Solar Flares

STFC Advanced Summer School in Solar Physics

H. S. Hudson
Space Sciences Laboratory
University of California, Berkeley
and University of Glasgow

Part 1: Introduction: observations
Part 2: The role of particles
Contents

Part 1: Introduction: observations
  • Overview “why study flares?”
  • History and basic observations
  • The newest things

Part 2: Two theoretical frameworks
How do we describe our uncertainty?

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns.

Systematic errors explained by D. Rumsfeld

There are random errors. These are things we know quantitatively. These are known unknowns. Then there are things that we know about but can't quite characterize quantitatively. These are the systematic errors. But there are also model uncertainties.

Systematic errors explained (as though) by Ineke De Moortel
What is observable?

\[ I_\nu(s) = I_\nu(s_0)e^{-\tau(s_0,s)} + \int_{s_0}^{s} j_\nu(s')e^{-\tau(s',s)} ds' \]

This equation is a general solution of the equation of radiative transfer, with \( j_\nu \) the spectral emissivity and \( \tau \) the optical depth, itself an integral of the spectral absorption coefficient along a given ray path.

Trick question No. 1: as astronomers, how do we observe \( I_\nu \)?
What is observable?

\[
I_\nu(s) = I_\nu(s_0)e^{-\tau(s_0, s)} + \int_{s_0}^{s} j_\nu(s')e^{-\tau(s', s)}\,ds'
\]

This equation is a general solution of the equation of radiative transfer, with \(j_\nu\) the spectral emissivity and \(\tau\) the optical depth, itself an integral of the spectral absorption coefficient along a given ray path.

Trick question No. 1: as astronomers, how do we observe \(I_\nu\)?

Answer: we can’t observe it, since it is a differential quantity. Instead we observe its integral as a flux.
Definitions

- A solar flare is, strictly speaking, the electromagnetic radiation from a coronal magnetic energy release.
- A coronal mass ejection (CME) is a catastrophic expansion of a part of the coronal field.

- Both flare and CME require a *magnetic storage* to supply the energy:

\[
\int_{\text{before}} B^2/8\pi dV > \int_{\text{after}} B^2/8\pi dV
\]
Why is flare physics interesting?

• With a flare, we get to perturb the solar atmosphere with an impulse. This is a standard engineering technique in mechanical design.

• Recently, a comet was detected as it dissipated in the solar atmosphere – another example of an “instrumented hammer”.
Why is flare physics interesting?

• With a flare, we get to perturb the solar atmosphere with an impulse. This is a standard engineering technique in mechanical design.

• Recently, a comet was detected as it dissipated in the solar atmosphere – another example of an “instrumented hammer”.

Strain

Stress
Historical: visual sighting and compass deflection

Carrington’s 1859 “White Light” flare

“Crotchet” in compass record due to ionization by flare UV radiation

Interplanetary shock wave smites Earth’s magnetosphere (ICME arrival)
Flare Classification

Table 5.1. Flare classifications

<table>
<thead>
<tr>
<th>GOES class</th>
<th>1-8Å peak W/m²</th>
<th>Hα class</th>
<th>Hα Area Millionths of hemisphere</th>
<th>CME fract. a percent</th>
<th>Events/year max/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&gt;10⁻⁸</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>&gt;10⁻⁷</td>
<td>S</td>
<td>&lt;200</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>&gt;10⁻⁶</td>
<td>1</td>
<td>&gt;200</td>
<td>20</td>
<td>&gt;2000/300</td>
</tr>
<tr>
<td>M</td>
<td>&gt;10⁻⁵</td>
<td>2</td>
<td>&gt;500</td>
<td>50</td>
<td>300/20</td>
</tr>
<tr>
<td>X</td>
<td>&gt;10⁻⁴</td>
<td>3</td>
<td>&gt;1200</td>
<td>90</td>
<td>10/one?</td>
</tr>
<tr>
<td>-</td>
<td>&gt;10⁻³</td>
<td>4</td>
<td>&gt;1200</td>
<td>100</td>
<td>few?/none?</td>
</tr>
</tbody>
</table>

aYashiro et al. (2005) (approximate values)

From Heliophysics II, eds. Schriver & Siscoe
Modern flare recording

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

The GOES passbands
• Quiet Sun; ~BB + EUV
• $\nu f_\nu = \lambda f_\lambda$ representation
TRACE: dimming, implosion, oscillations
What do we know about the atmosphere?

- The parameter ranges are enormous
- How do we know what is important?
- Where do we put the boundary conditions?
- Transparency and the 3\textsuperscript{rd} dimension

The classical “VAL-C” model, the paradigm for semi-empirical model atmospheres – static, 1D idealizations with limited physics
Flare effects are seen everywhere

1. Interior: Helioseismology
2. Cold atmosphere: UVOIR astronomy
3. Corona: Optical, X-ray, Radio
4. Solar Wind: Radio, in-situ

For flares, the cold atmosphere (photosphere, chromosphere, transition region) and the corona are the main venues as regards causation (we think)
Solar and Stellar Flare Spectra

SOL, mag -26

YZ Cmi, mag +11

Hiei, Neidig, Rust

Kowalski et al

Glasgow Summerschool 2011
Photospheric field changes (LOS only)

“Confusogram” values:
10x10 2.5” pixels
240 minutes time base
500 G magnetic range

Sudol-Harvey 2005
2 Nov. 2003 flare
cf Kosovichev & Zharkova 1999;
Wang et al. 2002
Sunquake discovery

Flares produce photospheric disturbances at the time of the impulsive phase.

Flare quakes first detected by Kosovichev & Zharkova (1996)

Quake origin is approximately co-spatial with hard X-ray sources, and requires about 0.1% of flare energy.

How do we get energy down into such deep layers of the atmosphere?
New \( \gamma \)-ray Results I (RHESSI)

HXRs and gamma-ray lines have similar time profiles, implying related acceleration. However, radiation produced by ions is in a different location from electron bremsstrahlung.

- Neutrons are produced by energetic ions (10s of MeV/nucleon).
- The capture line is predicted to form within 500 km of the neutron production site.
- But observed to be systematically offset from HXRs (electrons) by \( \sim 10,000 \text{km} (15") \).

Still a mystery….
New $\gamma$-ray Results II (Fermi)

- Long-duration signature above 100 MeV (H. Elliott?)
- Inverse Compton signal from galactic cosmic rays in the corona
Contents

Part 1: Introduction: observations

Part 2: Two theoretical frameworks
  • Global (~MHD) theory
  • Particle theory
Large and Small Scales

• The coronal magnetic energy release requires action on large scales:
  - Soft X-ray loops and arcades
  - Global waves (coronal, chromospheric, seismic)
  - Large-scale coronal phenomena (CMEs, radio and hard X-ray sources)

• But, we cannot neglect the microphysics:
  - Particle acceleration
  - Magnetic reconnection

This juxtaposition of scales implies that theoretical work must deal responsibly with boundary conditions, as well as with the solutions of the equations
Global theories I

The standard model ("CSHKP")

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons

Cargill & Priest
Global theories II

*Magnetic Explosion*

Moore & LaBonte 1973

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons
Global theories III

Magnetic Implosion

Field connections

Isomagnetobars

Hudson 2000

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons
Global theories at work

Coronal magnetic structure, from *Sun et al. 2011*

\[ \nabla \times \mathbf{B} = \alpha \mathbf{B} \]

\[ E_f = E_N - E_P = \sum (B_N^2 - B_P^2)/8\pi. \]
Global theories at work II

Graphs showing free energy, $E_{\text{NLFF}} / E_{\text{FF}}$, and GOES flux over time.
Particle theories I

The classical thick-target model

Accelerated electrons originate in corona.

Electron beam travelling along coronal \( \mathbf{B} \) carries flare energy to the chromosphere

\[
I(\epsilon) = \frac{nV}{4\pi R^2} \int_{\Omega} \int_{\epsilon} \bar{F}(E, \Omega', \Omega, \epsilon, E) dE d\Omega',
\]

Photon spectrum

Source-averaged electron spectrum

Need \( 10^{35} - 10^{36} \) electrons/s accelerated. Coronal \( n_e = 10^9 \) cm\(^{-3} \), so each second, all electrons in \( V = 10^{26} - 10^{27} \) cm\(^3 \) accelerated.

\[ \text{http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons} \]
• Alfvén waves transport energy from the corona as $\mathbf{E}\times\mathbf{B}$ flux
• The accelerated electrons originate in chromosphere.

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons
Particle theories III

The coronal/solar-wind shock

Elliott, 1973

Mewaldt et al., 1973

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons
Can we reconcile global and particle theories?
Separatrices and particles in

Separatrix intersections

Time evolution of HXR footpoint positions

Metcalf et al., 2003
Diffusive Shock Acceleration I

Large solar eruptions producing high speed CMEs (1000-3000km/s) are the principal source of energetic particles – protons, electrons and minor ions - in the solar system.

SEPs are accelerated both in flares (‘impulsive’ SEPs) and at CMEs (‘gradual’ CMEs).

Reames (1999)
Diffusive Shock Acceleration II

An MHD shock is essentially a bend in the magnetic field that is propagating faster than the upstream Alfven speed.

The shock-jump conditions (Rankine-Hugoniot conditions) describe conservation of mass, momentum, energy across a (collisionless) shock.

e.g., from pressure continuity

\[ \left[ \rho v^2 + p + \frac{B_{\perp}^2}{2\mu} \right]_{\text{upstream}} = \left[ \rho v^2 + p + \frac{B_{\perp}^2}{2\mu} \right]_{\text{downstream}} \]
Diffusive Shock Acceleration III

Ratio of magnetic field across a collisionless MHD shock $< 4$.

So particles don’t pick up much energy unless they cross and recross field many times.

Scattering on each side of the shock front allows many shock-crossings, so particle picks up energy.

The scattering is presumed to be due to wave-particle interactions; the acceleration can be described as a diffusion process.
Global Waves

- SSC* shock; Type II burst; Moreton wave; EIT wave
- Major controversy on the interpretation of the metric type II and Moreton wave: is it a blast wave (Uchida)?

*Storm Sudden Commencement (geomagnetic term)
Subtracted Doppler Images (R-B Wing) Showing Down-Up Pattern
Examples from Vourlidas et al. 2003

1999 April 2

2000/12/18 02:06
Comments on coronal shocks

- The evidence for blast waves independent of CME occurrence is lacking
- CME-driven waves may start in the flare core
- Shock signatures in LASCO don’t look like the cartoons, ie are not bow waves of the observed CME
Conclusions

• Flare physics grapples with extremely complex systems
• New and fundamentally important discoveries are being made
• Challenging problems are available for any enterprising individual; there is plenty of data and modeling capability is progressing rapidly
What challenging problems?

• What is the energy/momentum transport mechanism for sunquakes?
• How is flare energy redistributed?
• How do we explain the ubiquitous power law for microflares, $dN/dE \sim E^{-1.7}$?
• What segregates the ions from the non-thermal electrons?
• …
What new observational work?

- ALMA and FASR radio astronomy
- *NuSTAR* hard X-ray imaging
- *Observer* stereoscopy
- Optical astronomy at the highest resolution
- Stellar flares (e.g., *Kepler*) results
Bibliography

Benz article on Living Reviews “Flare Observations”
http://solarphysics.livingreviews.org/Articles/lrsp-2008-1/

Gudel article on Living Reviews “The Sun in Time”

Tandberg-Hansen & Emslie book
http://adsabs.harvard.edu/abs/1988psf..book.....T

RHESSI monograph chapters (9 total; specifically Fletcher et al.)
e.g., http://adsabs.harvard.edu/doi/10.1007/s11214-010-9705-4

Schrijver & Siscoe Heliophysics (3 volumes)

RHESSI Science Nuggets
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/RHESSI_Science_Nuggets

Hudson article “Global Properties of Solar Flares”
http://arxiv.org/abs/1108.3490
The new SDO comet