of $10^{14} \text{erg g}^{-1}$

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For blobs B–D, the cumulative heating energy is constrained to be less than $\sim 2–3$ times the kinetic energy.
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- For blob F, the cumulative heating energy is comparable to or greater to the kinetic energy.
Candidate mechanisms: wave heating

- Would need \( \gtrsim 100 \) times the wave heating rate of Allen et al. (1998) for coronal holes (e.g., Landi et al. 2010)
- In lab experiments of expanding flux ropes, fast magnetosonic waves generated by the eruption itself heat the plasma (Tripathi et al. 2010)
- Resonant absorption of Alfvén waves is another possibility (Evans et al., submitted)
Candidate mechanisms: small-scale reconnection

- Small-scale reconnection events within the expanding flux rope could heat the plasma (e.g., Kumar & Rust 1996)
- Analogous to Taylor relaxation in an expanding equilibrium
- UVCS measurements limit turbulent energy density
- Role of kink instability?
- Next step: simulate relaxation and reconnection in expanding flux rope
Candidate mechanisms: energetic particles

- Weak, C class flare → energetic particle heating unlikely?
- Glesener et al: energetic particles enough to heat event on 2010 Nov 3
- Need to be careful:
  - Non-thermal tail increases ionization rates
  - Are AIA temperature response functions affected?
- Next steps:
  - Quantify effect of energetic particles on ionization rates
  - Simulate hot particle evolution in an expanding flux rope
Flux rope models of CMEs predict the formation of an elongated current sheet behind the rising plasmoid.

Reconnection upflow could heat the ejecta.
Open questions

- Are post-eruption current sheets actively reconnecting?
- Are these current sheets energetically important to the eruption as a whole?
- Where is the principal X-line? $\leftarrow\rightarrow$ Where does the energy go?
- Are CME CSs responsible for mass input and plasma heating in CMEs?
- Are large-scale blobs due to the plasmoid instability?
  - Perhaps, but some show C $\text{\textsc{iii}}$ and other cool lines
We perform resistive MHD simulations of two initial X-lines which retreat from each other as reconnection develops (Murphy 2010)

- The 2-D simulations start from a periodic Harris sheet which is perturbed at two nearby locations \((x = \pm 1)\)
- Use the NIMROD extended MHD code (Sovinec et al. 2004)
- Domain: \(-30 \leq x \leq 30, -12 \leq z \leq 12\)
- Simulation parameters: \(\eta = 10^{-3}, \beta_\infty = 1, S = 10^3-10^4, Pm = 1, \gamma = 5/3, \delta_0 = 0.1\)
- Define:
  - \(x_n\) is the position of the X-line
  - \(x_s\) is the position of the flow stagnation point
  - \(V_x(x_n)\) is the velocity at the X-line
  - \(\frac{dx_n}{dt}\) is the velocity of the X-line
- \(\hat{x}\) is the outflow direction, \(\hat{y}\) is the out-of-plane direction, and \(\hat{z}\) is the inflow direction
- We show only \(x \geq 0\) since the simulation is symmetric
The CSs have characteristic single wedge shapes
Surprisingly, the relative positions of the X-line and flow stagnation point switch!

This occurs so that the stagnation point will be located near where the tension and pressure forces cancel.

Reconnection develops slowly because the X-line is located near a pressure minimum early in time.
Late in time, the X-line diffuses against strong plasma flow.

- The stagnation point retreats more quickly than the X-line.
- Any difference between $\frac{dx_n}{dt}$ and $V_x(x_n)$ must be due to diffusion (e.g., Seaton 2008, Murphy 2010).
- The velocity at the X-line is not the velocity of the X-line!
The X-line moves in the direction of increasing total reconnection electric field strength

- X-line retreat occurs through a combination of:
  - Advection by the bulk plasma flow
  - Diffusion of the normal component of the magnetic field
- X-line motion depends intrinsically on local parameters evaluated at the X-line
  - X-lines are not (directly) pushed by pressure gradients
Reconnecting magnetic fields are asymmetric:

\[ B_y(x) = \frac{B_0}{1 + b} \tanh \left( \frac{x}{\delta_0} - b \right) \]  

\(-7 \leq x \leq 7, \ 0 \leq y \leq 30; \) conducting wall BCs

\(-7 \leq x \leq 7, \ 0 \leq y \leq 30; \) conducting wall BCs

\[ \beta_0 = 0.18 \text{ in higher magnetic field upstream region} \]

Caveats: 1-D initial equilibrium, outer conducting wall BCs, and we do not consider the rising flux rope in detail
Reconnection with both asymmetric inflow and outflow
Again, the plasma velocity at the X-line differs greatly from the rate of X-line motion.

\[ V_x(x_n, y_n) \] and \[ V_y(x_n, y_n) \] give the velocity at the X-line.

\[ \frac{dx_n}{dt} \] and \[ \frac{dy_n}{dt} \] give the rate of X-line motion.

No flow stagnation point within the CS.
The post-flare loops develop a characteristic candle flame structure

- Magnetic flux contours for $B_L/B_R \in \{1, 0.5, 0.25, 0.125\}$ when $y_n \approx 2.9$
- Dashed green line: loop-top positions
- Dotted red line: analytic asymptotic approximation
The Tsuneta (1996) flare is a famous candidate event:

- Shape suggests north is weak B side
Asymmetric speeds of footpoint motion

- In two-dimensional models, the footpoints of newly reconnected loops move away from each other as more flux is reconnected.
- In two-dimensions, the amount of flux reconnected on each side of the loop must be equal to each other.
- When the magnetic fields are asymmetric, the footpoint on the strong $B$ side will move slowly compared to the footpoint on the weak $B$ side.
- Because of the patchy distribution of flux on the photosphere, more complicated motions frequently occur (e.g., Bogachev et al. 2005; Grigis & Benz 2005; Su et al. 2007; Yang et al. 2009).
Asymmetric hard X-ray (HXR) footpoint emission

- The standard model of flares predicts HXR emission at the flare footpoints from energetic particles (EPs) impacting the chromosphere.
- Magnetic mirroring reflects energetic particles (EPs) preferentially on the strong B side.
- More particles should escape on the weak B side, leading to greater HXR emission.
- This trend is observed in \(~2/3\) of events (Goff et al. 2004).
  - Additional factors include:
    - Asymmetry in initial pitch angle distributions of EPs
    - Directionality of the reconnecting electric field (Hamilton et al. 2005; Li & Lin, accepted)
    - Different column densities (cf. Saint-Hilaire et al. 2008)
  - More detailed energetic particle modeling is required.
The outflow plasmoid develops net vorticity because the CS outflow impacts it at an angle.

- Velocity vectors in reference frame of O-point
Conclusions

- Heating is an important but not well understood term in the CME energy budget
- For some features the plasma heating is comparable to or greater than the kinetic energy
- Candidate heating mechanisms include the CME current sheet, small-scale reconnection, energetic particles and dissipation of waves driven by the eruption
- X-line retreat is due to advection by the bulk plasma flow and diffusion of the normal component of the magnetic field
- Observational signatures of line-tied asymmetric reconnection include
  - Skewed candle flame shape of post-flare loops
  - Strong magnetic field footpoint moves less quickly (flux conservation) and has less hard X-ray emission (mirroring)
  - Circulation in rising flux rope
What sets the rate of X-line retreat?

- The inflow ($z$) component of Faraday’s law for the 2D symmetric inflow case is

$$\frac{\partial B_z}{\partial t} = -\frac{\partial E_y}{\partial x}$$  (2)

- The convective derivative of $B_z$ at the X-line taken at the velocity of X-line retreat, $dx_n/dt$, is

$$\frac{\partial B_z}{\partial t} \bigg|_{x_n} + \frac{dx_n}{dt} \frac{\partial B_z}{\partial x} \bigg|_{x_n} = 0$$  (3)

The RHS of Eq. (3) is zero because $B_z(x_n, z = 0) = 0$ by definition for this geometry.
Deriving an exact expression for the rate of X-line retreat

From Eqs. 2 and 3:
\[ \frac{dx_n}{dt} = \left. \frac{\partial E_y}{\partial x} \right|_{x_n} \frac{\partial B_z}{\partial x} \]

Using \( \mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} \), we arrive at
\[ \frac{dx_n}{dt} = V_x(x_n) - \eta \left[ \frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2} \right] x_n \]

\[ \frac{\partial^2 B_z}{\partial z^2} \gg \frac{\partial^2 B_z}{\partial x^2} \], so X-line retreat is caused by diffusion of the normal component of the magnetic field along the inflow direction

This result can be extended to 3D nulls and to include additional terms in the generalized Ohm’s law