Physical constraints on energy release and heating in solar flares

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Thanks:
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Resolved: Fast magnetic reconnection occurs on small spatial scales within a current sheet.

Q: Where is the magnetic energy stored prior to release?

Q: How does reconnection release/convert magnetic energy?

Q: How is plasma density enhanced as much as we observe?
Where is the energy stored?

\[ \Delta W_M = \frac{1}{8\pi} \int |\mathbf{B} - \mathbf{B}_0|^2 d^3x \]

\[ \mathbf{B}_{np} = \mathbf{B} - \mathbf{B}_0 \]
One (idiosyncratic) interpretation:
Energy stored as **Excess Length** of field lines

\[ W_M = \frac{1}{8\pi} \int B^2 dV = \frac{1}{8\pi} \int d\Phi \int B \, d\ell \]

\[ \Delta W_M = \frac{1}{8\pi} \int d\Phi \, \Delta \left[ \int B \, d\ell \right] \]

mostly from shortening field lines

... accompanied by compression

\[ \Delta V = \int d\Phi \, \Delta \left[ \int \frac{d\ell}{B} \right] < 0 \]
How reconnection (i.e. topological change) enables* field line shortening (a.k.a. energy release)

\[ W_M = \frac{1}{8\pi} \int d\Phi \int B \, dl \]

\[ \Delta W_M \sim \delta \Phi B w \]

\[ \Delta W_M \sim \delta \Phi B \Delta L \]

* BUT does not produce it
How does rapid field line shortening result in heating?

\[ \frac{E_{\|}}{E_{\text{kin}}} = \sin^2 \left( \frac{\Delta \theta}{4} \right) \]

A: thermalization @ shocks

no thermo-dynamic change @ RD
retraction starts

TFT model

fast & Alfven waves, FMTS

retraction ends

slow mode: remains w/ tube \( \Rightarrow \) heat

\[
\frac{E_{\parallel}}{E_{\text{rel}}} = \sin^2 \left( \frac{\Delta \theta}{4} \right)
\]
**Devil’s Advocate:** "This doesn’t seem like Petschek reconnection"

**Dana:** It captures same heating as 2.5D Petschek… compare using Rankin-Hugoniot relations*

* unrealistic – therm. conduction → isothermal shocks

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**Diagram:**

- 3D transient (Longcope et al. 2009)
- 2.5D steady (Soward 1982)
- 2D steady (Petschek 1964)
- 1D transient (Lin & Lee 1994)

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**Legend:**

- Little field-weakening ➔ SMS ~ GDS
- Energy source: field line shortening

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*M unrealistic – therm. conduction → isothermal shocks
Example I:
2004-Feb-26

Ribbons – sweep flux
\[ \Delta \Phi \sim 6 \times 10^{21} \text{ Mx} \]

\[ \Phi \sim 1.7 \times 10^{19} \text{ Mx/s} \]

140 Loops: \( \delta \Phi = 10^{19} \text{ Mx} \)

DWL, Qiu & Brewer 2016

SolFER 2021 Meeting
Ribbon measurements miss some flux slightly late.
15 keV used for $\dot{\Phi}(t)$

Used to adjust

$L_0 = 47 \text{ Mm}$

$T_{\text{max}} = 5.7 \text{ MK}$

$\Delta \theta = 105^0$
What a slow-mode shock looks like…

hot dense plug from SMS – persists @ base of CS

$\delta \Phi = 2 \times 10^{19} \text{ Mx}$

$\dot{\Phi} = 10^{19} \text{ Mx/s}$

RHESSI 12-25 keV

DWL, Qiu & Brewer 2016
Observing slow shocks – ~15 MK bar along top of arcade = bottom of plasma sheet
Q1: how can $n_e$ jump $\times 10$? models say $\times 2.5$

Q2: how does $n_e(x)$ fall off faster than equilib.?  

Q3: why does $T(x)$ peak near base of CS?

**Example II:** 2017-Sep-10
SADs or SADLs?

200 km/s
Through a sheet with varying $B(x)$, retraction decreases. $V_A$ and $V_{ap}$ are shown, with $T(x)$ increasing downward. A face-on view shows $B(x)$.
Points to consider

• Energy (\textcolor{blue}{mag}) stored by \textcolor{red}{current sheet} \ (not @ CS)
• Energy released by shortening field lines … \textcolor{red}{following} reconnection
• Shortening via Lorentz Force (tension):
  \textcolor{blue}{mag} \rightarrow \textcolor{green}{kin} \ (\textcolor{green}{ions})
• Global rate \neq local \textcolor{green}{E} \ field
• Fraction of energy remains w/ loop – \textcolor{red}{flare}
• Release must be accompanied by compression/density enhancement – important feature of observations