Solar Flares: Everything you need to know*

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*but were afraid to ask
Operational def’n: Flare: sudden brightening in X-rays
Close-up of that brightening
# Epistomology

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  • Spectrum  
  • Images | • Eruptive/compact flares  
  • Impulsive/gradual phases  
  • Neupert effect  
  • Flare ribbons  
  • X/M/C flares  
  • Above-the-loop-top source | • CSHKP model  
  • Reconnection  
  • Chromospheric evaporation  
  • Non-thermal electrons |

**Terminology & jargon**
- In progress
### Epistomology

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**Terminology & jargon**  
In progress
How they relate... the basic picture

CME

Current sheet

flare
Progress of a flare

1. Release of magnetic energy
2. Downward energy transport
   a. Thermal conduction (fluid)
   b. Non-thermal electrons (beyond fluid)
3. Evaporation: Loops fill
4. Loops Cool
   a. Thermal conduction
   b. Radiative cooling

Flare: X-ray brightening

most observations
magnetic energy released

loops cool
energy transport
conduction front
isothermal Petschek shock
hard x-ray region (> 10^8 K)

evaporation
chromospheric downflow

Forbes & Acton 1996
current sheet
Mach 2 jet
termination/post shock front/shock enhancement
condensation/conduction downflow
uv loops (10 to 500 A)
Hz loops (1 to 5 A)
flare ribbon
1. Energy release

- Based on Lin & Forbes 2000
- Fix flux rope (focus on flare)
- CS beneath
- Current density $K(z)$
- Integrates to current $I$
- Reconnected flux in arcade
- Maps to chromospheric ribbons
Electrodynamic work done

\[ W = \int I \, d\Phi \]

= drop in magnetic energy
– energy release

\[ E \times L = \frac{d\Phi}{dt} \]
AIA 1600 A:
100,000 K plasma
chromospheric feet

AIA 171 A:
1,000,000 K plasma
coronal loops
Flux measured from flare ribbons
2011 December 26 (hours in UT)

reconnection flux \( (10^{21} \text{ Mx}) \)

reconnection rate \( (10^{18} \text{ Mx}/\text{s}) \)

\[ W = \int I \, d\Phi \sim \frac{1}{2} I_0 \Delta \Phi \sim \frac{(\Delta \Phi)^2}{8\pi L} = \frac{(1.5 \times 10^{21})^2}{8\pi \cdot 7.5 \times 10^9} = 1.2 \times 10^{31} \text{ erg} \]
2. Energy transport
$\Delta L \approx \frac{N}{n_e} = 10^8 \text{cm}$

Electron collision cross section (Rutherford)

$\sigma_e = 10^{-17} \text{cm}^2 \times E_{\text{keV}}^{-2}$

Stopping column

$N = \int n_e \, d\ell = \frac{1}{\sigma_e} = 10^{17} \text{cm}^{-2} \times E_{\text{keV}}^2$

3 keV (T=30 MK) $\Rightarrow N=10^{18} \text{cm}^{-2}$
Electron collision cross section (Rutherford)

$$\sigma_e = 10^{-17} \text{ cm}^2 \times E_{\text{keV}}^{-2}$$

Stopping column

$$N = \int n_e \, d\ell = \frac{1}{\sigma_e} = 10^{17} \text{ cm}^{-2} \times E_{\text{keV}}^2$$

50 keV $\Rightarrow N = 3 \times 10^{20} \text{ cm}^{-2}$
Observed by RHESSI (Lin et al.)

e⁻'s trapped in CS?
Higher density corona or lower energy e^{-}'s:
All thermal (fluid)

\[ \vec{F} = -\vec{\kappa} \cdot \nabla T \]

\[ \vec{\kappa} = \kappa_\parallel \hat{b}\hat{b} + \kappa_\perp \left( \vec{I} - \hat{b}\hat{b} \right) \]

\[ \frac{\kappa_\parallel}{\kappa_\perp} \sim \left( \Omega_e \tau_{ee} \right)^2 \sim 10^{14} \]
3. Evaporation

From Yokoyama & Shibata 1998
Modeling evaporation

Krall & Antiochos 1980
\[
\frac{\partial n}{\partial t} + \frac{1}{A(s)} \frac{\partial}{\partial s} (Anv) = 0, \quad (1)
\]
\[
n \left( \frac{\partial}{\partial t} + v \frac{\partial}{\partial s} \right)v + \frac{1}{m} \frac{\partial p}{\partial s} = ng_{\parallel}(s), \quad (2)
\]
\[
3kn \left( \frac{\partial}{\partial t} + v \frac{\partial}{\partial s} \right)T + \frac{p}{A(s)} \frac{\partial}{\partial s} (Av) - \frac{1}{A} \frac{\partial}{\partial s} \left( AK \frac{\partial T}{\partial s} \right)
+ n^2 \Lambda(T) = H(s) \quad (3)
\]

Emslie & Nagai 1985
The Basic Picture

Transition region: density/temperature jump @ constant pressure

\[
\frac{\rho_{ch,0}}{\rho_{co,0}} = \frac{T_{co,0}}{T_{ch,0}} = R_{tr}.
\]
The Basic Picture

\[ T(z) \quad \rho(s) \quad p(z) \]

- Chromosphere
- Corona

Conduction
The Basic Picture

Transition region: pressure jump @ constant temperature

Riemann Problem

$T(z)$

$p(z)$

$\rho(s)$
Evaporation as Riemann Problem

- conduction creates uniform high temp. around TR
- evaporation occurs @ constant T for t>0

**Isothermal Riemann problem**
- isothermal – sound speed $a$; iso-T Mach #: $v/a = M^{(it)}$
- condensation shock (hypersonic) propagates down

\[
\frac{\rho_{ch,0}}{\rho_{co,0}} = \frac{T_{co,0}}{T_{ch,0}} = R_{tr}.
\]
Riemann’s Problem:
what happens when the dam breaks?
Riemann’s Problem: what happens when the dam breaks?

\( v(x,0) = 0 \)
Riemann’s Problem:
what happens when the dam breaks?

wave speed: 10 m/s

wave speed: 2 m/s

rarefaction wave
\[
[M_{es}^{(it)}]^2 = 4R_{tr} \exp \left( -\sqrt{3} - M_{es}^{(it)} + \frac{1}{M_{es}} \right),
\]

\[
\frac{\rho_e}{\rho_{co,0}} = \left[ M_{es}^{(it)} \right]^2
\]

Condensation shock (CS): (hypersonic)

\[ v_c = -\sqrt{3} a \]
\[ \rho_c = 4 \rho_{ch,0} = 4R_{tr} \rho_{co,0} \]

Rarefaction Wave (RW):

\[ v(\ell, t) = \frac{\ell}{t} + a, \]
\[ \rho(\ell, t) = \rho_0 \exp \left( -\frac{\ell}{at} \right) = \rho_0 \exp \left( 1 - \frac{v}{a} \right) = 4R_{tr} \exp \left( -\sqrt{3} - \frac{v}{a} \right) \rho_{co,0} \]
\[
[M_{es}^{(it)}]^2 = 4 R_{tr} \exp \left( -\sqrt{3} - M_{es}^{(it)} + \frac{1}{M_{es}^{(it)}} \right),
\]

\[
M_{es}^{(it)} \simeq 2.670 + 1.209 \log(R_{tr}/100) [1 + 0.126 \log(R_{tr}/100)].
\]

\[
v_{FCM} = \sqrt{\frac{6}{5}} \ln R_{tr} c_{s,*} = \sqrt{2 \ln R_{tr}} a.
\]

Fisher, Canfield & McClymont 1984
\[ E_K = \int \frac{1}{2} \rho v^2 d\ell = \frac{1}{2} \rho_{co,0} a^3 t \int \frac{\rho(\tilde{\ell})}{\rho_{co,0}} [M^{(it)}(\tilde{\ell})]^2 d\tilde{\ell}, \]

Flare energy flux \[ F = \frac{dE_K}{dt} \sim \rho_{co,0} a^3 \]

\[ v_e = aM_e^{(it)} \approx C_e \left( \frac{F}{\rho_{co,0}} \right)^{1/3} \]
Simulations from the past

\[ v_e = C_e \left( \frac{F}{\rho_{co,0}} \right)^{1/3} \]

\( C_e = 0.38 \)
Evaporation observed

Milligan & Dennis 2009

RHESSI 20-25 keV

Hinode EIS
4. Loops cool off

AIA 1600 Å:
100,000 K plasma
chromospheric feet

AIA 171 Å:
1,000,000 K plasma
coronal loops
• Energy released
• Feet brighten
• Loop appears @ 10^6 K – 44 min. later
\[
\frac{\partial}{\partial t} (c_v \rho T) = -\nabla \cdot (v c_p \rho T) - n_e^2 \Lambda(T) + \nabla \cdot (\kappa \nabla T)
\]

One cooling loop: Conduction drives evaporation – fills loop

\[\tau_c \ll \tau_r \quad \tau_c \sim \tau_r\]

\[\tau_c \sim \frac{c_v \rho T}{\nabla \cdot (\kappa \nabla T)} \sim n_e L^2 T^{-5/2}\]

\[\tau_r \sim \frac{c_v \rho T}{n_e^2 \Lambda(T)} \sim n_e^{-1} T^{3/2}\]

\[\frac{\tau_r}{\tau_c} \sim \frac{T^4}{(n_e L)^2}\]
\[ -H(t) = -\nabla \cdot (v c_p \rho T) - n_e^2 \Lambda(T) + \nabla \cdot (\kappa \nabla T) \]

slow draining \& \nabla p = 0 \quad \frac{\partial}{\partial t} \left( \frac{3}{2} p \right) \rightarrow -H(t)

One cooling loop

\[ n_e \sim L^{-1} T^2 \]

\[ \tau_c \sim \tau_r \]

\[ \tau_c < \ll \tau_r \]

\[ T \ [\text{MK}] \]

\[ \tau_c \sim \frac{c_v \rho T}{\nabla \cdot (\kappa \nabla T)} \sim n_e L^2 T^{-5/2} \]

\[ \tau_r \sim \frac{c_v \rho T}{n_e^2 \Lambda(T)} \sim n_e^{-1} T^{3/2} \]

\[ \frac{\tau_r}{\tau_c} \sim \frac{T^4}{(n_e L)^2} \]
Cooling observed
The population: flare statistics

Ignore details of events: focus on statistics

Count events in each bin

Define amplitude bins

April 2002

Convert to freq.

1 = 0.03/day
4 = 0.12/day
11 = 0.33/day
Wheatland 2005

M-flare 14X more likely than X-flare

undercounted

$S_{-2.15}$

$S_1$

$10^{1.15} = 14$
What could it mean?

Solar Flares

Earthquakes

$S^{-1.15}$
Distributions as a forecasting tool

Predicted based on prior power law

Wheatland 2005b
Summary

• A **Flare** is a sudden brightening of the entire star (the Sun) in X-rays
• Energy is released from the coronal magnetic field
• Non-magnetic energy is transported downward to drive chromospheric evaporation – **the actual ``flare”**
• Loops cool and then appear in various EUV images
• Flares of various amplitudes appear at different frequencies: larger flares less frequently