Solar activity:
Coronal Heating
and
Solar Flares

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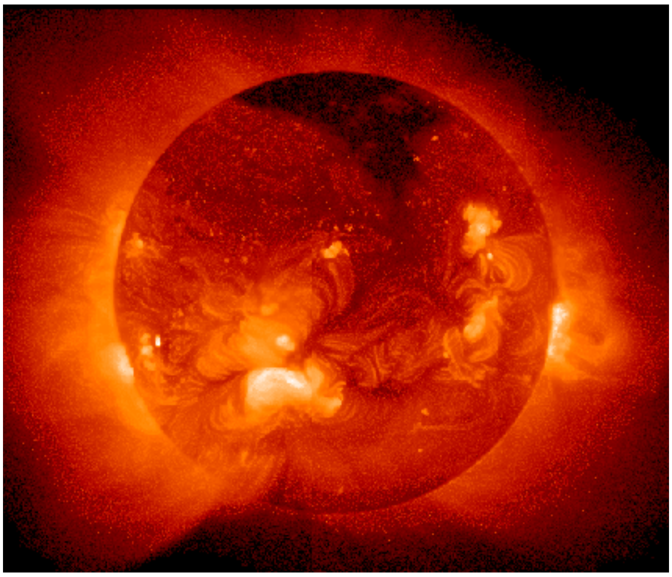
Coronal heating

Statement of the problem:

The solar photosphere is at ~ 5800K and the corona is at ~ 10^6K

Where does the energy come from, what form does it take, and how is it dissipated?



X-rays (~3MK) from Yohkoh SXT (JAXA/NASA/STFC)

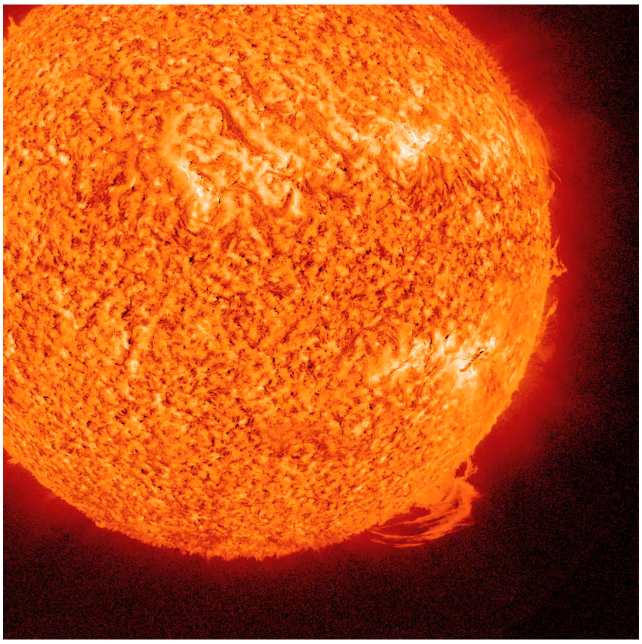
Solar flares

Statement of the problem:

A region of the Sun suddenly brightens, heats and produces copious accelerated particles.

Where does the energy to heat the corona come from, what form does it take, and how is it dissipated?

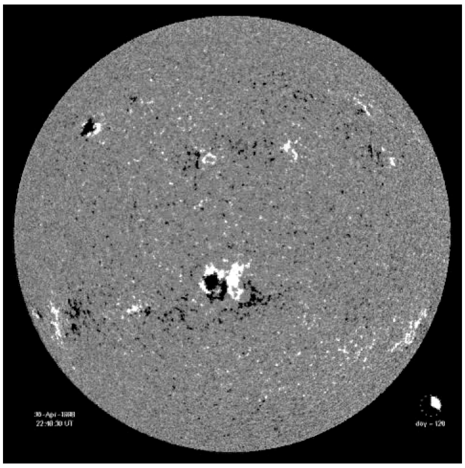
NB, the <u>flare</u> is the increase in <u>radiation</u>. The associated mass motion is the coronal mass ejection



Coronal heating and solar flares

What do they have in common?

- Magnetic stresses dissipated in the solar corona
- Magnetic free energy fed in from the lower layers
- Same basic problem – how to convert magnetic free energy into other forms (difficult in a highly-conducting plasma)
- Some coronal heating ideas propose a multitude of small flares



Coronal heating and solar flares

What is different?

- Coronal heating is quasi-steady: on observational timescales the plasma evolves slowly
- Flares are abrupt: plasma heats and evolves rapidly
- A further significant difference - flares involve large numbers of non-thermal electrons which are not detected in the 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

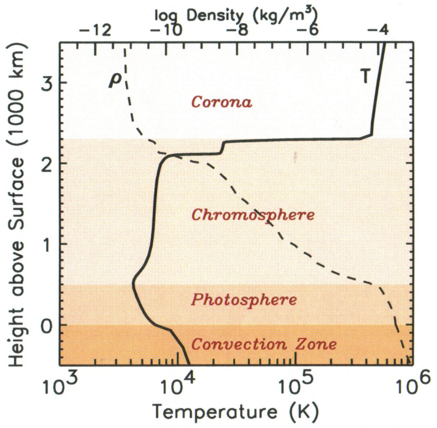
Flares:
- Rapid character of flare means very intermittent energy dissipation
- Need for long-term energy storage.
- Plasma becomes non-Maxwellian

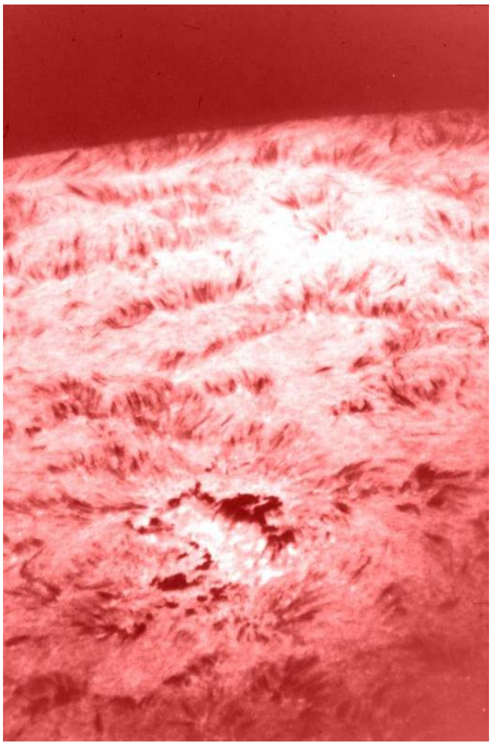
Chromospheric heating

The heating problem really begins in the chromosphere.

In fact, because of its greater mass, the energy requirement is greater.

vertical T structure



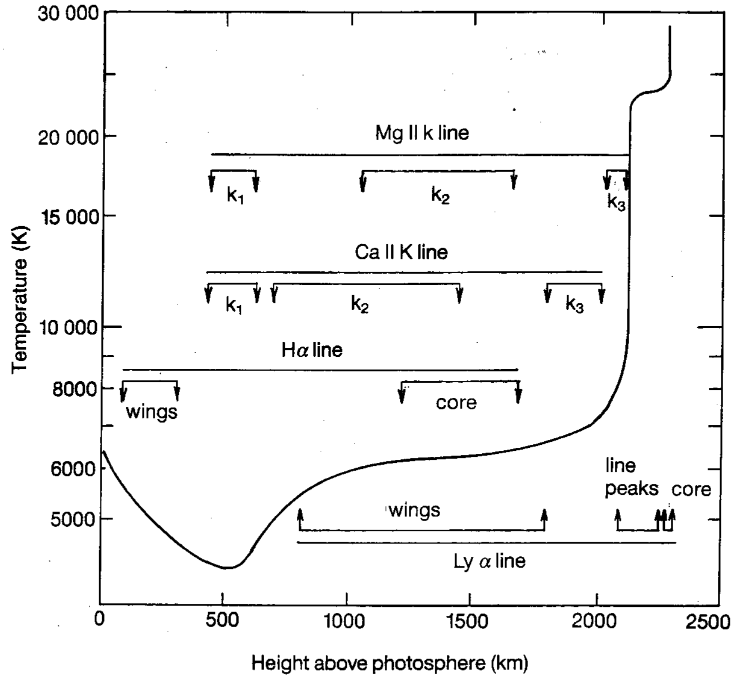


Chromosphere & corona

Plot of Temperature vs height above the photosphere

The height ranges of formation of the principal emission lines are shown

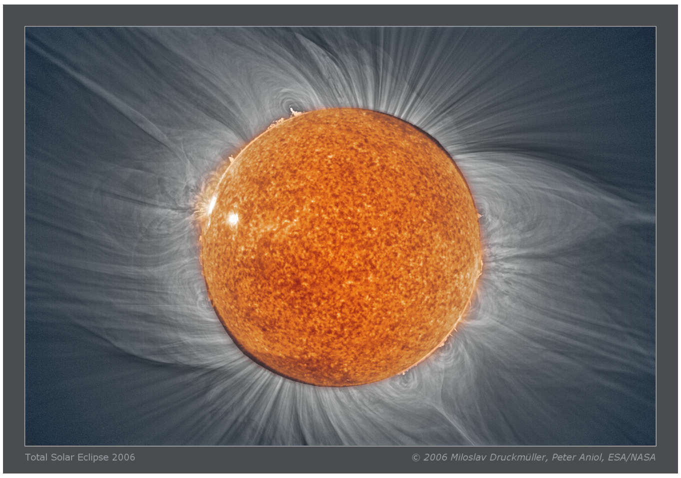
For h > 2300 km, radiated energy can no longer compete with the rate of energy input so the temperature rises rapidly



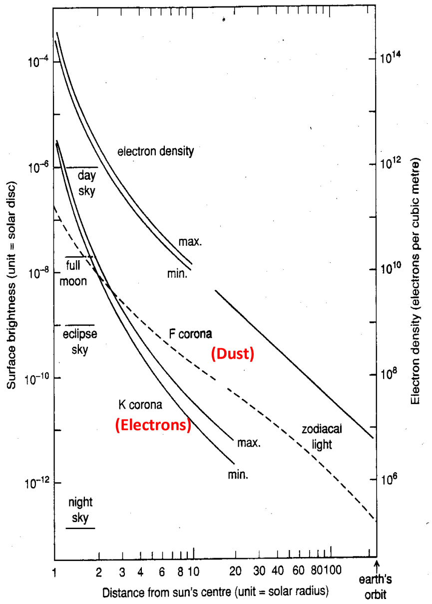
The corona

The ‘white light’ corona is formed by Thomson scattering of photospheric light by free electrons in the coronal magnetic field.

$\beta < 1$ out to ~ $2R_\odot$ (magnetic forces dominate)



Composite white light corona and UV image of the chromosphere



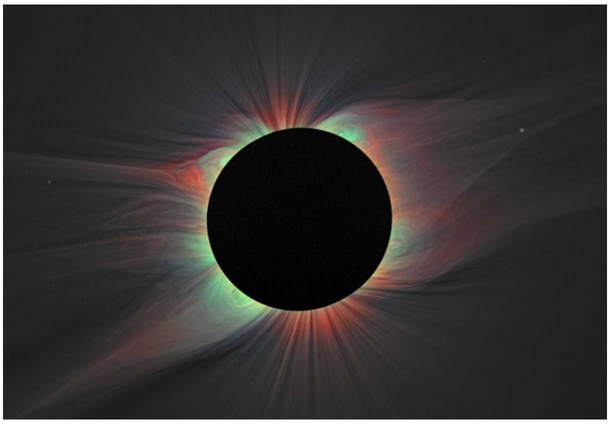
The hot corona

The first hint that the corona is a bit strange came from eclipse observations of the coronal ‘green line’ (Harkness & Young 1869)

This did not correspond to any of the atomic transitions expected at photospheric temperatures.

Its identification as a forbidden line of *Fe XIV* established the existence of a high T_e corona (Gotrian 1939, Edlén 1942)

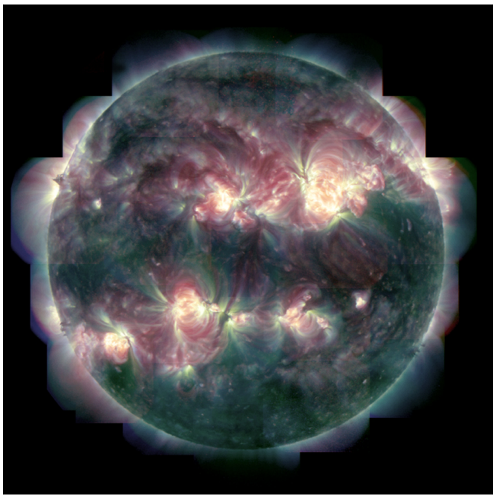
Fe X (red) line also identified



Red, green and white light corona during an eclipse. Habbal et al. (2010)

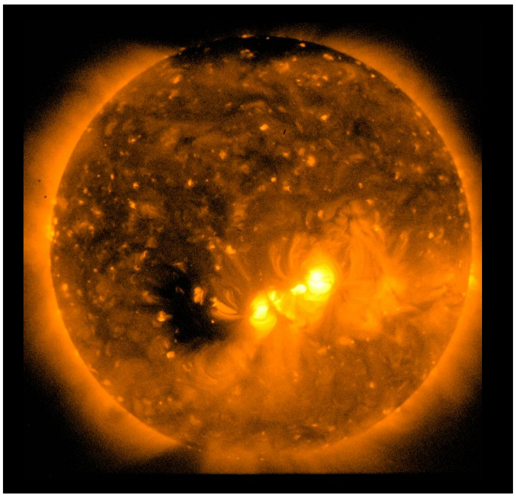
EUV and X-ray corona

From space, we have ample evidence of the million-degree corona



NASA/TRACE

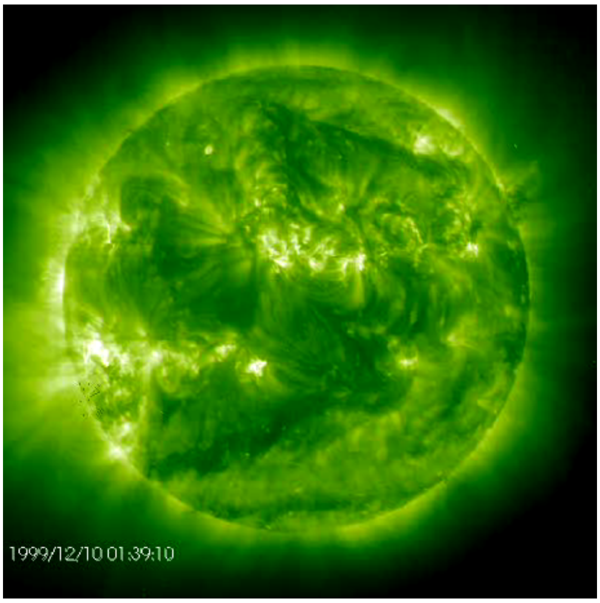
T ~ 1MK. EUV emission is line emission from highly ionised Fe (principal radiating coolant)



NASA/ISAS/JAXA/Hinode XRT

T ~ 3-5MK. Most X-ray emission is free-free (bremsstrahlung) from hot, quasi-thermal plasma

Energy budget



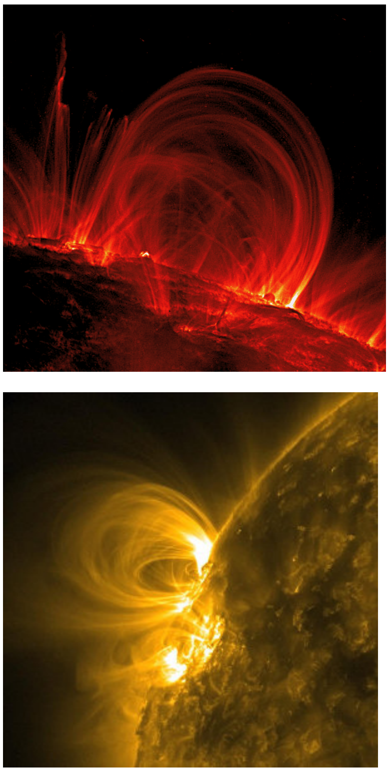
The chromosphere and the corona are heated by something other than conduction, convection or radiation.

Requirement is ~ 10^6 erg cm^{-2}

No problem with energy source - there is ≥ 10^7 erg cm^{-2} in turbulent & wave energy at photosphere…

The problem is understanding energy *transport* and *dissipation*.

Coronal loops



Coronal heating = loop heating

The hot corona is mostly confined in closed magnetic loops – the basic structural element for the corona.

Each loop is its own mini-atmosphere, thermally isolated from neighbours.

The observables are:

Intensity, doppler shift, line width *(directly from observation)*

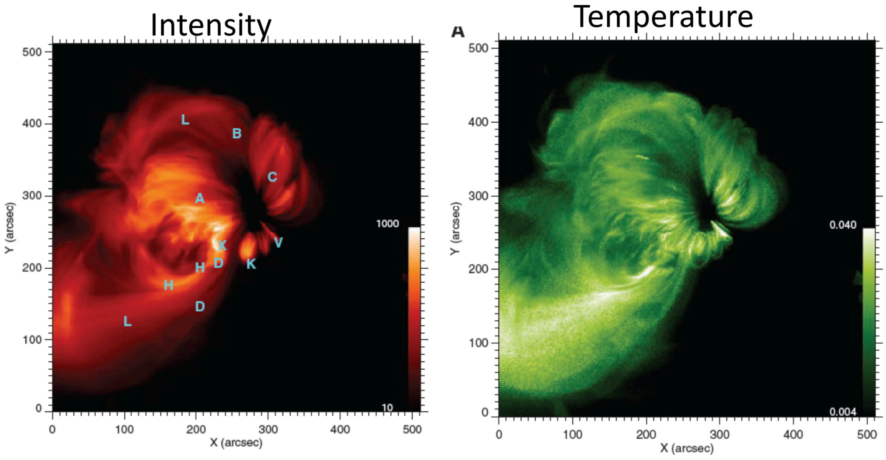
Temperature, density, emission measure *(deduced from diagnostics)*

Observational problems are very basic. e.g. How do you isolate and measure intensity in a loop?

Observed loop properties

- Possibly three ‘classes’ of loop; hot (~5MK), warm (~2MK), cool (<1MK), located in different parts of an active region.
- Loops don’t seem to evolve from hot to warm to cool.
- Only a small fraction of loops are isothermal (~10%)

See ‘Living Reviews in Solar Physics’ article by Reale (2010)



Temperatures obtained from Hinode XRT filter ratios show temperature gradients and fine structuring (Reale et al 2007)

T range from Log T = 6.3 - 6.6

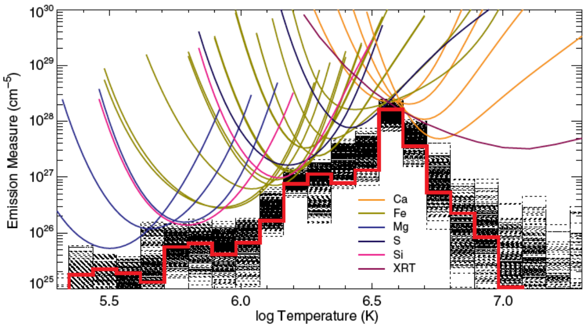
More about temperature

Note: there are 2 relevant temperatures, which could be different.

- electron temperature (determined from collisionally excited lines, or bremsstrahlung)
- ion temperature (from line widths).

Most modeling assumes these are the same – single fluid. Though see work by Bradshaw & collaborators

Temperature measurements are very difficult:
- Inconsistent results from photometry (i.e. filter ratios) and spectroscopy
- Considerably differences depending how background is subtracted



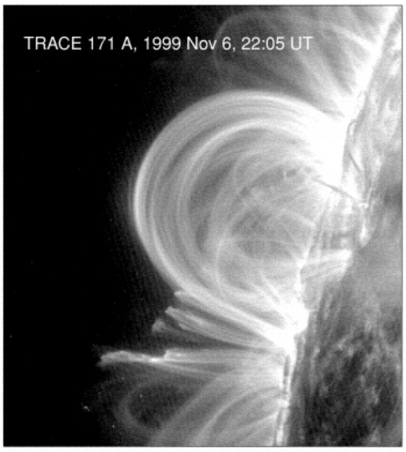
Possibly the most complete picture of temperate comes from emission measure analysis (e.g. Warren et al 2011)

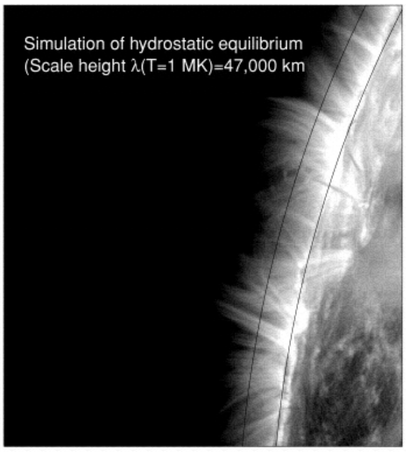
$d(EM(T)) = n_e(T)^2\, dL$

More loop properties

- Basic scale of transverse field structuring is still sub-resolution
- Intensity distribution inconsistent with hydrostatic equilibrium – implying heating and non-steady flows
- Loops exist for >> conductive or radiative cooling timescales – again implies heating

See 'Living Reviews in Solar Physics' article by Reale (2010)





Observed loop scale height > hydrostatic scale height.

⇒ Footpoint heating?

(Aschwanden et al 01)

Single loop modeling

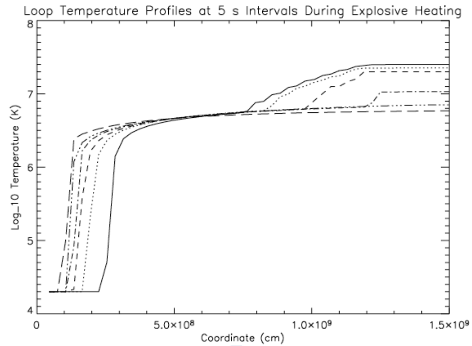
$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial s}(\rho v)=0,$$

$$\frac{\partial}{\partial t}(\rho v)+\frac{\partial}{\partial s}\left(\rho v^2\right)=-\frac{\partial}{\partial s}(P_e+P_i)-\rho g_{\parallel},$$

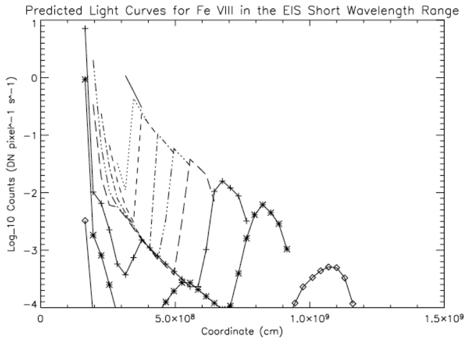
$$\frac{\partial E_e}{\partial t}+\frac{\partial}{\partial s}[(E_e+P_e)v] = -\frac{\partial F_{ce}}{\partial s}+v\frac{\partial P_e}{\partial s} +\frac{k_B n}{\gamma-1}\nu_{ie}(T_i-T_e)-R+H,$$

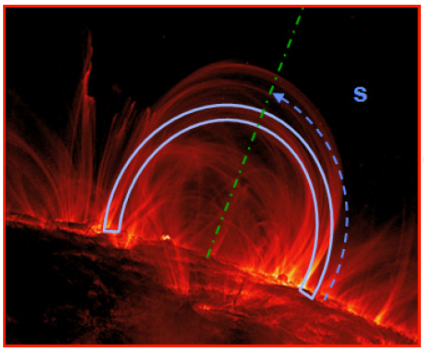
$$\frac{\partial E_i}{\partial t}+\frac{\partial}{\partial s}[(E_i+P_i)v] = -\frac{\partial F_{ci}}{\partial s}-v\frac{\partial P_e}{\partial s} +\frac{k_B n}{\gamma-1}\nu_{ie}(T_e-T_i)+\rho v g_{\parallel}.$$

$$H(s,t)=H_0\left(1-\exp\left[-\frac{t_D-t}{\tau_H}\right]\right)\exp\left[-\frac{|s-s_0|}{s_H}\right]$$



Bradshaw & Cargill 2006



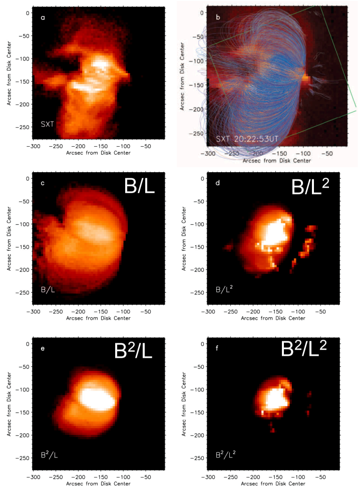


Parameterised active region modeling

Some models parameterise the heating input as simple functions of the active region loop parameters (e.g. B, L, ρ V...)

From observed parameters, calculate coronal B, assume a density then calculate heat input and temperature for an entire active region using 1D loop model

Description	Number	Reference	MDK Scaling
Stochastic buildup	1	1	$B^2L^{-2}V^2\tau$
Critical angle	2	2	$B^2L^{-1}V^1\tan\theta$
Critical twist	3	3	$B^2L^{-2}V^1R^1\phi$
Reconnection $\propto v_A$	4	4	$B^1L^{-2}\rho^{0.5}V^2R^1$
Reconnection $\propto v_{A\perp}$	5	5	$B^{1.5}L^{-1.5}\rho^{0.25}V^{1.5}R^{1.5}$
Current layers (DC)	6	6	$B^2L^{-2}V^2\tau\log R_m$
	7	7	$B^2L^{-2}V^2S^{0.1}\tau$
	8	8	$B^2L^{-2}V^2\tau$
Current sheets	9	9	$B^2L^{-1}R^{-1}V_{\mathrm{ph}}^2\tau$
Taylor relaxation	10	10	$B^2L^{-2}V_{\mathrm{ph}}^2\tau$
Turbulence (DC) with:			
Constant dissipation coefficients	11	11	$B^{1.5}L^{-1.5}\rho^{0.25}V^{1.5}R^{1.5}$
Closure	12	12	$B^{1.67}L^{-1.33}\rho^{0.17}V^{1.33}R^{0.33}$
Closure + spectrum ($s = 0.7$)	13	13	$B^{1.7}L^{-1.7}\rho^{0.15}V^{1.3}R^{0.7}$
Closure + spectrum ($s = 1.1$)	14	13	$B^{2.1}L^{-2.1}\rho^{-0.05}V^{0.9}R^{1.1}$
Resonance ($m = -1$)	15	14	B^0L^{-2}
Resonance ($m = -2$)	16	14	$B^{-1}L^{-1}\rho^{0.5}$
Resonant absorption I ($m = -1$)	17	15	B^0L^0
Resonant absorption I ($m = -2$)	18	15	$B^{-1}L^1\rho^{0.5}$
Resonant absorption II ($m = -1$)	19	16	$B^0L^1\rho^1$
Resonant absorption II ($m = -2$)	20	16	$B^{-1}L^2\rho^{1.5}$
Current layers (AC)	21	17	$B^1L^{-1}\rho^{0.5}V^2$
Turbulence (AC)	22	18	$B^{1.67}L^{-1.33}R^{0.33}$

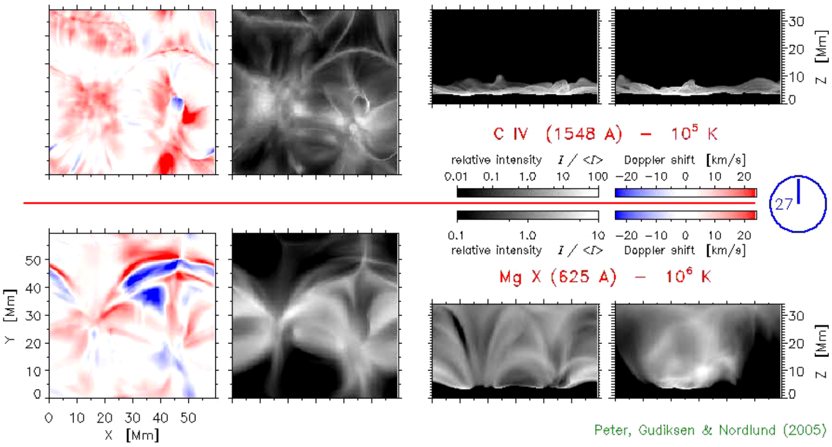


Lundquist et al. 2008

Ab initio modeling

'Ab initio' models - simulate the whole thing…

- Take a model for magnetoconvection and extend the field into the corona
- Use the energy input from lower atmosphere as the coronal heating term
- Explicit forms for energy dissipation (viscous heating, Joule heating)



Peter, Gudiksen & Nordlund (2005)

Looks great but it's so complicated… what do we really learn?

Coronal Energy Transport and Heating

Possibilities for energy transport to corona and heating include:

- Acoustic waves - now thought negligible for corona, since trapped in chromosphere, although some mode-coupling with MHD waves exists.

- Alfvén waves - good at transport, generally bad at dissipation (low shear viscosity in the corona)

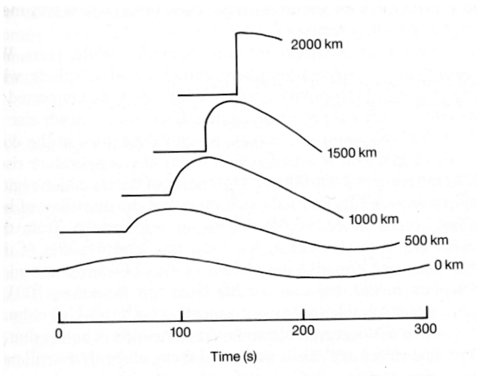
- Magneto-acoustic wave dissipation - longitudinal compressional waves will form shocks like acoustic waves

- Field ‘tangling’ and magnetic reconnection - dissipation of energy at current sheets.

Acoustic Waves

Biermann (1946) and Schwarschild (1948) proposed acoustic waves for heating the chromosphere and the corona

Basic idea – upwards-traveling acoustic compressions moving into low density regions steepen into shocks which dissipate & heat.



- Problem – this mostly happens in the lower chromsophere

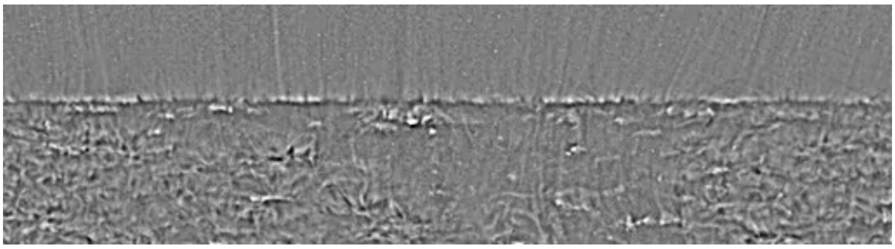
- Waves trapped in lower chromosphere by steep sound-speed gradient

- Acoustic flux in the chromosphere is ~ $10^2 – 10^3$ less than needed to heat the corona.

Upper chromosphere and corona must be heated by a **magnetically dominated** mechanism

MHD waves

Coronal plasma supports many wave modes. Imaging and spectroscopy detections of slow, fast and Alfven modes have all been claimed.



MacIntosh et al (2011)

Alfven wave energy density is unknown (hard to observe). Also, hard to dissipate Alfven waves, though this can happen via resonant absorption, phase mixing.

Slow magnetoacoustic waves are identified and – being compressional – dissipate readily.

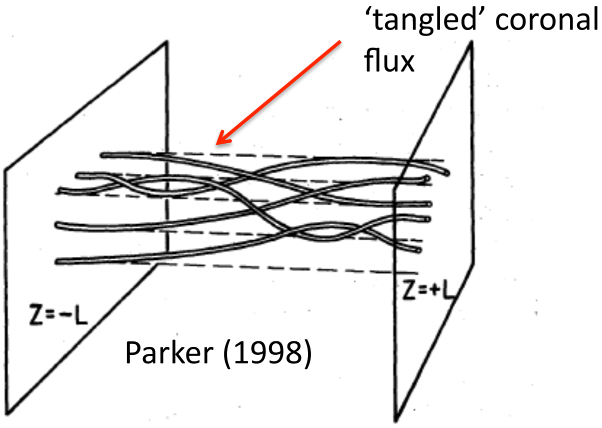
Energy flux in observed waves is too low: at higher frequencies this is unknown…

Dissipation in coronal current sheets

- Parker (1972) - slow random walk of flux -driven by photosphere and sub-photosphere - tangles coronal field.
- Current sheets form at magnetic interfaces (where curl B ≠ 0)
- Current may dissipate directly by Joule heating, or by a chain of events involving magnetic reconnection

Nanoflare energy is estimated to be 10^{25} erg for X-ray loops and 10^{23} erg for EUV loops.

The occurrence rate of nanoflares is about 0.4 nanoflares s^{-1} in a hot X-ray loop and 30 s^{-1} in an EUV loop

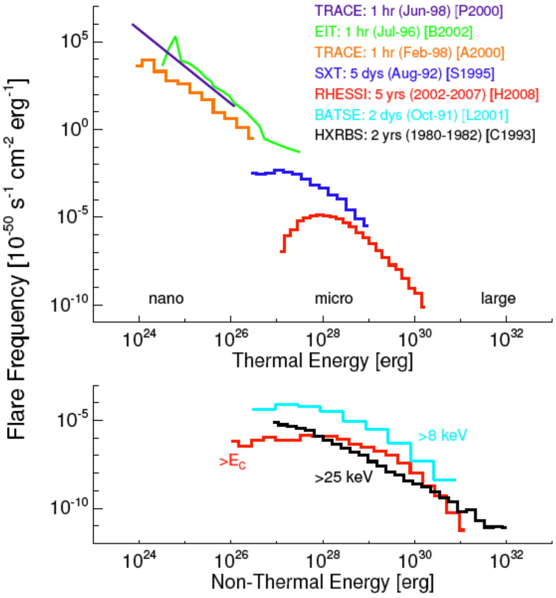


Parker (1998)

Microflares and nanoflares

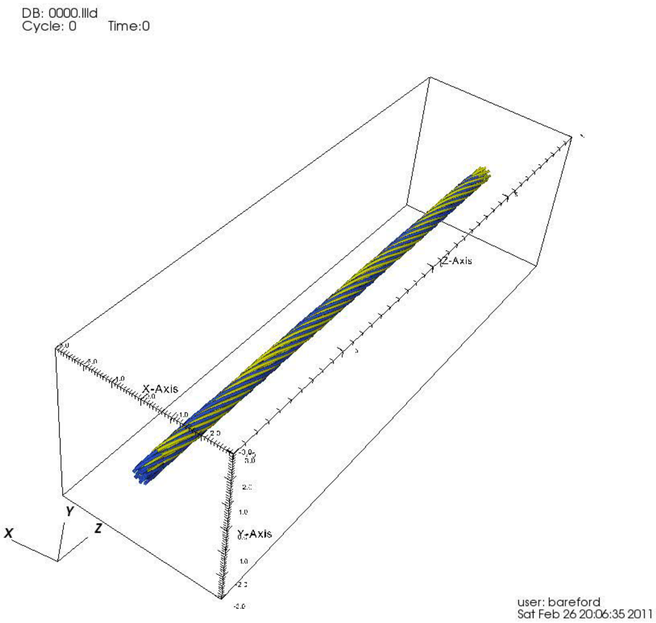
Observed flares span a large range in energies, from microflares (10^{24} ergs) to great flares (10^{32} ergs).

- Flares at 10^{23} erg have not been observed.
- Coronal heating requires a spectral index in flare frequency distribution of > 2 (Hudson 1991)
- Spectral index ranges from 1.5 to 2.1
- Big problems counting very small events near the noise
- Not clear that the readily observable properties (e.g. EUV intensity) are very good proxies for total flare energy.



Hannah et al. 2008

Loop instability and microflares



Another idea is that a single loop is driven (by footpoint twisting) to instability

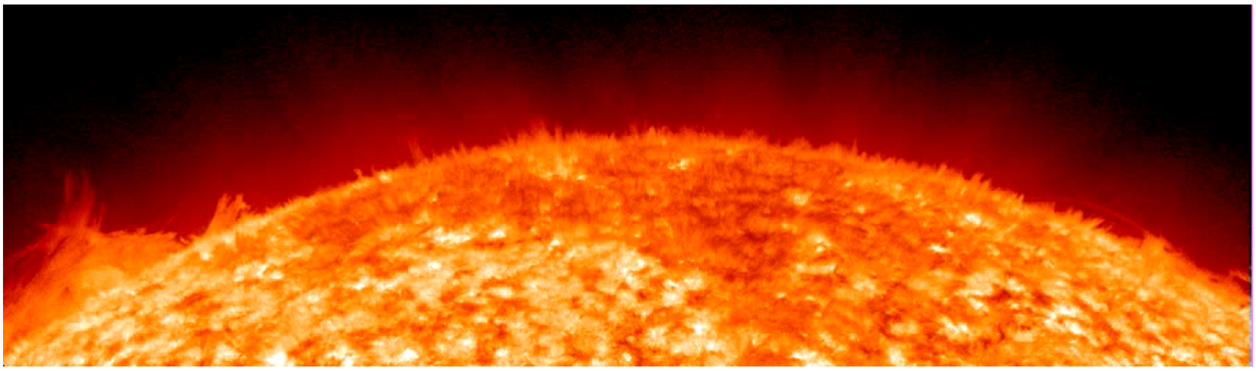
Internal current sheets form (red) leading to reconnection and heating

(Bareford et al 2011)

Heating by spicules?

The multitude of jets that on average comprise the chromosphere are known as spicules. Perhaps the energy contained in the mass motion of the spicules heats the corona?

NASA/SDO/AIA



Emission at 30.4nm, from singly-ionised He.

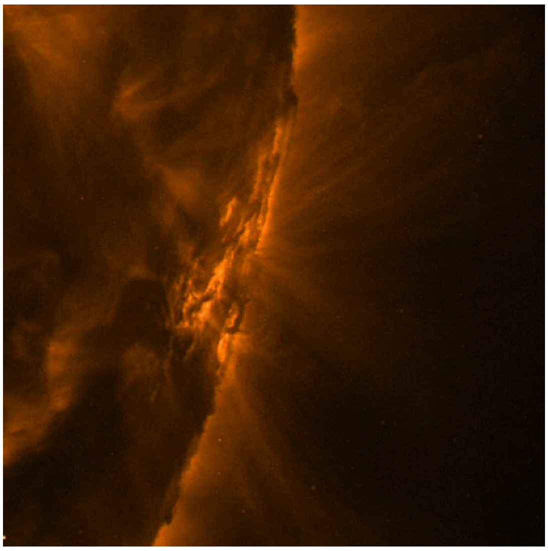
… probably not

What do we learn?

We've learned that this is a surprisingly difficult problem.

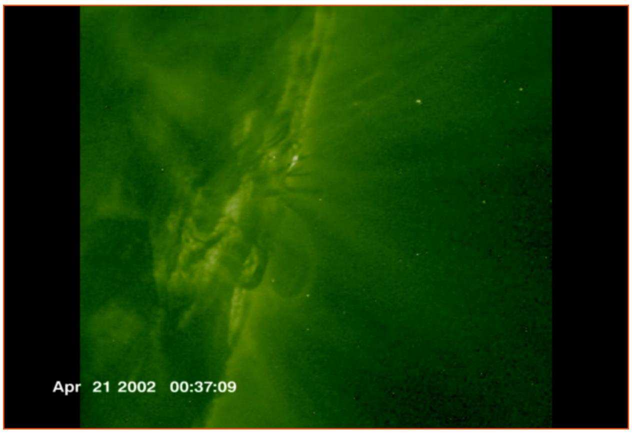
- High conductivity and rapid dynamic response of the coronal plasma smears out any clear signatures of different input models on (so far) observable timescales.
- Still plagued by basic things…how to subtract the background?
- Observed flare distribution provides marginal evidence for nanoflares
- nanoflare modeling (intermittent but quasi-steady energy input in multiple loops) does a good job at explaining hot (~5MK) loops and warm (~2MK) loops.
- Energy budget of waves is not well pinned down

Solar flares



Fe XII and Fe XXIV emission (TRACE)

T ~ 20 MK (~2keV)

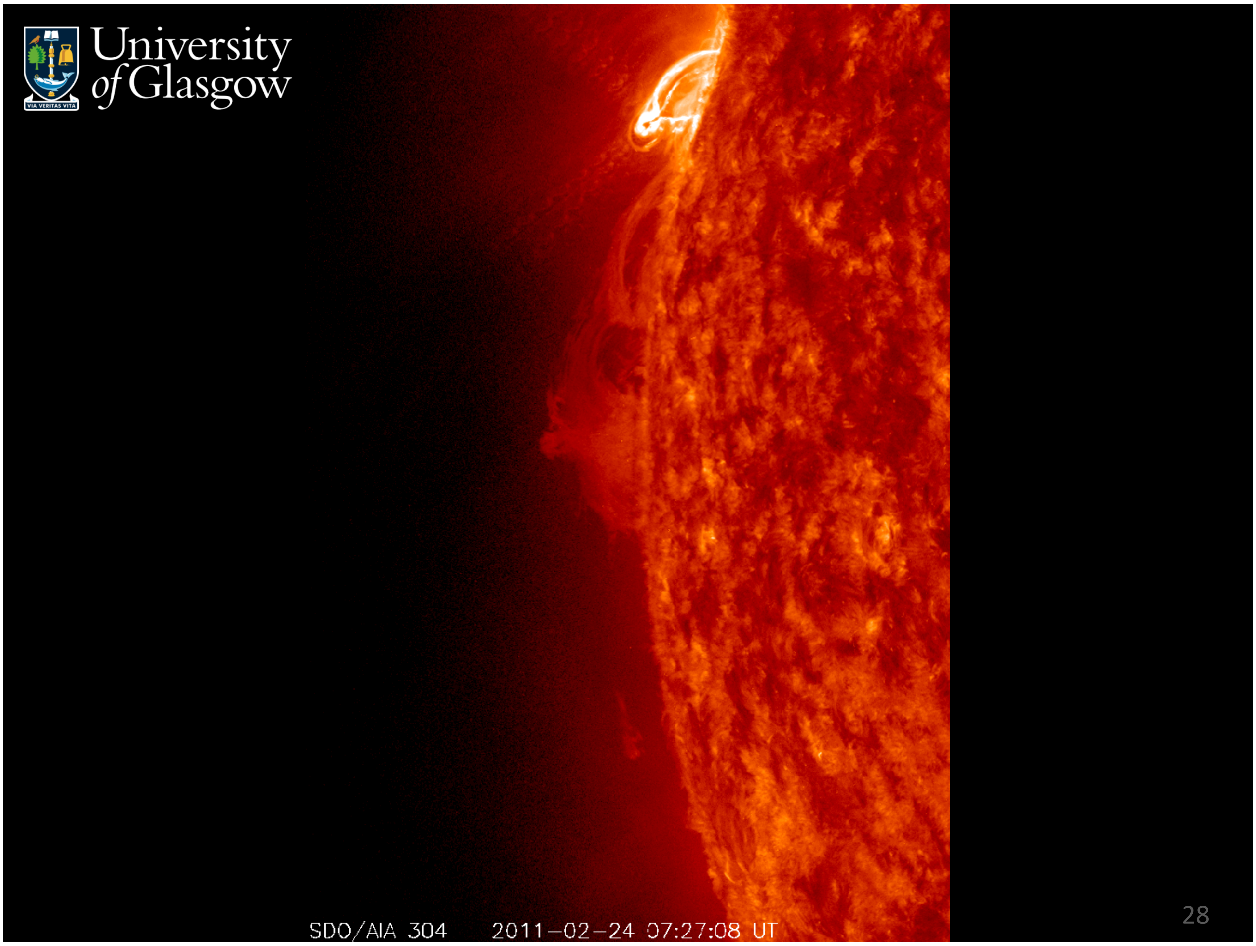


Bremsstrahlung emission:

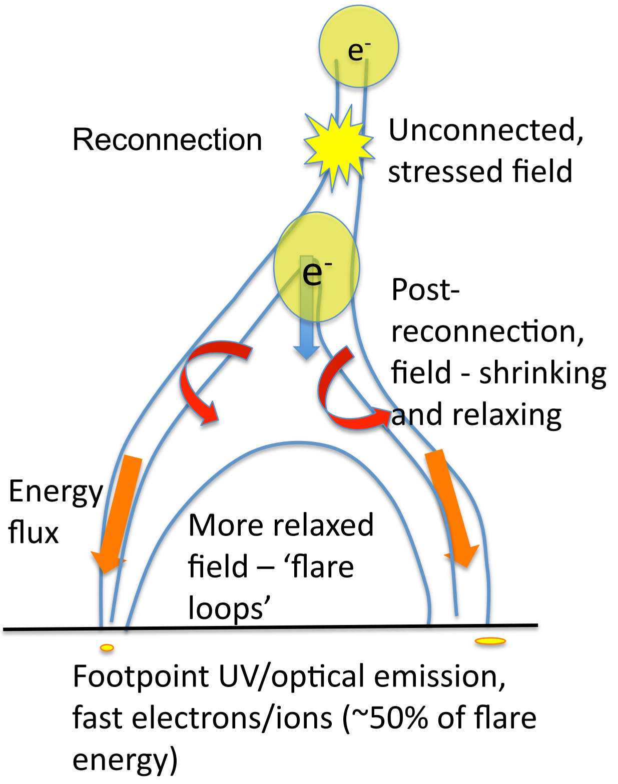
Red - 12-25 keV (RHESSI)

Blue - 25-50 keV – (RHESSI)

Green – thermal (TRACE)



Flare basics



Reconnection

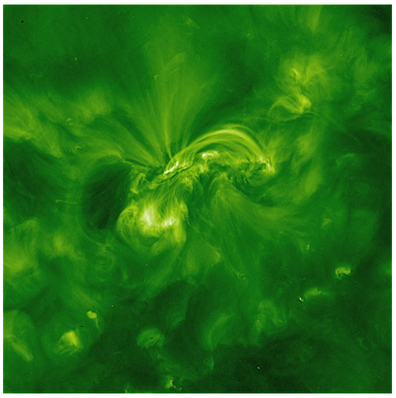
Unconnected, stressed field

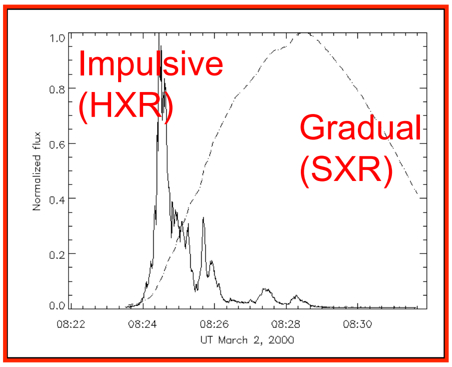
Post-reconnection, field - shrinking and relaxing

Energy flux

More relaxed field – 'flare loops'

Footpoint UV/optical emission, fast electrons/ions (~50% of flare energy)





The first known flare

e.g. The Carrington flare of 1859 - first recorded flare observation, and probably the largest. Had this occurred in the modern era its effects could have been catstrophic.

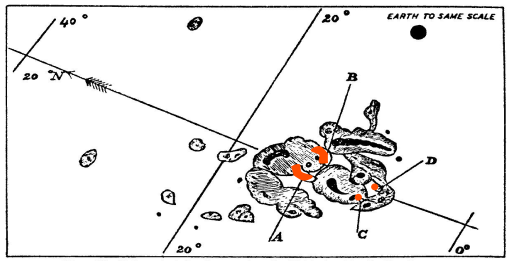


FIG. 36. Solar sketch, September 1, 1859, by R. C. Carrington

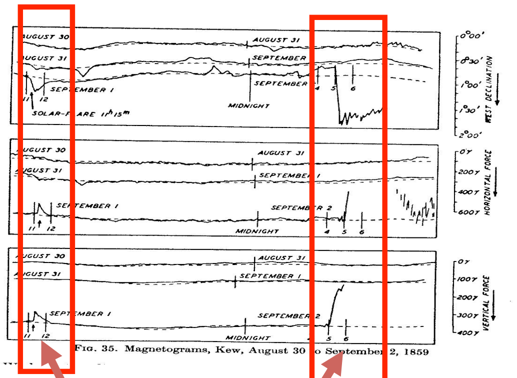


FIG. 35. Magnetograms, Kew, August 30 to September 2, 1859

First recorded flare – white light drawing by Carrington (1859)

- Likened to the star α Lyrae, in brilliance and colour (bluish-white)

Magnetometer disturbances following Carrington's Flare :

(i) flare UV increases ionisation of ionosphere

(ii) CME arrives, disturbing geomagnetic field

Energetics

Total flare energy is rather poorly known

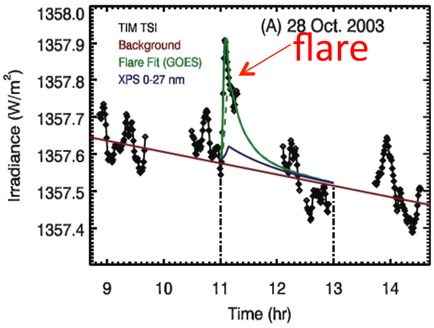
- most of the flare energy emerges in the UV to optical range
- Currently, this range is not well observed

(Can do much better for stellar flares which have great optical coverage)

Direct 'Sun as a Star' measurement gives X-flare power ~ 10^{29} erg s^{-1}
~ few x 10^{32} ergs total
(Woods et al 04, 05, Kretschmar et al 2010)

Comparable to power *inferred* for non-thermal electrons from hard X-rays.

Flare total irradiance



Woods et al 2005

Energetics

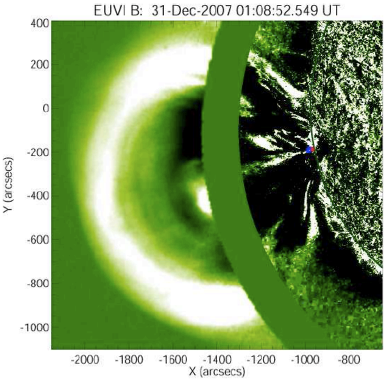
Energy per component in units of $\log_{10}$ E (ergs)

	21 April 2002	23 July 2002
Primary Energy		
Magnetic	32.3 ± 0.3	32.3 ± 0.3
Flare		
Intermediate Energies (1)		
Electrons ($> E_{\rm min}$)	31.3 ± 0.5	31.3 ± 0.5
Ions ($>$ 1 MeV nucleon^{-1})	< 31.6	31.9 ± 0.5
Thermal Plasma ($T > 5$ MK)	$31.1^{+0.4}_{-1.0}$	$30.4^{+0.4}_{-1.0}$
Radiant Energy		
From *GOES* plasma	31.3 ± 0.3	31.0 ± 0.3
L_{total} (2)	32.2 ± 0.3	32.2 ± 0.3
CME		
Kinetic	32.3 ± 0.3	32.3 ± 0.3
Gravitational Potential	30.7 ± 0.3	31.1 ± 0.3
Energetic Particles at 1 AU	31.5 ± 0.6	< 30

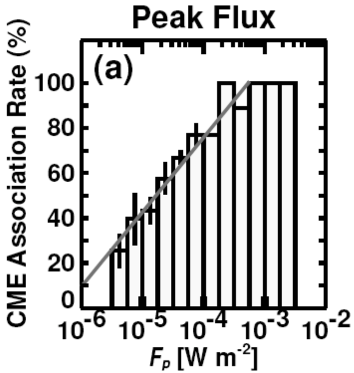
(1) E_{min} is largest value of low energy cutoff compatible with HXR spectrum.
(2) Assumes L_{total}/L_x = 100 (e.g. Kretschzmar 2011)

Flares and CMEs

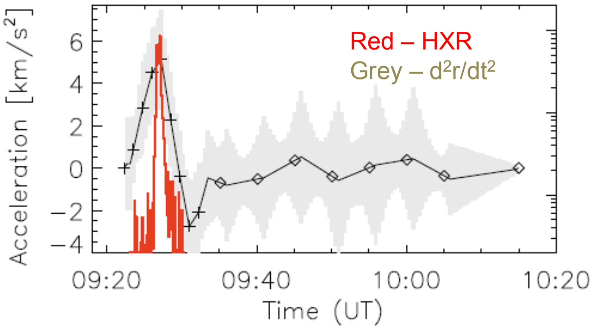
- 90% of GOES X-flares have a CME.
- Within instrumental time resolution, CME acceleration peaks simultaneously with hard X-rays
- Flare energy density >> CME energy density



Krucker et al. (2007)



Yashiro et al. (2007)



Temmer et al. (2010)

Coronal energy storage

MHD version of Ampère's Law

$$j = \nabla\times B/\mu$$

Twisting the field produces <u>'free energy'</u> in the form of current.

MHD Force balance equation

$$\cancel{-\nabla p}+\vec{j}\times\vec{B}+\cancel{\rho\vec{g}}=\cancel{\rho\frac{Dv}{Dt}}$$

Assume ~ steady state, with negligible gravitational forces and pressure gradients (low beta corona). Then

$$\vec{j}\times\vec{B}=0$$

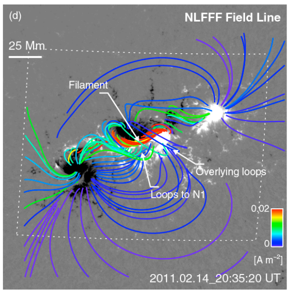
Force-free condition, i. e. field and current are aligned

So $(\nabla\times\underline{B})\times\underline{B}=0,$ meaning $(\nabla\times\underline{B})=\alpha\underline{B}$

α constant along field lines

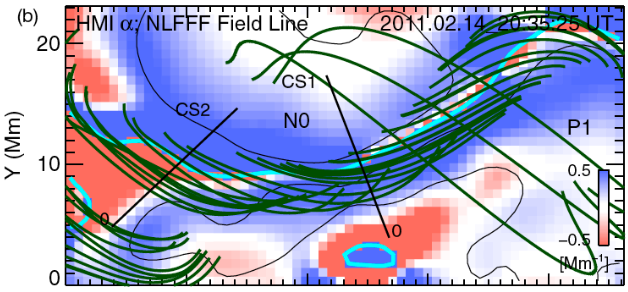
Energy storage

Prior to a flare, energy is stored as currents in the corona

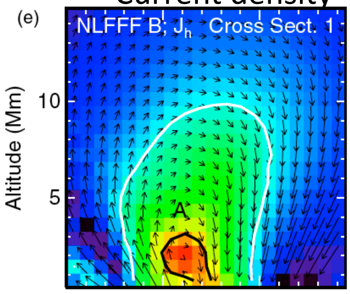


Methods for calculating non-potential fields becoming quite advanced, though still have problems

Demonstrate that energy is stored low in atmosphere (< 0.01 R_{sun}), close to polarity inversion line.



Current density



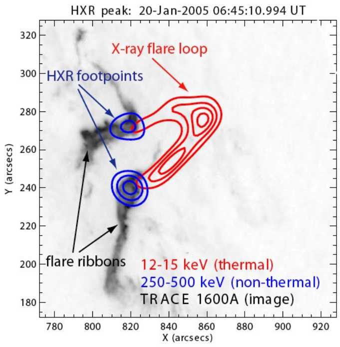
Red = 50 A/m^2

Height = 2Mm = 0.003 R_{sun}

Sun et al (2012)

Impulsive phase morphology

Krucker et al. 2008

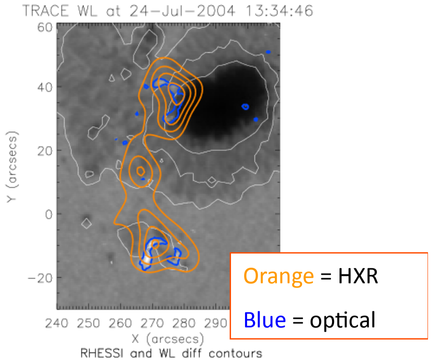


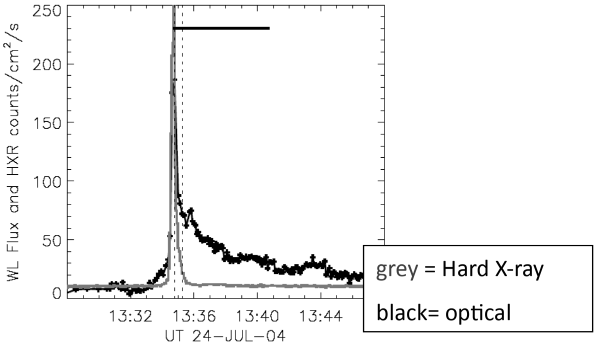
Typically a flare has ~2 strong hard X-ray ‘footpoints’ -> non-thermal electrons

Optical/UV/EUV also produced at the footpoints.

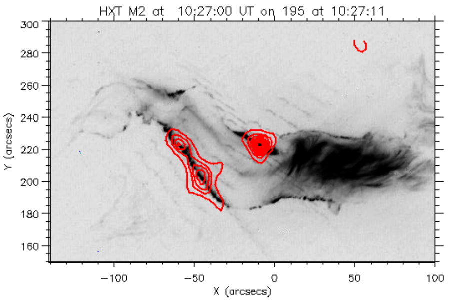
Power per unit area ~ 10^{11}-10^{12} erg s^{-1} cm^{-2}
This is a large perturbation!

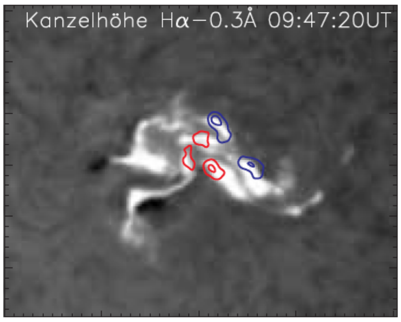
Fletcher et al. 2007





Impulsive phase morphology





- Most flares organised into 2 main ribbons of emission, bright in Hα, UV, EUV

- Can be 4 ribbons in quadrupolar field geometries

- Hard X-ray and optical sources locations are a subset of the UV/Hα ribbon locations

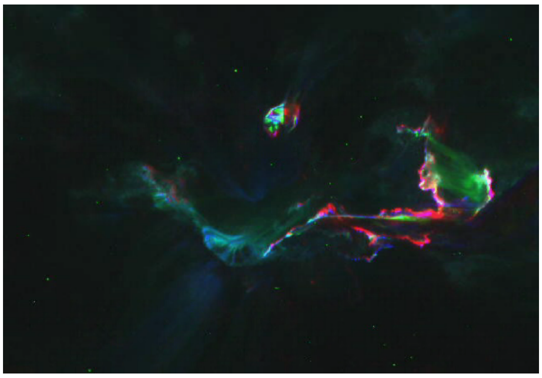
- Indicates regions of stronger and weaker energy input
    - probably related to magnetic topology

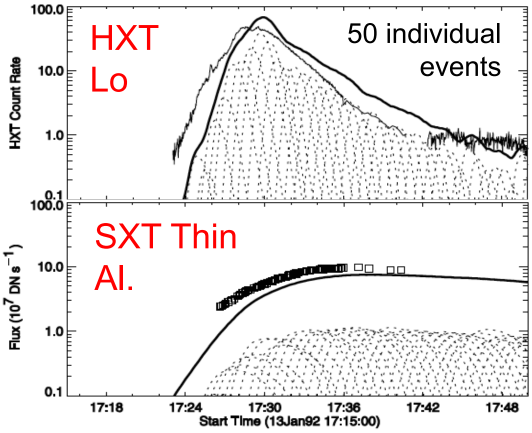
Multiple loops

Larger solar flares involve multiple resolvable loops, excited at different times.

A better agreement between flare EUV/SXR time profiles is obtained for multiple loops (e.g. Reale et al 2004., Warren 2006, Reale et al 2012, etc.)

Flare decay time is determined by single-loop cooling properties *and* overall loop excitation sequence





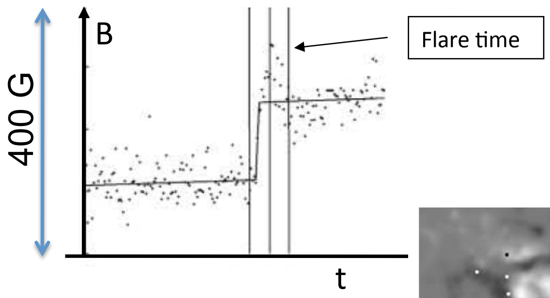
Warren (2006)

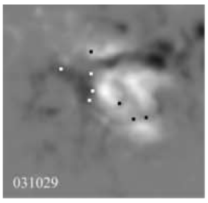
Flare effects on deep atmosphere

There is evidence that deep layers of the solar atmosphere are affected:

Non-reversing field changes

Photospheric LOS field changes of typically ~100 G coincident in space & time with impulsive phase

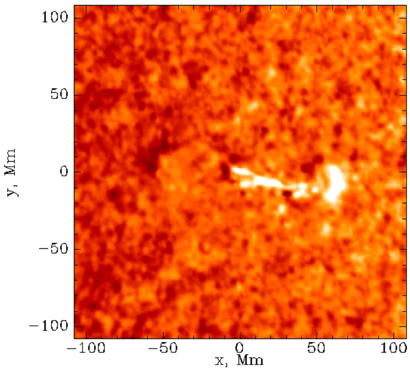




(Sudol & Harvey 2005)

Sunquakes

Requires ~ 0.1% of flare energy to penetrate photosphere

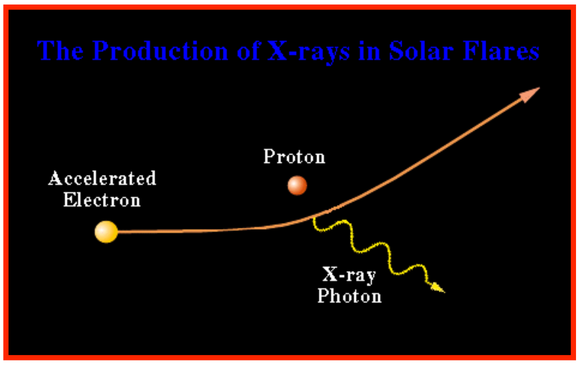


Kosovichev & Zharkova (1996)

Hard X-rays

Hard X-rays observed by RHESSI are electron-proton bremsstrahlung from energetic electrons (> 25keV).

These are the primary diagnostic for flare electrons.



- Most high energy bremsstrahlung is produced in the dense chromosphere.
- In the chromosphere, $E_{electron} >> E_{target}$, and bremsstrahlung is very inefficient.
- Only ~ 10^{-5} of the electron energy is radiated as HXRs
- Inferred number: 10^{35}-10^{36} electrons/s accelerated (would empty flare corona in 10s)

Electron spectra

Electron spectral fitting is the basic way we currently assess solar flare energetics.

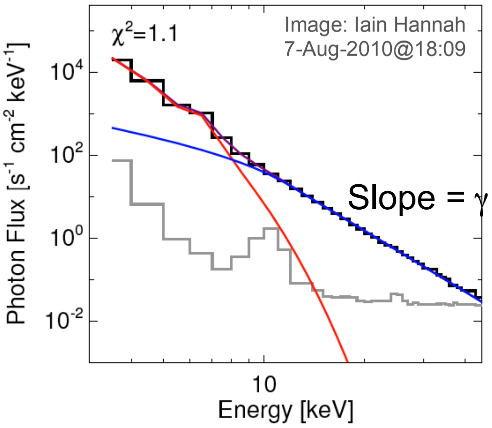


Image: Iain Hannah
7-Aug-2010@18:09

Assumptions:

- 2 distinct electron populations – thermal & non-thermal
- Non-thermal emission generated by collisionally-stopped electrons in a cold target

Fit parameters from observations:
Nonthermal: F_o, δ (= γ+1), E_{min}
Thermal: T, EM

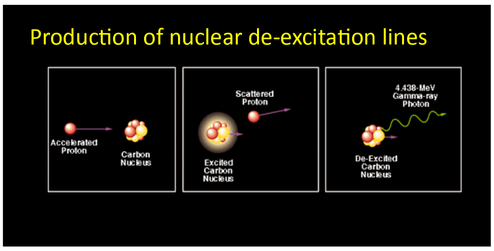
Only *upper limits* can be set on E_{min}

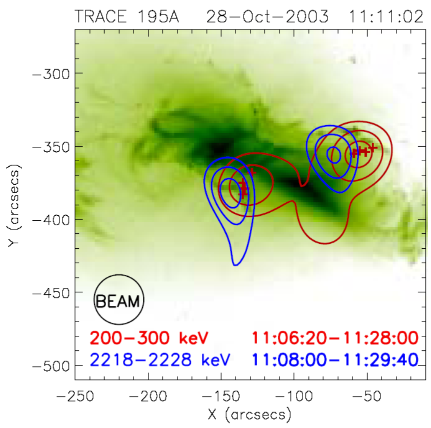
flare power = $P(> E_{min}) = \frac{F_o}{\delta - 2} E_{min}^{\;2-\delta}$ so *lower limit* on P is determined

Gamma rays

The presence of accelerated ions in flares is revealed by gamma-rays

Nuclear de-excitation lines caused by bombardment of nuclei by > 30MeV protons



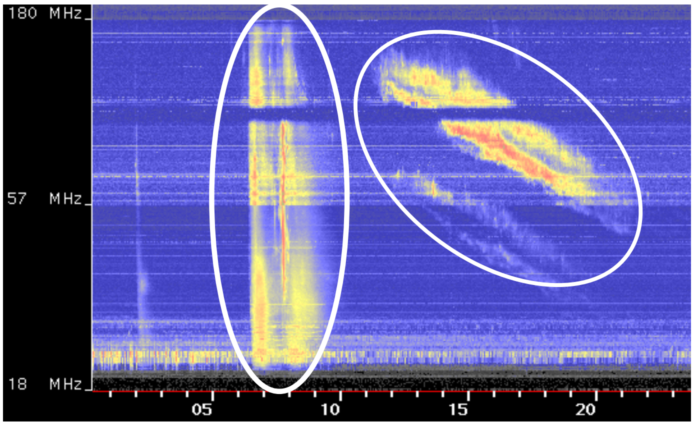


Neutron capture line at 2.23 MeV - n(p,γ)D

- shows location of 10s of MeV ions

Others: The positron annihilation line at 511keV
Continuum γ-rays by bremsstrahlung (~ 10MeV)

Coronal radio signature of flare beams and shocks



<u>Type III bursts</u> drift rapidly from high to low frequency.

-produced by flare-accelerated electron beams streaming into space which generate Langmuir waves. These mode-convert to EM radiation.

<u>Type II bursts are</u> produced by electrons accelerated at a super-Alfvenic coronal shock wave, driven by a coronal mass ejection.

Radio frequency = plasma frequency

Particle acceleration in flares

Analysis of flare X-rays and white-light shows that around 10^{36}-10^{37} electrons per second must be accelerated to 10s of keV (and a similar number of ions). This is a significant problem.

Theories for the origin of the acceleration electric field include:

- due to changing B in or near reconnection ($\nabla\times E = - \partial B/\partial t$)
- generated by locally increased resistivity in a loop ($E = \eta j$)
- resulting from small-scale EM or electrostatic turbulence
- generated in an MHD shock (e.g. CME driven)

All of the above can produce electrons of a high energy in a short time, but none can readily maintain the *rate* implied by observations.

(rate ~ 10^{36} e/s $\Rightarrow$ essentially all electrons from the corona local to a flare are accelerated within 10s. But the acceleration can last for minutes.)

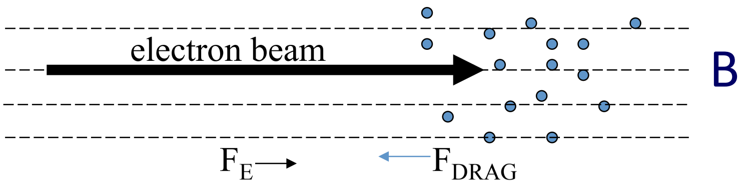
Field-aligned DC fields

- For example, a local increase in resistivity in a current loop leads to large potential drop (since huge inductance of circuit prevents rapid change in current)

- Electrons accelerated if this DC field is greater than the Dreicer field, $\mathcal{E}_d$ The Dreicer field is the value of the DC field such that the force exerted on the electrons exceeds drag force from e-e Coulomb collisions

- $\mathcal{E}_d$ typically 10^{-4} V/cm

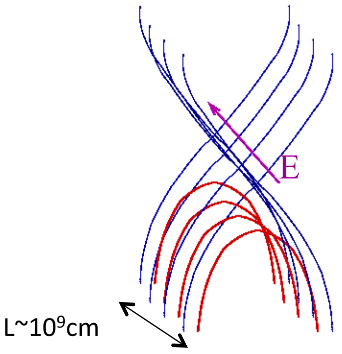
- Electrons with speeds greater than a critical speed $=v_{Te}\,(E_d/E)^{1/2}$ are freely accelerated → ‘runaway’ electrons



DC electric fields in a current sheet

Observations suggest that high electric fields occur in reconnection regions.

Inferred values of reconnection electric field are ~ 1 V/cm



total potential drop = 10^{10} V

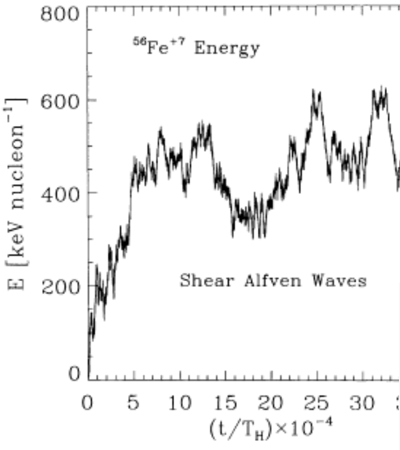
But E ⊥ B almost everywhere. Leads to drifts rather than acceleration

Near X-line or current sheet, there may be an ‘unmagnetised’ region B(x,y) → 0, or a component of E parallel to B

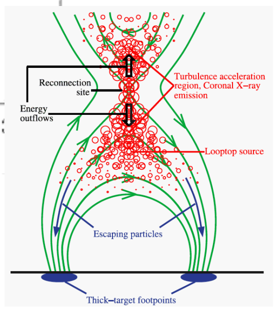
Here, efficient particle acceleration can occur – but only in a small volume (radius ~ r_L)

Stochastic resonant acceleration

Particle resonates with high-frequency wave. If a wave spectrum exists, it can ‘hop’ stochastically from one resonance to another



Miller & Viñas (1993)



Liu et al (2010)

Energy can be lost or gained in each interaction, but overall, energy of particle increases

In principle can operate throughout a <u>large volume</u>, and accelerate many particles.

But process is rather <u>inefficient</u> (~ 1 in 10^4 particles accelerated)

Closing thoughts

Solar flares affect all layers in the solar atmosphere and produce radiation and particles right across the spectrum.

Understanding them requires harnessing all branches of plasma physics (along with nuclear and atomic physics, radiative transfer… etc)

Some formidable challenges ahead, e.g.:

- How do we extend our understanding of 2-D reconnection to 3-D?
- How do we tie together the MHD and kinetic theory?
- Are our trusted old models for flare energy transport still viable?

Answering these will involve the detailed plasma physics which has been painfully learned in lab and magnetospheric plasmas…take every opportunity to learn about these other fields!