Solar flares and CMEs: Their physics and their observation

Lecture 1
Jan 18, 2017
What is a solar flare?
Krucker & Hudson, RHESSI nugget #218
What is a solar flare?

Operational def’n: **Flare: sudden brightening in X-rays**
What is a solar flare?

A member of a population

April 2002

define amplitude bins

event freq.

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

GoES

1976-2003

$S^{-2.15}$

undercounted

$S_1$

$S^{-1.15}$

M-flare 14x more likely than X-flare

$10^{1.15} = 14$
What is a solar flare?
What is a solar flare?

AIA 1600 Å:
100,000 K plasma
Chromospheric/TR feet

AIA 171 Å:
1,000,000 K plasma
coronal loops
What is a solar flare?
How they relate...
the basic picture

CME

Current sheet

flare
# Epistemology

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<td>• Eruptive/compact flares • Impulsive/gradual phases • Neupert effect • Flare ribbons • X/M/C flares • Above-the-loop-top source</td>
<td>• CSHKP model • Reconnection • Chromospheric evaporation • Non-thermal electrons</td>
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Terminology & jargon In progress
## Epistemology

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**Terminology & jargon**

**In progress**
1. magnetic energy released
2. energy transport
3. evaporation
4. loops cool

CSHKP*: the standard model (of big eruptive flares)

1. Magnetic energy released

2. Energy transport

3. Evaporation

4. Loops cool

Forbes & Acton 1996
Progress of a flare

0. Storage of magnetic energy
1. Release of stored 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
Progress of this course

0. Storage of magnetic energy
1. Release of stored energy
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   a. Thermal conduction (fluid)
   b. Non-thermal electrons (beyond fluid)
3. Evaporation: Loops fill
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   a. Thermal conduction
   b. Radiative cooling

I. Energy release & eruption (CMEs)
   III. Impulsive phase
   II. Flare loops
1. Energy release

- MHD – large scale, slow evolution (> msec)
- Instability
- Reconnection

$\beta \ll 1$

→ focus on magnetic field
MHD equations

Dynamical evolution of fluid densities & $\mathbf{B}$

$$
\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u}) \quad \text{mass continuity}
$$

$$
\rho \left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u} = -\nabla p + \frac{1}{4\pi} \mathbf{J} \times \mathbf{B} + \rho g \quad \text{momentum}
$$

$$
\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\frac{5}{3} p \nabla \cdot \mathbf{u} + \frac{\eta}{6\pi} |\mathbf{J}|^2 + \cdots \quad \text{energy}
$$

$$
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (\eta \mathbf{J} - \mathbf{u} \times \mathbf{B}) \quad \text{induction (Faraday+Ohm)}
$$

$$
\mathbf{J} = \nabla \times \mathbf{B} \quad \text{Ampere}
$$
MHD equations

Dynamical evolution of fluid densities & B

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\mathbf{J} = \nabla \times \mathbf{B} \quad \text{Ampere}
\]
A CME is an MHD instability
Questions to address

• What is the nature of the MHD instability driving a CME?
• How does magnetic energy get released?
  – What triggers the release?
  – What roles is played by magnetic reconnection?
• Into which other forms is the magnetic energy converted? How?
\[ W = \int I \, d\Phi \]

= drop in magnetic energy
– energy release

\[ E \times L = d\Phi/dt \]
AIA 1600 Å:  
100,000 K plasma  
Chromospheric/TR feet

AIA 171 Å:  
1,000,000 K plasma  
coronal loops
Flux measured from flare ribbons
\[ W = \int I \, d\Phi \sim \frac{1}{2} I_0 \Delta \Phi \sim \frac{(\Delta \Phi)^2}{8\pi L} = \frac{(1.5 \times 10^{21})^2}{8\pi \cdot 7.5 \times 10^9} = 1.2 \times 10^{31} \text{ erg} \]
3. Evaporation

From Yokoyama & Shibata 1998
Modeling loops

1d gas-dynamics

Krall & Antiochos 1980

\[
\frac{\partial n}{\partial t} + \frac{1}{A(s)} \frac{\partial}{\partial s} (Anv) = 0, \quad (1)
\]

\[
n \left( \frac{\partial}{\partial t} + v \frac{\partial}{\partial s} \right) v + \frac{1}{m} \frac{\partial p}{\partial s} = ng_{\parallel}(s), \quad (2)
\]

\[
3kn \left( \frac{\partial}{\partial t} + v \frac{\partial}{\partial s} \right) T + \frac{p}{A(s)} \frac{\partial}{\partial s} (Av) - \frac{1}{A} \frac{\partial}{\partial s} \left( AK \frac{\partial T}{\partial s} \right) + n^2 \Lambda(T) = H(s) \quad (3)
\]

energy input (i.e. 1 & 2)
Modeling evaporation

Emslie & Nagai 1985
Observing loops

EUV solar spectrum

80,000 K

6 MK

10 MK

1 MK

2 MK

NASA SDO/EVE
Fe XXIII

$V = -208 \text{ km/s}$

$T = 14 \text{ MK}$

Brosius 2013
\[ v \approx 0: \text{loop has returned to equilibrium} \]
4. Loops cool off

- 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 loop

enthalpy flux  \hspace{0.5cm} \text{radiation}  \hspace{0.5cm} \text{conduction}

\begin{align*}
T \text{ [MK]} \\
5 & \rightarrow 30 \\
0 & \rightarrow 30
\end{align*}

\begin{align*}
ne [10^9 \text{ cm}^{-3}] \\
0 & \rightarrow 15 \\
5 & \rightarrow 15
\end{align*}
More dense = more visible
Raftary et al. 2009

EBTEL result

+ 15:17 - RHESSI
× 15:19 - GOES
○ 15:24 - Fe XIX
△ 15:35 - Fe XVI
□ 15:37 - Mg X
○ 15:49 - OV

EM \times 10^{49} [cm^{-3}]

Temperature [K]
Lightcurves 26-March-2002

Intensity [arb units]

Start Time (26-Mar-02 14:50:00)

EBTEL result
+ 15:17 - RHESSI
× 15:19 - GOES
○ 15:24 - Fe XIX
△ 15:35 - Fe XVI
□ 15:37 - Mg X
○ 15:49 - 0 V

Raftery et al. 2009
Cooling observed

![Diagram showing a graph with normalized counts on the y-axis and time in UT (hours) on the x-axis. The graph includes lines for different iron ions (Fe XXI, Fe XVIII, Fe XVI, Fe XII, Fe XI) with corresponding peak times and counts. There are also images of solar events at 11:32, 12:20, and 12:44.](image)
2. Energy transport
Electron collision cross section (Rutherford)

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

"stop": $$\int \sigma_e n_e d\ell = 1$$

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) \(\rightarrow\) \(N=10^{18} \text{ cm}^{-2}\)
$\sigma_e = 10^{-17} \text{ cm}^2 \times E_{\text{keV}}^{-2}$

$\Delta z \approx H_\rho \ln \left( \frac{N}{n_{e,0} H_\rho} \right) = 10^8 \text{ cm}$

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

$50 \text{ keV} \Rightarrow N = 3 \times 10^{20} \text{ cm}^{-2}$
How do we “see” 50 keV e⁻s?

1. From ~ 50 keV photons they emit: hard X-rays
2. From plasma waves they create: µ-waves and radio waves

Kuroda et al. 2015
Observed by RHESSI (Lin et al.)

e^{-}'s trapped in CS?
Modeling the $e^-$ population

\[ \mu = \cos \theta \]

\[ f(s, \mu, p, t) \, ds \, d\mu \, dp \]

= \# $e^-$s in volume of $(s, \mu, p)$ space

NB: Maxwellian

\[ f(\mu, p) \sim e^{-p^2/2mkT} \]

Fokker-Planck equation:

\[
\frac{\partial f}{\partial t} + v \frac{\partial f}{\partial s} = \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left( D_{pp} \frac{\partial f}{\partial p} + D_{p\mu} \frac{\partial f}{\partial \mu} \right)
\]

\[ + \frac{\partial}{\partial \mu} \left( D_{\mu\mu} \frac{\partial f}{\partial \mu} + D_{\mu p} \frac{\partial f}{\partial p} \right) - \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 \dot{p} f \right) + S, \]
\[ \frac{\partial f}{\partial t} + v \frac{\partial f}{\partial s} = \frac{1}{p^2} \frac{\partial}{\partial p} p^2 \left( D_{pp} \frac{\partial f}{\partial p} + D_{p\mu} \frac{\partial f}{\partial \mu} \right) \]
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Summary

• CME/Flare consists of 4 things:
  erg. release, erg. Xport, evaporation, loop cooling
• Involve different elements of Physics:
  Fluids (MHD), radiation, kinetic theory
• Will cover all 4 in this course – out of order

Next

Physics of eruption: MHD instabilities