SOLAR CORONA AND FLARES

SOME INSIGHTS ON 3D RECONNECTION

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FUNDAMENTAL PLASMA PHYSICS
Waves, Reconnection, Instabilities

DIAGNOSTICS
Plasma imaging, Spectroscopy, Thomson scattering

DYNAMO THEORY
Theory, simulation, helioseismology

TURBULENCE
Current layers, as the source of the solar wind

COSMIC RAYS
Solar Energetic Particles (SEPs)
What we see here is the photosphere
The reddish structures show the chromosphere.

The haze is the **corona**.
Table A1: IA wavelengths bands.

<table>
<thead>
<tr>
<th>Channel name</th>
<th>Primary ion(s)</th>
<th>Region of atmosphere</th>
<th>Other (log T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>white light</td>
<td>continuum</td>
<td>photosphere</td>
<td>3.7</td>
</tr>
<tr>
<td>1700Å</td>
<td>continuum</td>
<td>temperature minimum, photosphere</td>
<td>3.7</td>
</tr>
<tr>
<td>304Å</td>
<td>He II</td>
<td>chromosphere, transition region</td>
<td>4.7</td>
</tr>
<tr>
<td>1600Å</td>
<td>O IV+neutral</td>
<td>transition region + upper photosphere</td>
<td>5.0</td>
</tr>
<tr>
<td>171Å</td>
<td>Fe IX</td>
<td>quiet corona, upper transition region</td>
<td>5.8</td>
</tr>
<tr>
<td>193Å</td>
<td>Fe XII, XXIV</td>
<td>corona and hot flare plasma</td>
<td>6.1, 7.3</td>
</tr>
<tr>
<td>211Å</td>
<td>Fe XIV</td>
<td>active-region corona</td>
<td>6.3</td>
</tr>
<tr>
<td>335Å</td>
<td>Fe XVI</td>
<td>active-region corona</td>
<td>6.4</td>
</tr>
<tr>
<td>131Å</td>
<td>Fe VIII, XXIII</td>
<td>flaring regions (partial resolution possible)</td>
<td>6.8</td>
</tr>
<tr>
<td>193Å</td>
<td>Fe VIII, XXIII</td>
<td>flaring regions (partial resolution possible)</td>
<td>5.6, 7.0, 7.2</td>
</tr>
</tbody>
</table>

The table provides information about different wavelengths and their corresponding regions in the solar atmosphere, along with other relevant data.
THE TEMPERATURES IN THE SUN’S CORONA

- 6000K
- 50000 MK
- 10 MK
- 1.25 MK
- 6000K
The corona: what conditions?

The corona has $\beta<1$: the magnetic pressure dominates

Magnetic field extrapolations

Simulations of the magnetic field behaviors

Problem: it is « sandwiched » between two $\beta>1$ regions!

See Gary 2001
THE STRUCTURES IN THE CORONA

Coronal holes (regions of open magnetic field lines)

« Quiet » sun regions (bright points)

Active regions (flares)

Coronal loops
**WHAT IS A FLARE?**

« Flare »: sudden brightening in solar atmosphere

- Large number of non-thermal electrons (not detected in the non-flaring hot corona)

Fev.15, 2011 X-class flare

- X-ray 100 keV (Yohkoh)
- X-ray 20 keV (Yohkoh)
- Microwave 6.6 GHz (OVSA)

Qiu et al. (2004)

Schrijver et al. (2011)

**Flare** is a sudden brightening in the solar atmosphere, often accompanied by increased radiation and energy dissipation. This phenomenon is characterized by the presence of a large number of non-thermal electrons, which are not observed in the non-flaring hot corona. The specific event on February 15, 2011, was classified as an X-class flare.
What is a flare?

Depends on peak of X-ray flux

A GOES soft X-ray time series: 1-8Å and 0.5-4Å passbands

Largest flare:
Halloween flare (Nov 4 2003) $10^{33}$ erg ($10^{26}$ J) X28
Super flares?
Up to $3 \times 10^{36}$ erg ($10^{29}$ J)
CORONA HEATING VS FLARES: what’s similar/different?

- Coronal heating is quasi-steady, plasma seems to evolve slowly
- Flares are abrupt: plasma heats and evolves rapidly, structural changes, non-thermal electrons not detected in non-flaring hot corona

**Coronal heating:**
- Quasi-steady hot corona means a quasi-continuous dissipation process
- No need for coronal energy storage
- Plasma remains almost Maxwellian

**Flares:**
- Rapid character of flare means very intermittent energy dissipation
- Need for long-term energy storage.
- Plasma becomes non-Maxwellian
Coronal heating is quasi-steady, plasma seems to evolve slowly

« Spicules », or small « jets » coming from the chromosphere, Alfvén waves due to motions convective/photospheric layers
**CORONA HEATING VS FLARES: what's similar/different?**

- Flares are abrupt: plasma heats and evolves rapidly
  - But if it happens at small scales everywhere, can it work?

Coronal heating by reconnection-generated Joule heating and Alfven wave dissipation

Adapted from Schrijver (2009)
NUSTAR: SHOWING MICRO-FLARES IN QUIET SUN REGIONS

- EUV from SDO
- Low X-rays from Hinode
- High X-rays from NuSTAR

Coronal heating?
Probably a combination of all mechanisms...
Adapted from Schrijver (2009)
Kepler data suggests continuation up to $5 \times 10^{35}$ erg.
FROM SOLAR FLARES TO STELLAR FLARES

Kepler data suggests continuation up to \(5 \times 10^{35}\) erg.

But frequency scaling with more active stars fails...

Understanding of solar flares may (or may not!) help us understand flaring activity on other stars....
WHAT HAPPENS DURING A SOLAR FLARE?

From observational aspects to models
CHARACTERISTICS OF SOLAR FLARES: observations

Flares can be **eruptive** or **confined**

Eruptive flares:
- associated with a CME

Confined flares
Eruptive flares

**LASCO 2002/02**

Eruptive flares: associated with a CME
CHARACTERISTICS OF SOLAR FLARES: confined flares

Flare – Emission & Loops

03/2014 (SDO)

Failed filament eruption

Ji et al. (2003)
CHARACTERISTICS OF SOLAR ERUPTIVE FLARES: prominences/filaments

11 August 1980: Hα image

Source: NOAA/SEL/USAF
Pre-eruptive sigmoid & filament
(not always)

Rust & Kumar (1996), Green & Kliem (2009), Schmieder (2013), Aulanier et al. (2012)

We think they are indicative of the presence of a FLUX ROPE
Flux ropes are expected to be at the heart of solar eruptions.
CHARACTERISTICS OF SOLAR ERUPTIVE FLARES: flare loops

Flare loops

⇒ Low-to-high altitude loop brightening
⇒ Strong-to-weak shear transition
Hard X-ray source above the loop top: particle acceleration at reconnection site

Masuda et al. (1994), Hudson et al. (2001), Sui et al. (2003)

SXR high temperature ridges along outer or newly formed loops: heating takes place

Tsuneta et al. (1996)
CHARACTERISTICS OF SOLAR ERUPTIVE FLARES: the CSHKP model

Forbes & Malherbe (1986)

Standard flare model is developed
WHAT HAPPENS DURING A SOLAR FLARE?
From observational aspects to models

WHERE DOES MAGNETIC RECONNECTION OCCUR?
From null points to QSIs, a topology story
MAGNETIC TOPOLOGY: UNDERSTANDING LOCATIONS OF ENERGY RELEASE

Method:

Input the photospheric magnetogram

Compute the coronal field

Compute magnetic null points & separatrices

2D separatrices

3D separatrices: 2 intersecting cupola

4 connectivity domains

Titov et al. 2002
**TOPOLOGY OF SOLAR FLARES: 3D extensions**

**Magnetic Charge Topology Models:**

From 4 point charges...
- Baum & Brathenal 1980, Gorbachev & Somov 1988, Lau 1993

...to multiple ones:

**Démoulin et al. 1994b:**
Photospheric mapping of the magnetic field:
Flares occur in regions where no null points are found

If no null points: mapping functions of field line footpoints from one boundary to another are continuous

- Schindler et al. 1988
- Hesse & Schindler 1988
  - Separatrices/Separators do not need to exist
  - « Reconnection » takes place where \( E_\parallel \) is important (« non-idealness »)

Also: Priest & Forbes 1989, 1992
FLARES IN 3D: no null point configuration

Priest & Démoulin 1995
Démoulin et al. 1996-1997

Idea of reconnection happening in regions of strong magnetic field distortion:

« Quasi » separatrix layers

Reconnection can occur (and does) {

physically} in regions where ideal MHD breaks down

Since then: numerous evidences of flaring activity associated with quasi-separatrix layers:

Schmieder et al. 97, Démoulin et al. 97, Mandrini et al. 97, Bagala et al. 00, Wang et al. 00, Fletcher et al. 01, Mandrini et al. 06, Masson et al. 09, Chandra et al. 11, Savcheva et al. 12, Inoue et al. 13, Zhao et al. 14, Savcheva et al. 14, Dudik et al. 14

e.g. to explain « non-standard » flare: Dalmasse et al. (2015), Joshi et al. (2019)
**In 3D:**

**Strong distortion of magnetic field ⇒ Current layer**

Ideal MHD can still break down in those finite-J regions.

**Localized, drastic** change of magnetic connectivity (but continuous without null points)

**QSL definition:** regions where

$$Q = \frac{\| F \|^2}{B_{n,+} / B_{n,-}} \gg 1$$

Démoulin et al. (1996), Titov et al. (2002), Pariat et al. (2012)

"Squashing degree"
QSLS in twisted configuration

Hyperbolic Flux Tube: X-shape in a 2D plane (largest Q region)

- 2.5 D
- Separator
- Q large → thin volume
- PIL
- 1 turn
- 1.5 turn
- 2 turns

QSLS in Twisted Configuration
Valiation from Observations

Topology Analysis with Magnetic Field Extrapolations

- $1^{st}$ QSLs from a data-constrained model
- More complex than previous analytical model but similarities in shape

$\xrightarrow{\text{Similar shape as for an analytical model (so-called Titov-Démoulin model)}}$

Hinode/XRT

Twisted flux rope

Savcheva et al. (2012a,b)

Titov & Démoulin (1999)
WHAT HAPPENS DURING A SOLAR FLARE?
From observational aspects to models

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From null points to QSLs, a topology story

HOW DOES MAGNETIC RECONNECTION OCCUR?
From the trigger to slipping reconnection
Démoulin et al. (1996), Titov et al. (2002), Pariat et al. (2012)

In 3D:

Strong distortion of magnetic field $\Rightarrow$ Current layer

Ideal MHD can still break down in those finite-$J$ regions.

$\Rightarrow$ Slipping reconnection

Successive reconnection due to the continuous change of connectivity

$\Downarrow$ Current layers: Similar location as QSLs

See also: (Galsgaard et al. 00, 03, Pontin et al. 05, Aulanier et al. 05, 06, Pariat et al. 06, Büchner 06, Dreher et al. 08, ...
**Threshold for eruptions?**

**OHM code** \( \beta = g = 0 \)

- Photospheric magnetic diffusion of \( B_{x,y,z} \)
- Photospheric shearing motions \( u_{x,y} \)

Aulanier, Török, Démoulin & DeLuca (2010)
Threshold for eruptions?

- Coronal arcades
- Erupting flux rope

(no driving, from $t = 125 \, t_A$)

Flux rope is stable

stop driving $\rightarrow$ relax to an equilibrium

Apex of the overlying arcade

Flux rope erupts

Time / $t_A$

Reconnection in 3D: slipping reconnection

$\rightarrow$ Torus Instability

Démoulin & Aulanier (2010)

Aulanier et al. (2012)

Janvier et al. (2013)

Dudik et al. (2014)
Threshold for eruptions?

- Coronal arcades
- Erupting flux rope

- Shear transferred from pre-eruptive field lines via reconnection

- Formation of flare loops:
  - strong-to-weak shear transition
  - Low to high altitude formation

- Envelope formation of the flux rope
FLUX ROPE: A FULLY 3D STRUCTURE
BEFORE

AFTER

FLUX ROPE: A FULLY 3D STRUCTURE
WHERE DOES RECONNECTION TAKE PLACE IN THE SIMULATION?

Coronal arcades
Erupting flux rope

Janvier, Aulanier, Pariat & Démoulin (2013)
WHERE DOES RECONNECTION TAKE PLACE IN THE SIMULATION?

- Current layers: Similar location as QSLs
  
  See also: (Galsgaard et al. 00, 03, Pontin et al. 05, Aulanier et al. 05, 06, Pariat et al. 06, Büchner 06, Dreher et al. 08, ...)

- Collapse of the coronal current layer (=thinning)
  Prediction from the model (not yet observable)

\[ Q = \text{squashing factor} \]

\[ J = |\text{curl } B| \text{ electric currents} \]

Janvier, Aulanier, Pariat & Démoulin (2013)
Slipping reconnection (reconnection in 3D)

Creation of new magnetic structures (here, the flux rope):
So... Does it really exist?

X-class flare of July 2012

Dudik et al (2014)
Slipping in a flare

Slipping reconnection with QSLs:
successive change of magnetic connectivity

Janvier, Aulanier, Pariat & Démoulin (2013)

Leads to:

- Apparent field line motion
  See also: Aulanier et al. (2007)

- Kernel motion
  See also: Young et al. (2013)

X-class flare of July 2012
Further evidences...

Now further evidences pointed out + detailed analysis

- Moving kernels (footpoints) + plasma upflows (spectroscopy diagnostics)

- To explain flickering at the end points of some coronal loops

Direct observations:
2007: 1st observation (Hinode) Aulanier et al. 2007
Dudik et al. 2014 (1st observation for flares)
WHAT HAPPENS DURING A SOLAR FLARE?
From observational aspects to models

WHERE DOES MAGNETIC RECONNECTION OCCUR?
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HOW DOES MAGNETIC RECONNECTION OCCUR?
From the trigger to slipping reconnection

CONCLUSION & REMAINING CHALLENGES
Where are the particles? What's the energy equipartition?
FROM MHD TO PARTICLE MODELS? (ENERGETIC PERSPECTIVES)

**Remaining Challenges**

**Energetics of flares**

- **Emslie**: kinetic energy ~ same or 3x bolometric energy
- **Model prediction**: kinetic energy ~ 5-10% of flare energy

Amari et al. (2003), also: Jacobs et al. 2006; Lynch et al. 2008; Reeves et al. 2010; Aulanier et al. 2012

**Why such discrepancies?**
- Observational biases?
- Numerical problems in ALL codes?

**What's the energy partition during solar flares?**
FROM MHD TO PARTICLE MODELS?

Macroscopic dynamics of magnetic fields
flux ropes, field distortion, current layers
+ instabilities, forcing (e.g. photospheric motions)

Current layer collapse, reconnection, large-scale morphology changes

Transport of Energy
Particles acceleration, Waves

Chromospheric/Photospheric reaction (e.g. White-light flares),
FROM MHD TO PARTICLE MODELS?

Ex with RADYN code:
- Allred et al. (2015) (electron + ion)
- Kerr et al. (2016) (waves)
- Kowalski et al. (2017) (electron but WL flare)

**Macroscopic dynamics of magnetic fields**
- flux ropes, field distortion, current layers
- instabilities, forcing (e.g. photospheric motions)

**Current layer collapse, reconnection, large-scale morphology changes**

How is magnetic energy converted during reconnection?
Energetic partition between particles and waves?

**Transport of Energy**
- Particles acceleration, Waves
- Chromospheric/Photospheric reaction (e.g. White-light flares)
Magnetic islands, turbulence, shocks, Alfvèn waves...

Allred et al. (2015), Yamada et al. 2014, 2016, MRX experiment (Princeton) « >50% of the magnetic energy is converted to particle energy, 2/3 of which transferred to ions and 1/3 to electrons. » Also confirmed in MMS mission (see Toledo-Redondo et al. 2017)
WHY I NEEDED MORE TIME

Types/class of flares
- Confined flare (localised)
- Eruptive flare (with CME)

Driver of eruptive flares:
- Large flux dispersal
  - Coronal tension + Flux rope formation
  - Torus unstable flux rope

Storage

Emergence/boundary motions
- Currents are important!

Topology of flares
Null points and QSLs
- QSLs extend the concept of separatrices

Reconnection
Observations, models