Solar flares and solar activity

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Plasma in the universe

- Plasma - a quasi-neutral gas of charged and neutral particles which exhibits collective behaviour

- > 99% of baryonic matter in universe is in plasma state

- Plasmas create magnetic fields and interact with magnetic fields
• Introduction to the Sun and the heliosphere
• Introducing solar flares
• Energetic particles in solar flares
• Space weather
• Beyond solar flares – coronal heating, stellar flares
Introducing the Sun

- G type Main sequence star

- Energy generated in hot core (16 million degrees K) by nuclear fusion of hydrogen into helium

- Convection zone in outer layers

- Photons freely escape from the photosphere – the visible surface
The Sun’s atmosphere

- Photosphere: Thin "skin" layer - about 500 km thick
- Temperature 6000 degrees

- Chromosphere - complex and highly structured
The corona and the solar wind

- Temperature 1 -2 million degrees – much hotter than photosphere!
- Constantly streaming out into space as the Solar Wind - a supersonic flow of particles with speed about 450 km/s at the Earth’s orbit

Svalbard total eclipse
Druckmuller 2015
Space observations

Solar Dynamic Observatory
SDO

- Corona emits most strongly in x-rays and EUV which can only be observed in space: SoHO, TRACE (*RIP*), RHESSI, Hinode, Stereo, Solar Dynamic Observatory, Solar Orbiter (2018)…
The corona
— SDO Atmospheric Imaging Assembly
Magnetic field and emission

All structure and activity in solar corona is controlled by magnetic field

Thermal pressure >> magnetic pressure
$\beta \ll 1$

We can model interaction of magnetic field and plasma with MagnetoHydroDynamics (MHD)
- See Hood lecture
The Sun today

Photosphere
SDO HMI

Magnetogram

Corona
(SDO AIA 193)

Chromosphere
(SDO AIA 304)
The solar cycle

Yearly Averaged Sunspot Numbers 1610-2007

Sunspot cycle – showing 11 year variation – a signature of changes in solar magnetic field

Solar corona over one cycle from Solar Heliospheric Observatory (SoHO) Extreme ultraviolet Imaging Telescope (EIT) – from minimum (1996) to maximum (2001) to next minimum (2006)
The Sun-Earth system
The Earth’s Magnetosphere
The bigger picture – the Heliosphere
Introducing solar flares
The story begins......September 1859

Richard Carrington observes strange brightening on the Sun
European telegraph network (1854)
Earth’s magnetic field measurements 1859

“One swallow doesn’t make a Summer”
Carrington 1859
What is a solar flare?

- Dramatic events releasing up to $10^{25}$ J over a period of hours – strong brightening in soft x-rays
- Flares generate plasma heating and fast particle beams - signatures across the em spectrum from gamma rays to radio
- Must be a release of stored magnetic energy as only magnetic field has sufficient energy to account for observed emission

Schematic
From Benz 2008
Flare energy – a worked example

Consider a region of the corona with dimensions 10 Mm.
Taking parameters $B = 0.03 \, \text{T}$, $T = 10^6 \, \text{K}$, $n = 10^{15} \, \text{m}^{-3}$
calculate the magnetic energy and thermal energy.

\[
W_B = \frac{1}{2 \mu_0} B^2 L^3 \approx 4 \times 10^{23} \, \text{J}
\]

\[
W_T = \frac{3}{2} 2nkTL^3 \approx 4 \times 10^{19} \, \text{J}
\]

Constants:

\[
k_B = 1.4 \times 10^{-23} \, \text{J K}^{-1}, \quad \mu_0 = 4\pi \times 10^{-7}, \quad m_p = 1.7 \times 10^{-27} \, \text{kg}
\]
Multi wavelength emission from flare

From Fletcher et 2011.

- Emission in soft X-rays (GOES), Hard X-rays (HXT and WBS) and radio (microwaves) as functions of time
- Soft X-rays from hot thermal plasma, hard X-rays and microwaves from high energy non-thermal particles
Flare classification

- According to peak 100 – 800 pico metre X-ray flux near Earth – measured by GOES satellite

<table>
<thead>
<tr>
<th>Classification</th>
<th>Peak Flux in $\text{W m}^{-2}$</th>
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<td>A</td>
<td>$&lt; 10^{-7}$</td>
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<td>C</td>
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<tr>
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<td>$&gt; 10^{-4}$</td>
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Series of large flares from Active Region 2192 October – November 2014
SDO X class flare – Cinquo Mayo 2015
5 flares June 21st – 25th 2015
How do flares work? Magnetic reconnection

- Magnetic fields are pushed together - fieldlines break and reconnect, releasing magnetic energy
- “Ideal” outer region - magnetic field frozen to plasma
- Narrow “dissipative” region – field topology changes
- Heats and accelerates plasma – also strong electric fields accelerate charged particles

See Hornig lecture
Magnetic reconnection

[Diagram showing the process of magnetic reconnection with labels for separatrix, reconnection layer, plasma flow, X-line, and magnetic field line.]
Standard flare model
Figure 2: Phenomenological models for flares based on magnetic reconnection. Lines with arrows on them indicate magnetic field lines. (a) Carmichael (1964), (b) Sturrock (1966), (c) Hirayama (1974), (d) Kopp and Pneuman (1976).

From Shibata and Magara Living Reviews of Solar Physics 2011
Eruptive flare schematic (from Priest and Forbes 2002)

Key observed features:

a Erupting filament or Coronal Mass Ejection; soft X-ray loops with hot dense plasma; Hα ribbons at footpoints of loops in chromosphere; outward movement of ribbons as reconnection site moves upwards

b Initial rise of fieldlines in sheared arcade

c reconnection of rising field lines
Filament formation

- From Van Ballegoijen and Martens 1989
- Bipolar arcade of magnetic loops
- Shear flow + inflow + magnetic reconnection
Observation of reconnection inflow in flare

- Reconnection inflows are slow and difficult to observe

- First seen in SOHO EIT images of March 18, 1999 flare

Yokoyama et al. 2001
Arcade of soft X-ray flare loops (from TRACE)
See Ex 4.5
Brightening in chromosphere due to fast particles from corona impinging on chromosphere - Hα ribbons

Flare may be associated with coronal mass ejection
Standard flare model

Simplified version!

- Magnetic energy is stored in the corona due to shearing or twisting of the photospheric footpoints of the magnetic field
- A cool dense filament forms, suspended by magnetic field
- The field loses equilibrium or becomes unstable - filament rises and erupts, field lines become stretched
- Rising field lines reconnect – magnetic reconnection heats plasma and accelerated charged particles

- Chromosphere is heated – observed as Hα ribbons
- Dense chromospheric material evaporates and fills soft X-ray loops
Flares are observed through a wide range of electromagnetic radiation, different wavelengths indicating different physical processes

- **Microwaves** - Synchrotron radiation from high energy electrons gyrating around fieldlines $\omega = eB/m$

- **H\(\alpha\)** From chromosphere. Heated due to impact of high energy charged particles from corona and/or thermal conduction. Two parallel ribbons emission in “two ribbon flares”, marking footpoints of soft x-ray loops
• **Soft x-rays** - Thermal radiation from hot plasma – mainly confined in loops (rising arcade of loops or single loop)

• **Hard X-rays** - Bremstrahlung due to slowing down of high energy (non thermal) particles and/or from very hot thermal plasma – may be footpoint and looptop sources

• **Gamma rays** - From collisions of high energy protons and other ions – nuclear reactions/excitations
Coronal Mass Ejections (CMEs)

- Flares often associated with Coronal Mass Ejections

See Harrison Lecture
Some flux rope eruption models

- Flux cancellation
- Tether cutting
- Kink or torus instability
- Loss of equilibrium

From Shibata and Magara Living Reviews of Solar Physics 2011
Energetic particles in solar flares
Flares – the overall picture

Benz Living Reviews of Solar physics 2008
High energy particles in flares

- Emission from flares shows both thermal and non-thermal components (hard x-rays, gamma rays) due to Bremsstrahlung of electrons and nuclear reactions/excitations of ions
- Electron energies of up to \( \approx 100 \text{keV} \), protons up to \( \approx 1 \text{GeV} \)

- Up to 50% of flare energy is carried by non-thermal energetic electrons and ions
- High energy particles detected *in situ* by particle detectors in space and indirectly near Sun through radiation

RHESSI spectrum (Grigis and Benz 2004)
• Electrons accelerated in corona at/near loop top
• Beams propagate out into space and down to surface
• Electrons impinging on dense chromosphere slow down and emit Hard X-rays (gamma rays) through Bremsstrahlung
• Footpoint and (sometimes) loop-top Hard X-Ray sources
RHESSI Hard X-ray sources

From Raymond et al SSR 2012

A Simple loop – thermal emission in loop/nonthermal footpoint sources

B, C Also coronal HXR sources

D (rare) No footpoint HXR sources
Observations of high energy particles – radio

- High energy electrons from flares excite plasma waves and hence radio emission
- Density and hence plasma frequency decrease with height
- Type III burst (right)

\[ f_p = 8.9\sqrt{n} \text{ Hz (n in m}^{-3}\text{)} \]

See Tsiklauri lecture

Electron plasma frequency

Plasma oscillations

Radio emission

Solar flare electrons

A-D03-116-3

Sun Radial distance from sun (A.U.) Earth

$\rho n^2$
Reconnection and energetic particles in flares

• Much indirect and some (fairly) direct evidence for magnetic reconnection in large-scale flare – and associated generation of energetic particles

*e.g. Su et al, Nature Physics 2013*

flare reconnection imaging su 13.mov
Reconnection and energetic particles in flares

- Much indirect and some (fairly) direct evidence for magnetic reconnection in large-scale flare – and associated generation of energetic particles e.g. Su et al, Nature Physics 2013
Acceleration site

- Suggests current sheet between HXR sources

*Sui and Holman Ap J 2003*
Particle acceleration mechanisms

• Strong candidate for particle acceleration is effect of direct electric field in reconnecting current sheet (at loop top in “standard model”)

• Also waves, turbulence, shocks proposed....

• Some difficulties with standard model and “Collisional Thick Target Model” - acceleration in highly-localised monolithic coronal current sheet
  - Accelerating large number of particles in a very small volume
  - Intense electron beams with very strong currents....

• May be alleviated by a distributed acceleration site

From Liu et al 2008
Electric fields in flares

• Flare electric fields can be estimated from flux conservation arguments (\(E = -\mathbf{v} \times \mathbf{B}\)), from observed motion of “ribbons” (footpoints of flare loop)
  – Estimate electric fields of around 1000 Vm\(^{-1}\)

• The Dreicer electric field is the critical value of \(E\) above which electrons are freely accelerated as in a vacuum (Coulomb collisions are insignificant)
  – This limit arises because Coulomb collision rate is a decreasing function of velocity (temperature) – fast electrons have few collisions

\[
E_d = \frac{e \ln \Lambda}{4\pi \varepsilon_0 \lambda_D^2} \propto \frac{n}{T} \left( \lambda_D = \sqrt{\frac{\varepsilon_0 kT}{n e^2}}, \text{ the Debye length; } \ln \Lambda \approx 20 \right)
\]

  – Typical flare electric fields are super-Dreicer (\(E_d \approx 0.01\)Vm\(^{-1}\))

• Particles may thus gain significant energies if directly accelerated along the electric field for long enough
Worked example

- Assuming an electric field of 1000 V/m, calculate the energy gain by a electron/proton if it is accelerated over a distance of 10 Mm

\[ W = eEL = 1000 \times 10^7 \text{ eV} = 10 \text{ GeV} \]

- Taking magnetic field to be 200 G, calculate gyro radius of a thermal electron (temperature 10^6 K)

\[ r_{L,e} = \frac{m}{eB} \sqrt{\frac{kT}{m}} \approx 1 \text{ mm} \]

\[ r_L = \frac{mv}{qB} \quad v_t \approx \sqrt{\frac{kT}{m}} \]

\[ e = 1.9 \times 10^{-19} \text{ C}; \quad m_e = 9.1 \times 10^{-31} \text{ kg}; \quad k_B = 1.4 \times 10^{-23} \text{ m}^2 \text{ kgs}^{-2} \text{ K}^{-1} \]
Particle trajectories in simple magnetic/electric fields

• If $B = 0$ or $E \parallel B$, direct acceleration along the electric field, velocity increases linearly with $t$

• If $E = 0$, particles gyrate around magnetic fieldlines

$E=0$:

• Strong perpendicular electric field:

$E>0$:

• Perpendicular electric field introduces a drift (perpendicular to $E$ and $B$) with velocity

$$v_E = \left( \mathbf{E} \times \mathbf{B} \right) / B^2$$
Particle trajectories in reconnecting fields

- Magnetic field inhibits acceleration – direct acceleration only by parallel electric field or where $B = 0$
- Reconnection electric field transverse to current sheet – may also be magnetic field components perpendicular to sheet ($B_\perp$), small, and parallel to electric field ($B_{\parallel}$)
- Particles are brought into current sheet by $E \times B$ drift
- Within sheet they gyrate around $B_{\parallel}$ and are accelerated along electric field – until ejected from sheet gyromotion associated with ($B_\perp$)
- Energy gain depends on time spent in sheet (length travelled along sheet)

Current sheet – reversal of magnetic field

See Litvinenko (2003)
Modelling particle acceleration: test particles

• “Guiding Centre” theory described charged particle motion in magnetic fields which are almost uniform

  See Tsiklauri Lecture

• Charged particle behaviour in reconnecting fields - especially with magnetic null points or layers (B = 0) – is far from fully understood!

• Take magnetic and electric fields representative of reconnection

• Integrate charged particle equations of motion numerically

• Neglect the fields generated by the test particles and (usually) collisions
  – OK if number of high energy particles is few compared with “background” plasma

\[ \frac{dv}{dt} = \pm e (E + v \times B) \]


• 3D null points e.g. Dalla and Browning 2005, 2006, Stanier et al 2013
2D steady reconnection - test particles

- Efficient acceleration provided the electric field is strong enough to allow efficient drift towards the null point / current sheet.
- Energy gain strongly dependent on a particle’s initial position.
- Presence of a guide field (transverse to current sheet) results in more efficient acceleration and in charge separation.

- Ions and electrons accelerated to different loop footpoints.
- Asymmetry increases with guide field.
  Zharkova and Gordovskyy 2004, 2005

- Power law spectra similar to observations.
  Wood & Neukirch, 2005

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[Graphs and diagrams illustrating 2D steady reconnection and test particles.]
Space weather
What is space weather?

Conditions on the Sun that affect the Earth and our space environment
Space weather

Solar flares produce
X-rays which affect Earth’s atmosphere – may cause radio blackouts
High-energy charged particles – may reach Earth and affect satellites
Coronal mass ejections which may disrupt Earth’s magnetic field

Geo effective flare
Bastille Day Flare
Aurorae

Solar wind particles entering Earth’s magnetic field at polar cusps may form Aurorae when they interact with neutral atmosphere.
The auroral oval

November 17th 2012
POES satellite
Hazards to humans

- High energy particles may be hazardous or even fatal to humans in space
- Crew/Passengers in high-flying jets receive significant radiation dose

Also may damage satellites, communication technology, power systems etc
• Solar storms added to National Risk Register 2011

• UK Met Office Space Weather forecast service commenced October 2014
Solar flare effects on ionosphere and radio transmission
Space weather impacts
Some final topics

A model of confined flares
Coronal heating
Stellar flares
3D MHD simulation of unstable coronal loops

Magnetic field lines

Electric currents

Gordovskyy, Browning, Bian and Kontar A&A 2014
Bareford, Gordovskyy, Browning and Hood, submitted to Sol Phys; Pinto, Gordovskyy, Browning and Vilmer, submitted to A&A
Heating and particle acceleration in twisted loops – methodology

Potential field in stratified atmosphere

3D MHD simulations
- Derivation of twisted loop configuration (ideal phase)
- Magnetic reconnection triggered by kink (resistive phase)

Test-particles (with collisions)
- Proton & electron trajectories
- Energy spectra, pitch angles, spatial distributions

Thermal emission
Magnetic field topology

Gordovskyy, Browning, Kontar and Bian Sol Phys 2014
Gordovskyy, Pinto, Browning and Vilmer in preparation
Temperature distribution

Pinto, Gordovskyy, Browning and Vilmer
Energetic particles and Hard X-ray emission

- Synthesise spatial and temporal dependence of Hard X-ray emission, compare with RHESSI observations

Synthesised HXR $\varepsilon=10$keV
Gordovskyy et al 2014

Top View

Side View

~ 30s after kink

Onset of reconnection

~ 120s

Maximum dE/dt in MHD model

~ 220s

Decay phase

~ 320s
Hard X-rays from kinking filament
Liu and Alexander 2009
• Compact self-contained flare
• Kink instability in the strongly twisted loop?
Nanoflares and coronal heating

• Need heat source to balance losses due to conduction and radiation - $T \gtrsim 10^6$ K

• Sub-surface motions shuffle the footpoints of the coronal magnetic field $\rightarrow$ free magnetic energy in the corona

• For slow driving, field evolves through equilibria - free energy associated with static currents

• Magnetic reconnection may dissipate this energy efficiently in highly-conducting coronal plasma

• Corona may be heated by combined effect of many small “nanoflares” (Parker 1988)
Do nanoflares have enough energy to heat corona?

- Suppose occurrence rate of events of energy $E$ is
  \[ f(E) \sim E^{-\alpha} \]
- Total energy release
  \[ W = \int_{E_{\text{min}}}^{E_{\text{max}}} Ef(E) dE = \frac{1}{2-\alpha} \left[ E_{\text{max}}^{2-\alpha} - E_{\text{min}}^{2-\alpha} \right] \]
- Hence for small events to dominate, require $\alpha > 2$
- For larger events (flares, microflares etc, current observations suggest $\alpha < 2$ - but MAY be steeper spectrum for smaller events? Observations inconclusive...Nanoflares cannot be resolved observationally!

Reconnection and flare stars

- Flare stars may release $10^4$ – $10^6$ times the energy of a large solar flare
- Physical processes believed to be similar – energy release by magnetic reconnection
- Flares occur in range of stars across Hertzsprung-Russell diagram – classic flare stars are red dwarfs, especially UV Ceti stars e.g. Proxima Centauri (our nearest non-solar star)
- Fast rotators with deep convection zones -expect strong magnetic dynamo process – starspots with similar field strength to sunspots but covering large fraction of surface
- Flares also found in close binaries (RS CVn) and T-Tauri stars
Superflares

Kepler super-flare stars: what are they?

R. Wichmann¹, B. Fuhrmeister¹, U. Wolter¹, and E. Nagel¹

The Kepler mission has led to the serendipitous discovery of a significant number of ‘super flares’ - white light flares with energies between $10^{33}$ erg and $10^{36}$ erg - on solar-type stars. It has been speculated that these could be ‘freak’ events that might happen on the Sun, too. We have started a programme to study the nature of the stars on which these super flares have been observed. Here we present high-resolution spectroscopy of 11 of these stars and discuss our results. We find that several of these stars are very young, fast-rotating stars where high levels of stellar activity can be expected, but for some other stars we do not find a straightforward explanation for the occurrence of super flares.

Astronomy and Astrophysics 2014

• Flares around million times more powerful than largest solar flare observed by Kepler on solar-type stars
• Could this happen on the Sun??
Summary

From Shibata and Magara 2008)
Problems in flare modelling

• Energy storage

• Flare trigger
  – Instability or loss of equilibrium

• Energy release
  – Magnetic reconnection
  – Huge range of spatial scales

• Partitioning of energy release
  – Thermal, non-thermal (electrons and ions), CME
  – Energetic particle acceleration and transport

• Coupling to chromosphere
  – Particles, thermal conduction
  – Chromospheric physics
Selected reading list - reviews

• A Benz “Flare observations” Living Rev Sol Phys, 5, 1 (2008)
• V Zharkova et al “Recent advances in understanding particle acceleration in solar flares” Space Sci Rev 159, 357 (2011)
• E R Priest “MHD of the Sun”, Chapter 12, Camb. Univ. Press (2012)