Summer School 2006
High Energy Solar Physics

Thermal Radiation

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Monday, June 19, 2006, 11 – 12:30 EDT
Outline

- Introduction
- Thermal continua & line emission
- Atomic data bases - CHIANTI v. 5.2
- TRACE movie
- FIP effect
- Flare Fe XXV emission lines
- DEM
- Blue shifts & line broadening
- Flare energetics
- Future Possibilities
Introduction

- Text Books
  - Aschwanden – Physics of the Solar Corona
  - Emslie and Tandberg-Hansen - Solar Flare Physics
  - Harra & Mason – Space Science
  - Herzberg – Atomic Spectra & Structure
  - Semat – Introduction to Atomic Physics (~1950)

- Thermal Radiation
  - relevance to high energy solar physics
  - Optical, UV, EUV, X-rays
  - Lines & continua
  - Radio not covered
Why study thermal radiation?

- **Negatives**
  - Can’t differentiate between energy release processes
    - All energy release processes produce heat.
  - Nonthermal products become thermal.
  - Line spectra complicated.

- **Positives**
  - Line spectra give lots of information.
  - Provides context information for high energy processes.
    - Images, spectra, light curves.
    - Morphology, temperature, density, abundances.
    - Magnetic field from Zeeman splitting
      - Optical lines in photosphere
      - IR lines in corona.
  - Total energy in thermal plasma
  - Total radiated energy
    - The best measure of the total flare energy.
Thermal Radiation

- **Visible Radiation**
  - Temperature structure of atmosphere
  - Element abundances (Fraunhofer lines, “curve of growth analysis.”)
  - Lower chromosphere (Hα, Ca II H & K optically thick, cores emitted in chromosphere)
  - Magnetic field

- **UV & EUV**
  - Chromosphere (H Ly-α, He I & II)
  - Transition region & corona (1600, 171, 195 Å)

- **Soft X-rays**
  - Active regions
  - Flares

- **Radio**
Intensity & Flux

Specific Intensity
(erg cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) ster\(^{-1}\))

Detected Flux
(erg cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\))

received intensity
(erg cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) ster\(^{-1}\))
Intensity & Flux

- Specific Intensity of Source
  - Units - erg cm\(^{-2}\) s\(^{-1}\) [keV/erg/Hz/cm]\(^{-1}\) ster\(^{-1}\)
  - Energy emitted by source per unit area of source, time, photon parameter, & solid angle.

- Flux of photons from source detected in space
  - Units - photons cm\(^{-2}\) s\(^{-1}\) [keV/erg/Hz/cm]\(^{-1}\)
  - Number of photons detected per unit detector area, time, & photon energy.

- Total rate of energy emitted by source
  - Units - erg s\(^{-1}\) [keV/erg/Hz/cm]\(^{-1}\)
  - \(=\) Flux \(\times\) \(2\pi\) \(D^2\)
  - \(D\) = distance between source and detector (1 AU)
  - Assumes isotropic emission over upward hemisphere.
Solar Spectrum

![Graph showing the solar spectrum with logarithmic scales for flux and wavelength. The graph includes labels for Corona, Chromosphere, Photosphere, and a black-body spectrum with a temperature of 5762 K.]
Black-Body Radiation

- Equilibrium between emission & absorption
  - Applies to photosphere

- Kirchhoff’s Law: \[ \epsilon_\nu = n_\nu^2 \alpha_\nu B_\nu(T) \]

- \( \epsilon \) - emission coefficient (erg s\(^{-1}\) cm\(^{-3}\) Hz\(^{-1}\) rad\(^{-1}\))
- \( \alpha \) - absorption coefficient (erg s\(^{-1}\) cm\(^{-3}\) Hz\(^{-1}\) rad\(^{-1}\))
- \( n \) - refractive index of the medium
- \( B(T) \) - universal brightness function at temperature T (erg s\(^{-1}\) cm\(^{-2}\) cm\(^{-1}\) steradian\(^{-1}\))
- \( \nu \) - frequency (Hz)
Planck’s Law
Blackbody Brightness vs. $\lambda$ (or $\nu$) and $T$

$$B_\lambda(T) = \frac{2hc^2n^2}{\lambda^5}[\exp\left(\frac{hc}{\lambda k_BT}\right) - 1]$$

$B(T)$ – Planck function (erg s$^{-1}$ cm$^{-2}$ cm$^{-1}$ steradian$^{-1}$)
$h$ – Planck’s constant = 6.63 10$^{-27}$ erg s
$\nu$ – frequency in Hz
$\lambda$ – wavelength in cm
$n$ – refractive index of the medium
$c$ – velocity of light = 3.0 10$^{10}$ cm s$^{-1}$
$k_B$ – Boltzmann’s constant = 1.38 10$^{-16}$ erg K$^{-1}$
$T$ – temperature in K
Black-Body Radiation
Planck’s Function - $B_\lambda(T)$

![Graph showing the distribution of brightness across different wavelengths for various temperatures.](image-url)
Planck’s Function - $B_\lambda(T)$

- **Wien Displacement Law**
  
  Wavelength at which $B_\lambda$ is maximum

  $$\lambda_{max} = \frac{0.2898}{T(K)} \ (cm)$$

- **Stefan-Boltzmann Law**
  
  Total flux - all wavelengths over the visible hemisphere

  $$\pi B(T) = \pi \int_0^\infty B_\lambda(T)d\lambda = n_\nu^2 \sigma T^4$$

  $\sigma$ - Stefan-Boltzmann constant $= 5.67 \times 10^{-5}$ erg s$^{-1}$ cm$^{-2}$ K$^{-4}$
Planck’s Law Approximations

Short Wavelengths (UV, X-rays)

Wien’s Law
\[ B_\nu(T) = \frac{2h\nu^3 n_\nu}{c^2} \exp\left(-\frac{h\nu}{k_B T}\right) \]

\( k_B \) – Boltzmann’s constant = 1.38 \( 10^{-16} \) erg K\(^{-1}\)

Long Wavelengths (Radio)

Rayleigh-Jeans Law
\[ B_\nu(T) = \frac{2\nu^2 k_B T n_\nu^2}{c^2} \]
LTE
Local Thermodynamic Equilibrium

- Maxwellian velocity distribution
  Mean energy = $\frac{3}{2} k T$ per particle
  $$f(v) = n \left(\frac{m}{2pk_B T}\right)^{\frac{3}{2}} 4\pi v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)$$
  particles cm$^{-3}$ (cm s$^{-1}$)$^{-1}$

- Applies in photosphere

- Ionization equilibrium

  Saha Equation
  $$\frac{N_k}{N_0} = \frac{2}{n_e} \frac{(2\pi m_e k_B T)^{3/2}}{\hbar^3} \frac{g_k^l}{g_0} \exp\left(-\frac{\epsilon_k}{k_B T}\right)$$

  Fraction of ions in k state of ionization
Solar Spectrum

Quiet Sun & Flares - Gamma-rays to Radio
Chromosphere & Corona

Chromosphere
- partially ionized

Corona
- fully ionized

Transition Region

Particle density (cm$^{-3}$)
- $n_e$
- $n_{H_0}$

Temperature $T_e$ [K]

Height above photosphere (km)
- $T_e$
- $n_e$
Chromosphere & Corona

- Not black-body
  - Optically thin in EUV & X-rays
  - Line emission from H, He, ionized metals, etc.
- Not LTE
- Chromosphere partially ionized
- Corona is fully ionized
Principal Radiations

- Continuum Emission
  - Free-free emission - thermal bremsstrahlung
  - Free-bound emission – radiation recombination
  - Two-photon emission

- Line Emission
  - Bound-bound transitions in atoms & ions

- Scattered Radiation
  - Thompson scattering of photospheric emission
    (→ LASCO images)
Free-Free Emission
Bremsstrahlung

Free-free emission

Electron in hyperbolic orbit
Free-Free Emission
Thermal Bremsstrahlung

■ Photon Spectrum

\[ F(\epsilon) \approx 8.1 \times 10^{-39} \int_V \frac{\exp \left( -\frac{\epsilon}{k_B T} \right)}{T^{1/2}} n^2 \, dV \]

Units - keV s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\)
\(\epsilon\) - photon energy = \(h\nu\)
n - electron and ion density
V - source volume
Free-Bound Emission
Recombination Radiation

Photon
Energy: $\epsilon = E_e - E_L$?

Electron $e^-$
Energy: $E_e$

Nucleus $+Ze$
Energy Level: $E_L$

Continuum emission
Spectral edges at atomic energy levels
Two-Photon Continuum

- Ion in excited $J = 0$ state, energy $E_1$
  (J is total angular momentum)
- De-excites to ground state with $J = 0$, energy $E_0$
- Single photon cannot be emitted
  (because photon spin = 1)
- 2 photons with opposite spins can be emitted
- Photon energies, $\epsilon_1 + \epsilon_2 = E_1 - E_0 \rightarrow$ continuum
- Important for He-like ions
- Lowest excited state is $2^1S_0$
Thermal Continuum Emission

T = 20 MK  
Coronal Abundances  
CHIANTI v. 5.2
Continuum Fractions
(CHIANTI v. 5.2)

Coronal abundances & Mazzotta et al. ionization equilibrium

T = 20 MK
- Free-bound
- Free-free

T = 40 MK
- Free-free
- Free-bound
Free-Bound Fraction

Coronal abundances

Free-bound fraction of total flux

Temperature ($10^6 \, ^\circ K$)

(b)
Line Emission
Hydrogen Atom

Balmer Series

Lyman Series

H β
H α
H γ

Ly α
Ly β
Ly γ
Ly δ
Hydrogen

Emission Lines
Quantum Numbers

- Principal quantum number
  \[ n = 1, 2, 3, 4... \]
  \[ K, L, M, N,... \]

- Orbital angular momentum
  \[ l = 0, 1, 2, 3, 4, 5,... \]
  \[ s, p, d, f, g, h,... \text{ where } l < n \]

- Electron spin
  \[ s = \frac{1}{2} \]

- Projected angular momentum
  \[ m_l = l, l - 1, l - 2,...-l \]

- Projected electron spin
  \[ m_s = \pm \frac{1}{2} \]
## Electron States

<table>
<thead>
<tr>
<th>Shell</th>
<th>K</th>
<th>L</th>
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<tbody>
<tr>
<td>n</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>l</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>s</td>
<td>p</td>
</tr>
<tr>
<td>m_l</td>
<td>0</td>
<td>-1 0 +1</td>
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<tr>
<td>m_s</td>
<td>±(1/2)</td>
<td>±(1/2) ±(1/2) ±(1/2)</td>
</tr>
<tr>
<td>m</td>
<td>±(1/2)</td>
<td>±(1/2) -1/2 -3/2</td>
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</table>

<table>
<thead>
<tr>
<th>Shell</th>
<th>K</th>
<th>L_1</th>
<th>L_2</th>
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<tr>
<td>n</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l</td>
<td></td>
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</tbody>
</table>
Spectral Notation
Electron Configuration

- Electron Configuration = n l^N
  - n - principal quantum number
  - l – orbital angular momentum
  - N - number of electrons in given configuration

- H ground configuration: 1s (means 1s^1)

- Neutral Fe ground configuration
  1s^22s^22p^63s^23p^64s^24p^6
  "one s squared…"

- Neutral He & Fe XXV ground configuration
  1s^2
  "one s squared…"
Spectral Notation
Atomic or Ionic States

- Specification of ion state = \(2S+1L_J\)
  
  \(S = \) vector sum of all electron spins
  
  \(2S+1 = \) number of possible values of \(J\) (“multiplicity”)
  
  \(L = \) vector sum orbital angular momentum of all electrons
  
  \(0,1,2,3,4,5,...\)
  
  \(S, P, D, F, G, H,...\)
  
  \(J = \) vector sum angular momentum of atom
  
  \(= L + S\)

- Fe XXV ground state = \(1s^2 \ 1S_0\) (“one s squared singlet \(S\) zero”)

- Fe XXVI = \(1s \ 2S_{1/2}\) (“one s doublet \(S\) one half”)

- Fe XXVII = \(1s \ 2S_{3/2}\) (“one s doublet \(S\) three half”)
Atomic Data Bases

Available Codes
- CHIANTI (v. 5.2)
- ATOMDB - APEC/APED
  Astrophysics Plasma Emission Database and Code
  [http://cxc.harvard.edu/atomdb](http://cxc.harvard.edu/atomdb)
- MEKAL (Mewe-Kaastra-Liedahl) – semi-empirical
- SPEX (v. 2, Kaastra at sron.nl) – includes MEKAL

Parameters
- Temperature \(10^3 – 10^8\) K
- Photon wavelength/frequency/energy
- Density
- Abundances
- Ionization equilibrium
Data Bases Compared (2003)

2 – 35 Å

APED v. 1.10

SPEX

CHIANTI v. 4.0 Intensities
CHIANTI v. 5.2
(Landi et al., ApJSS, 2006, 162, 261)

☐ In SSW/packages or stand-alone
☐ GUI (type ch_ss in IDL)
☐ IDL command-line interface
☐ Great users guide!
☐ Now used in RHESSI OSPEX

CHIANTI is a collaborative project involving NRL (USA), RAL (UK), and the following Universities: College London (UK), of Cambridge (UK), George Mason (USA), and of Florence (Italy).
Flares
High Temperature Emissions

☐ Highest temperature plasmas tell most about the energy release process.

☐ Produced by
  Direct heating in corona
  and/or
  Indirect heating via nonthermal particles
  \(\rightarrow\) chromospheric evaporation
### TRACE Spectral Bands

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Emission</th>
<th>Bandwidth (Å)</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>171</td>
<td>Fe IX/X</td>
<td>6.4</td>
<td>1.6–20 × 10⁵</td>
</tr>
<tr>
<td>195</td>
<td>Fe XII/XXIV</td>
<td>6.5</td>
<td>5.0–20 × 10⁵,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.1–2.6 × 10⁷</td>
</tr>
<tr>
<td>284</td>
<td>Fe XV</td>
<td>10.7</td>
<td>1.25–4.0 × 10⁶</td>
</tr>
<tr>
<td>1216</td>
<td>H I Lα</td>
<td>84</td>
<td>1.0–3.0 × 10⁴</td>
</tr>
<tr>
<td>1550</td>
<td>C IV</td>
<td>30</td>
<td>6.0–25 × 10⁴</td>
</tr>
<tr>
<td>1600</td>
<td>UV cont, C I, Fe II</td>
<td>275</td>
<td>4.0–10 × 10³</td>
</tr>
<tr>
<td>1700</td>
<td>Continuum</td>
<td>200</td>
<td>4.0–10 × 10³</td>
</tr>
<tr>
<td>5000</td>
<td>White light</td>
<td>broad</td>
<td>4.0–6.4 × 10³</td>
</tr>
</tbody>
</table>
TRACE

Temperature Coverage

$EM = 10^{44} \text{ cm}^{-3}$

TRACE & EIT
171 Å Filter Response

TRACE & EIT
195 Å Filter Response

RHESSI – EIT - TRACE Movie
X1.5 Flare on 21 April 2002

Click to show movie
High-Temperature Component

Bastille Day Flare
14 July 2007

A&B – hot spine
- T ~ 15 MK
- needs continuing energy input.
FIP Effect

- Magnetic and/or electric fields move ions but not neutrals.
- Ions dragged up into corona from chromosphere/T minimum/photosphere.
- Consequently, low FIP ions
  - FIP < 10 eV
  - Fe, Ni, K, Na, Ca, Al, Mg, Si, ...
  - Preferentially moved to corona
  - Coronal abundances
    - ~4 times photospheric
First Ionization Potential (FIP) Effect

Solar wind particles?

Abundance ratio $A_{\text{Cor}}/A_{\text{Phot}}$

First ionization potential [eV]

Feldman & Widing 2003
Feldman - Flares

- Chromospheric evaporation vs. in situ heating in the corona.
- Bright source at top of loop.
Fe Ionization-Recombination Equilibrium

Ions with Complete Outer Shells:
- Fe IX
- Fe XVII
- Fe XXV

are more stable, so higher fraction
Highly Ionized Iron - FeXXV

- Ion - Fe$^{+24}$
- Spectrum - FeXXV
- 2 electrons remaining in K shell
- “helium-like”
- Ground state
  - $1s^2$ (“one s squared”) $^1S_0$ (“singlet S zero”)
- Transitions between levels give emission lines

Fe-line Complex (~6.7 keV)

- **Fe XXV w line ("resonance line")**
  - Energy: 6.699 keV
  - Wavelength: 1.8508 Å
  - Transition: $1s^2 \, ^1S_0 - 1s2p \, ^1P_1$
  - Strongest line "quantum mechanically allowed"

- Many satellite lines at lower energy
- Series $1s - 2p$ in presence of other electrons
- From FeXXV – FeII Kα doublet
- FWHM ~ 0.1 keV
CHIANTI Spectrum
$T = 20$ MK Coronal Abundances

Temperature (MK) = 20.0000

Emission measure = $10^{46}$ cm$^{-3}$
CHIANTI Spectrum
Fe Line Complex near 6.7 keV
RHESSI Sensitivity

![Graph showing HESSI SHUTTER TRANSMISSION - subcoll 3 with curves labeled A0, A1, and A3 against energy (E(keV)) and transmission on a logarithmic scale.](Image)
RHESSI Imaging Spectroscopy
Caspi & Lin, 2005

\[ T = 27.65 \times 10^6 \text{ K} \]
\[ EM = 8.346 \times 10^{49} \text{ cm}^{-3} \]
\[ \gamma = 2.70 \]
Fe-line Complex \( \sim 6.7 \text{ keV} \)
Fe/Ni-line Complex $\sim 8$ keV
Equivalent Width Definition

Area of emission line above continuum \( = 1.0 \times w \)
Fe & Fe-Ni Line Complexes
Equivalent Widths vs. Temperature

Fe complex at ~6.7 keV

Fe-Ni complex at ~8 keV
Fe Line Complexes
Equivalent Width vs. Temperature

30/31 May 2002

CHIANTI
Fe 4x photospheric

RHESSI data
A1 Attenuator state
Flux Ratio vs. Temperature
Caspi & Lin, 2005
Blue shifts – flare dynamics
SMM/BCS Spectrum
Fe XXV lines and satellites

Lemen et al. 1984 Gabriel 1972
SMM/BCS
Fe Spectra

- Solid: SMM/BCS data
- Dashed: Fe XXII-XXV line spectra
- Single temp. fits
- \( w - \) Fe XXV resonance line
- \( f(T,Z) = \frac{Z^4}{T} \)

Blue Shifts and Line Broadening

P78
SOLFLEX
Bragg Crystal Spectrometer

FeXXV

Blue Shifts and Line Broadening

SMM/BCS
CaXIX


Fig. 2.—Calcium spectra of solar flares. The ratio $k/w$ is used to determine temperature.
Blue Shifts and Line Broadening

- Blue shift $\rightarrow$ upflow velocity $100 - 300$ km s$^{-1}$
- Unshifted component always dominates – why?
- Thermal line broadening $\rightarrow T_e$
- Nonthermal line broadening $\rightarrow T_{Doppler}$
- $T_{Doppler} - T_e \rightarrow$ plasma turbulence.
Multithread Model

- Multithreads heated successively each on a time scale of 200 s.
- Explains lack of 100% blue-shifted component early in flare
- Shorter time scales lead to higher temperatures than observed.

![Graph](image-url)
Emission Measure Demystified

Column Emission Measure
\[ \text{CEM} = \int n_e n_H \, dh \, [\text{cm}^{-5}] \]

Volume Emission Measure
\[ \text{VEM} = \int n_e n_H \, dV \, [\text{cm}^{-3}] \]
\[ \text{VEM} = \int_{A_{\text{source}}} \text{CEM} \, dA \]
\[ \text{VEM} = A_{\text{source}} \, \text{CEM} \, \text{cm}^{-3} \]
Photon Flux at Earth

SI(CEM27) - specific intensity for CEM = 10^{27} cm^{-5}

Flux(CEM27, \lambda)

= I(\lambda) (A_{\text{detector}} / D^2) / A_{\text{detector}} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}

= A_{\text{source}} SI(CEM27, \lambda) / D^2 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}

= A_{\text{source}} 10^{27} SI(CEM1, \lambda) / D^2 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}

(Note that the detector area cancels out.)

This corresponds to the flux from a CEM of 10^{27} cm^{-5} or a VEM of A_{\text{source}} 10^{27} cm^{-3}.
Column to Volume EM

VEM of $10^{49} \text{ cm}^{-3} \equiv \text{CEM} \times 10^{49} / (A_{\text{source}} 10^{27})$

$F_{\text{VEM}49}(\lambda) = F_{\text{CEM}27}(\lambda) \times 10^{49} / (A_{\text{source}} 10^{27})$

$= 10^{(49 - 27)} D^{-2} \text{SICEM}27(\lambda) \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$

Source area cancels out.

$D = 1.5 \times 10^{13} \text{ cm, } D^2 = 2.25 \times 10^{26} \text{ cm}^2 = 10^{26.352} \text{ cm}^2$

$F_{\text{VEM}49}(\lambda) = 10^{(49 - 27 - 26.352)} \text{SICEM}27(\lambda) \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$

$= 10^{-4.352} \text{SICEM}27(\lambda) \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$

$= 4.45 \times 10^{-5} \text{SICEM}27(\lambda) \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$

$= \text{SICEM}(27-4.352)(\lambda) \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$

$= \text{SICEM} 22.648(\lambda) \text{ photons cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$

SICEM22.648 is the specific intensity obtained from CHIANTI for CEM $= 10^{22.648} \text{ cm}^{-5}$. 


DEM Analysis

Instrument response (dF/dEM) vs. Temperature

![Graph showing the relationship between instrument response and temperature. The graph includes different curves for various instruments like TRACE, SXT/Al12, SXT/Be, and HXT, each associated with specific wavelengths and temperature ranges.]
DEM Analysis

Normalized G(T) functions
DEM Analysis

Bastille Day event – 14 July 2000

Best fit double half-Gaussian DEM model at flare peak.

![Graph showing differential emission measure (DEM) against temperature (T) with fitted parameters.]

- $T = 10.87$ MK
- $\sigma_{T1} = 3.30$ MK
- $\sigma_{T2} = 9.01$ MK
- $E_0 = 1.53 \times 10^{51}$ cm$^{-3}$
- $E_M = 1.05 \times 10^{51}$ cm$^{-3}$
CORONAS-F
DEM for the active region and the flare 28.12.2001
Markov-Chain Monte Carlo (MCMC) DEM Analysis (Liwei Lin, SAO)

DEM $Q T^{-\alpha}$ (OSPEX)

MCMC analysis with uncertainties

July 26, 2002 23:08–23:16 UT RHESSI
DEM Analysis Limitations

Sylwester

AIA DEM for set: 10; Trange: [0.2 – 30.0] MK

Log DEM [cm⁻³ K⁻¹]

Log T [MK]
Deal or No Deal!
Thermal or Nonthermal

The standard mythology

- Time history
  - Thermal is slow and smooth
  - Nonthermal is fast and impulsive

- Spectrum
  - Thermal is exponential
  - Nonthermal is power-law
  - >50 keV is nonthermal

- Image
  - Thermal is coronal & extended
  - Nonthermal is footpoints & compact

Many exceptions!
Energy Dependent Time Delays
Aschwanden, 2006, preprint
Energy Dependent Time Delays
Aschwanden, 2006, preprint
Energy Dependent Time Delays
Aschwanden, 2006, preprint
Flare Energetics

- Sum energies of flare components:
  - thermal plasma
  - nonthermal electrons from X-rays
  - nonthermal ions from gamma-rays
  - turbulent and bulk motions

- Measure total radiated energy over all wavelengths
  - Increase in total solar irradiance
Radiated Energy Losses

- Energy radiated from thermal plasma over all wavelengths

\[ L_{\text{rad}} = EM \cdot f_{\text{rad}}(T) \text{ ergs s}^{-1} \]

  - \( EM \) – emission measure
  - \( T \) - temperature
  - \( f_{\text{rad}}(T) \) - radiative loss function

- Total radiated energy from the flare plasma

\[ L_{\text{total}} = \sum [ L_{\text{rad}}(t) \cdot Dt ] \text{ erg} \]

  Sum is over the duration of the flare
CHIANTI Radiative Loss Function

Radiative Energy Loss (erg cm$^3$ s$^{-1}$)

- Ly alpha
- C, O, Si
- FeIX
- Fe XVII
- Coronal abundances
- Photospheric abundances
- Continuum

Mazzotta ionization equilibrium

Log T(K)

10$^{-23}$ 10$^{-22}$ 10$^{-21}$
Thermal Energy

Thermal energy of plasma

\[ U_{th} = 3 \ n_e \ V \ k_B \ T = 3 \ k_B \ T \ [EM \ f \ V_{\text{apparent}}]^{1/2} \ \text{erg} \]

- \( n_e \) – electron density in \( \text{cm}^{-3} \)
- \( V \) – volume of emitting plasma in \( \text{cm}^3 \)
- \( V_{\text{apparent}} \) – volume from image
- \( f \) - filling factor (assumed to be 1)
- \( k_B \) – Boltzmann’s constant
- \( T \) – temperature (from GOES and RHESSI)
- \( EM = n_e^2 \ V \) – emission measure in \( \text{cm}^{-3} \) (from GOES and RHESSI)
- \( V = f \ V_{\text{apparent}} \sim f \ A^{3/2} \)
- \( A \) - source area from image
Increase in Total Solar Irradiance
X17 flare on 28 October 2003
CME vs Flare Energies
Dennis et al. 2006

- SXR-Emiting Plasma
- TSI Increase (SORCE)
- Peak Plasma Energy (Upeak)
- Ions
- Equipartition

28 October 2003
4 November 2003
21 April 2002
23 July 2002
SORCE / TIM

CME Kinetic Energy (10^30 ergs)
Total Energy (10^36 ergs)
Future Missions

- **Stereo – 2006**
  - Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI)
    - Coronagraphs 1.1 – 15 R_{Sun}
    - EUV Imager – 2 x EIT spatial resolution, N x cadence

- **Solar B – 2006**
  - Solar Optical Telescope – magnetic fields with 0.2 arcsec resolution
  - Solar X-ray Telescope (SXT) – Yohkoh/ST-like – 1 arcsec. resolution
  - EUV Imaging Spectrometer (EIS) CDS-like images in TR & corona

- **GOES N - 2006**
  - SXI

- **Coronas – 2008**
  - SphinX – Solar Photometer in X-rays (0.5 – 15 keV, DE<190 eV)
  - EIT look alike

- **Solar Orbiter – 2017?**
  - Hard X-ray imager

- **Sentinels**
  - X-ray imager
  - Gamma-ray spectrometer

- **Indian 2\textsuperscript{nd} solar spacecraft**
  - Soft X-ray imaging spectrometer (SoXIS)
Conclusions

Thermal radiation is useful!

- Morphology
- DEM
- Plasma turbulence from line broadening
- Bulk motions from line shifts
- Abundances
- Magnetic field in corona
- Total flare energy