Summer School 2006
High Energy Solar Physics

Thermal Radiation

Brian R. Dennis
NASA
Goddard Space Flight Center
Greenbelt MD USA

Kenneth J. H. Phillips
University College
Mullard Space Science Lab.
London, UK

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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.

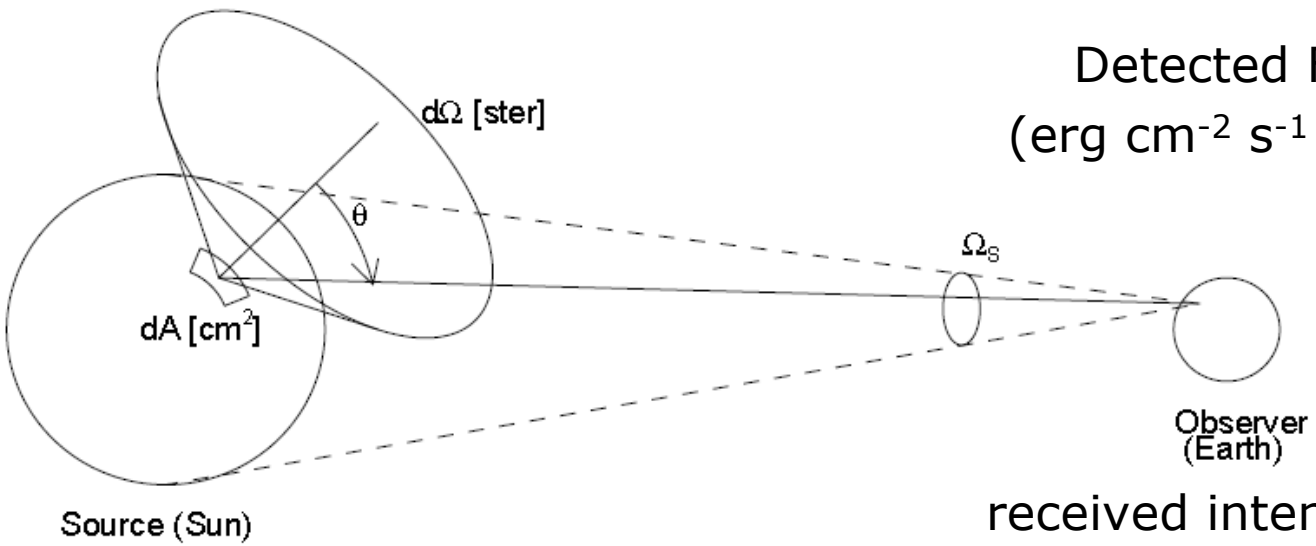
Thermal Radiation

- **Visible Radiation**
  - Temperature structure of atmosphere
  - Element abundances (Fraunhofer lines, "curve of growth analysis.")
  - Lower chromosphere (H**a**, Ca II H & K optically thick, cores emitted in chromosphere)
  - Magnetic field
- **UV & EUV**
  - Chromosphere (H Ly-**a**, 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})

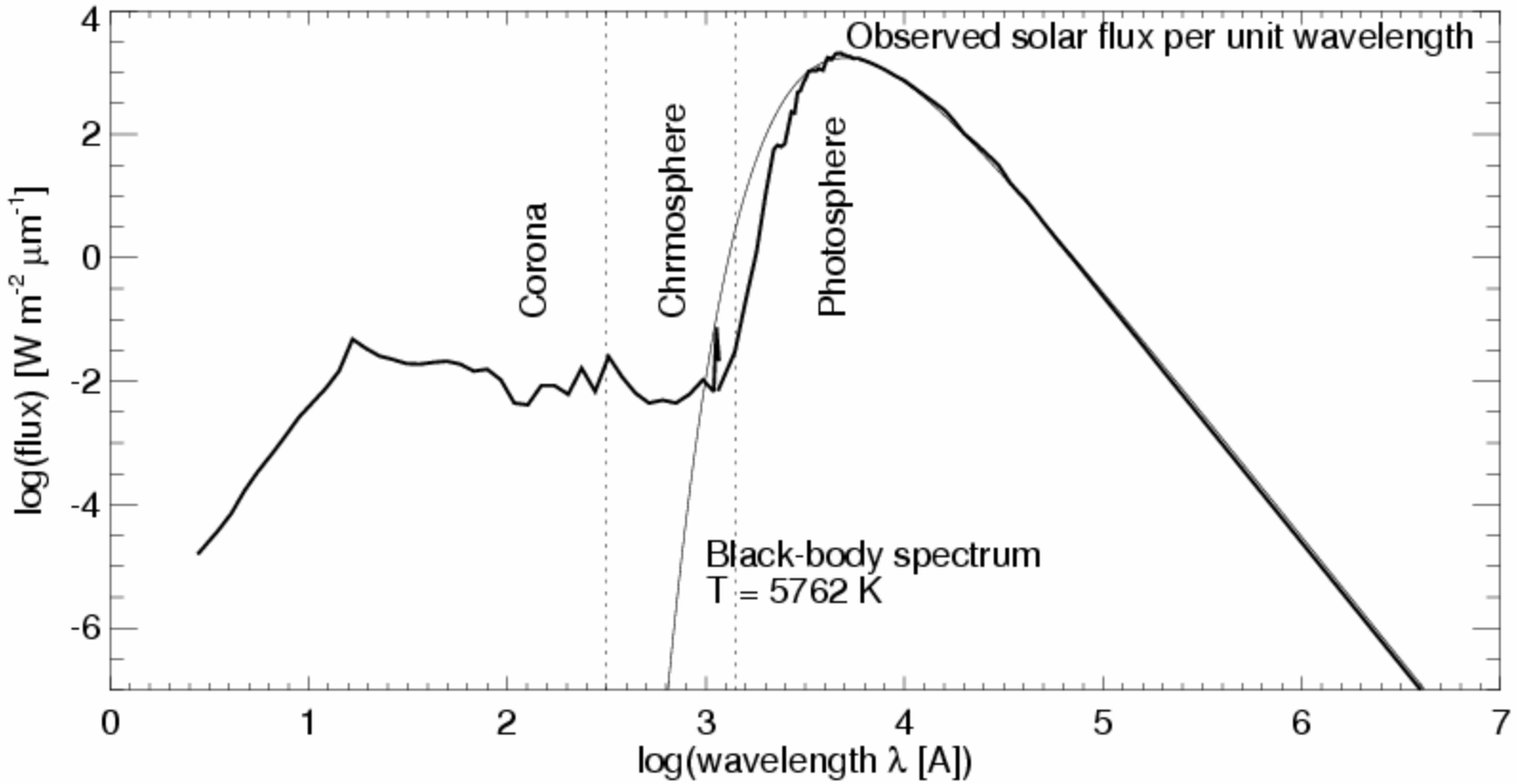


received intensity
(erg cm^{-2} s^{-1} keV^{-1} $ster^{-1}$)

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} $[keV/erg/Hz/cm]^{-1}$
  - $= \text{Flux} \times 2\pi D^2$
  - D = distance between source and detector (1 AU)
  - Assumes isotropic emission over upward hemisphere.

Solar Spectrum



Black-Body Radiation

- Equilibrium between emission & absorption
  - Applies to photosphere

- **Kirchhoff's Law**: $$\epsilon_\nu = n_\nu^2 \alpha_\nu B_\nu(T)$$

ϵ - emission coefficient (erg s^{-1} cm^{-3} Hz^{-1} rad^{-1})

α - 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} $steradian^{-1}$)

ν - frequency (Hz)

Planck's Law

Blackbody Brightness vs. λ (or ν) and T

$$B_\lambda(T) = \frac{2hc^2 n_\nu^2}{\lambda^5} \frac{1}{[\exp(hc/\lambda k_B T) - 1]}$$

$B(T)$ – Planck function (erg s^{-1} cm^{-2} cm^{-1} $steradian^{-1}$)

h – Planck's constant = 6.63 10^{-27} erg s

ν – frequency in Hz

λ – wavelength in cm

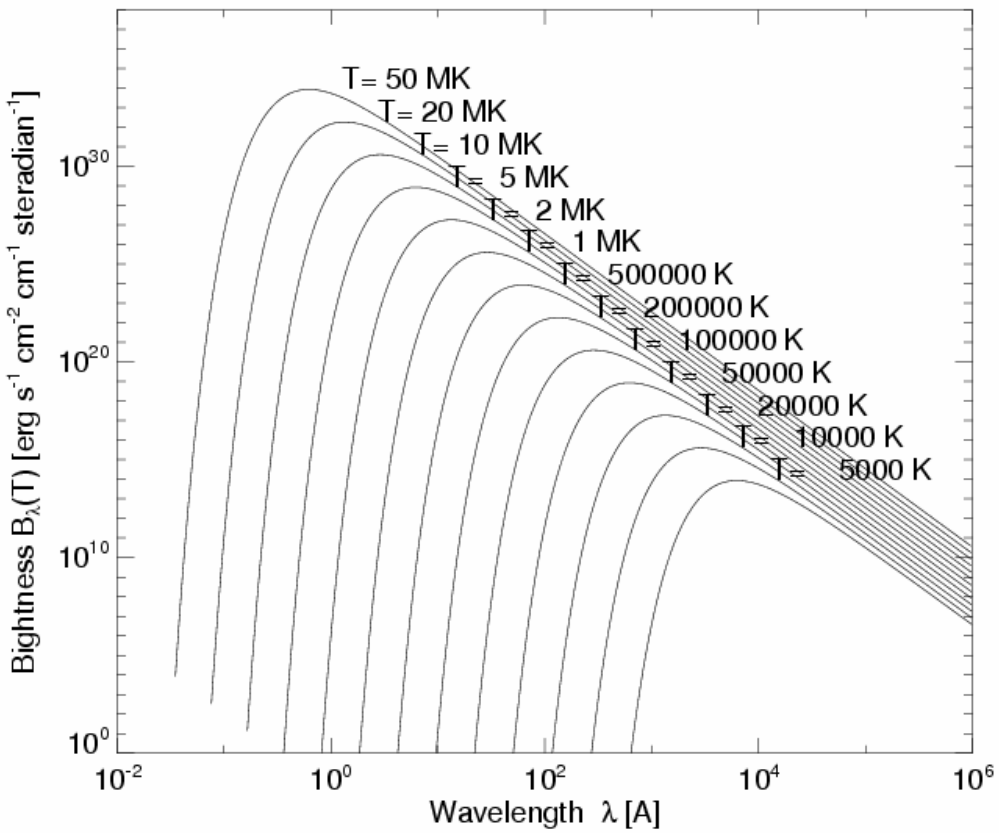
n – refractive index of the medium

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 - $B_\lambda(T)$



Planck's Function - $B_\lambda(T)$

- **Wien Displacement Law**

  Wavelength at which B_λ is maximum

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

- **Stefan-Boltzmann Law**

  Total flux - all wavelengths over the visible hemisphere

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

σ - Stefan-Boltzmann constant = 5.67 10^{-5} erg s^{-1} cm^{-2} K^{-4}

Planck's Law Approximations

Short Wavelengths (UV, X-rays)

Wien's Law

$$B_\nu(T) = \frac{2h\nu^3 n_\nu^2}{c^2} \exp\left(-\frac{h\nu}{k_B T}\right)$$

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 = 3/2 k T per particle

  $f(v) = n\,(m/2\mathbf{p}k_BT)\,4\mathbf{p}v^2\,\exp(-mv^2/2k_BT)$

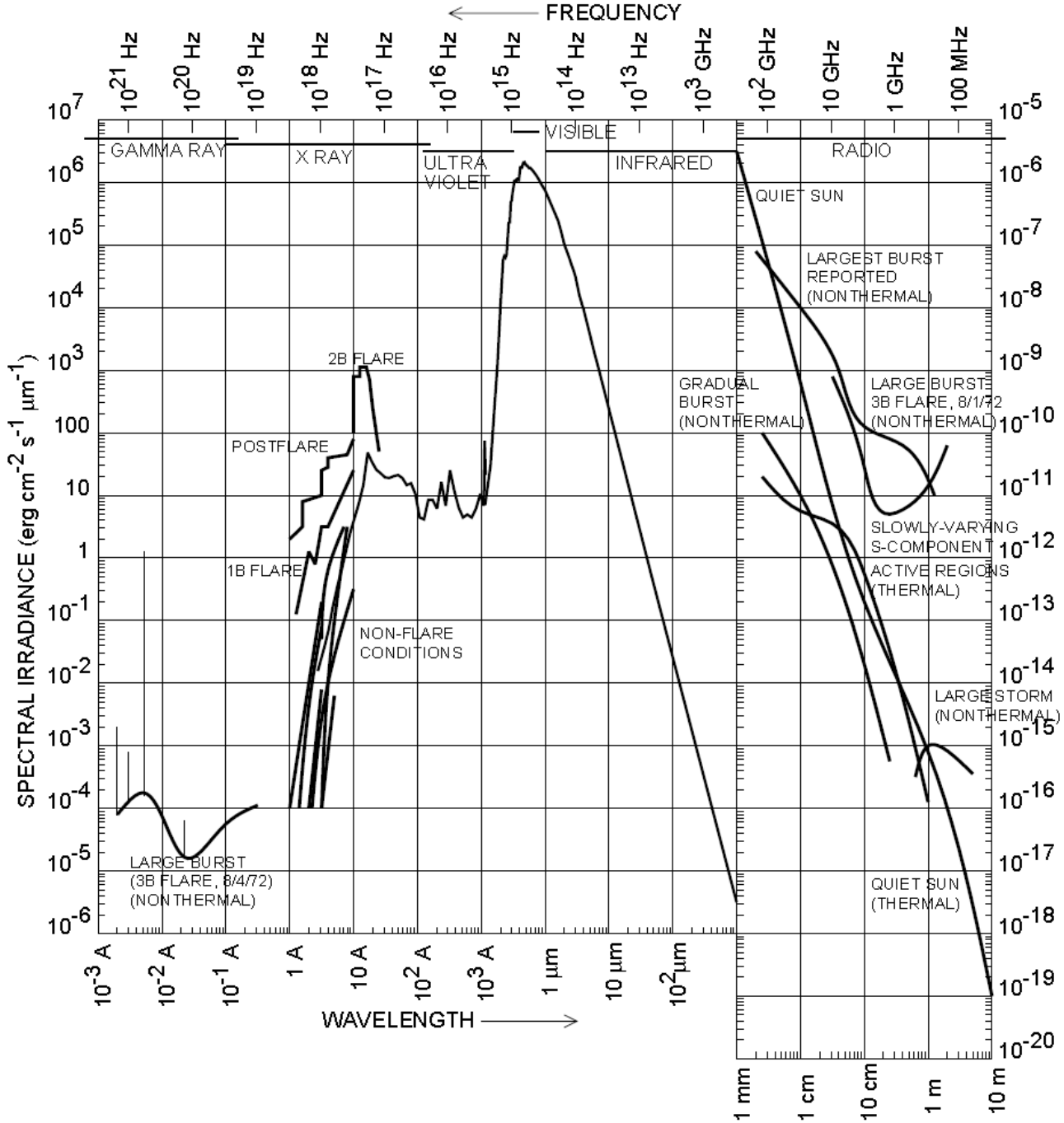
  particles $cm^{-3}\,(cm\,s^{-1})^{-1}$
- Applies in photosphere
- Ionization equilibrium

Saha Equation $$\frac{N_k}{N_0} = \frac{2}{n_e}\frac{(2\pi m_e k_B T)^{3/2}}{h^3}\frac{g'_k}{g_0}\exp\left(-\frac{\epsilon_k}{k_B T}\right)$$

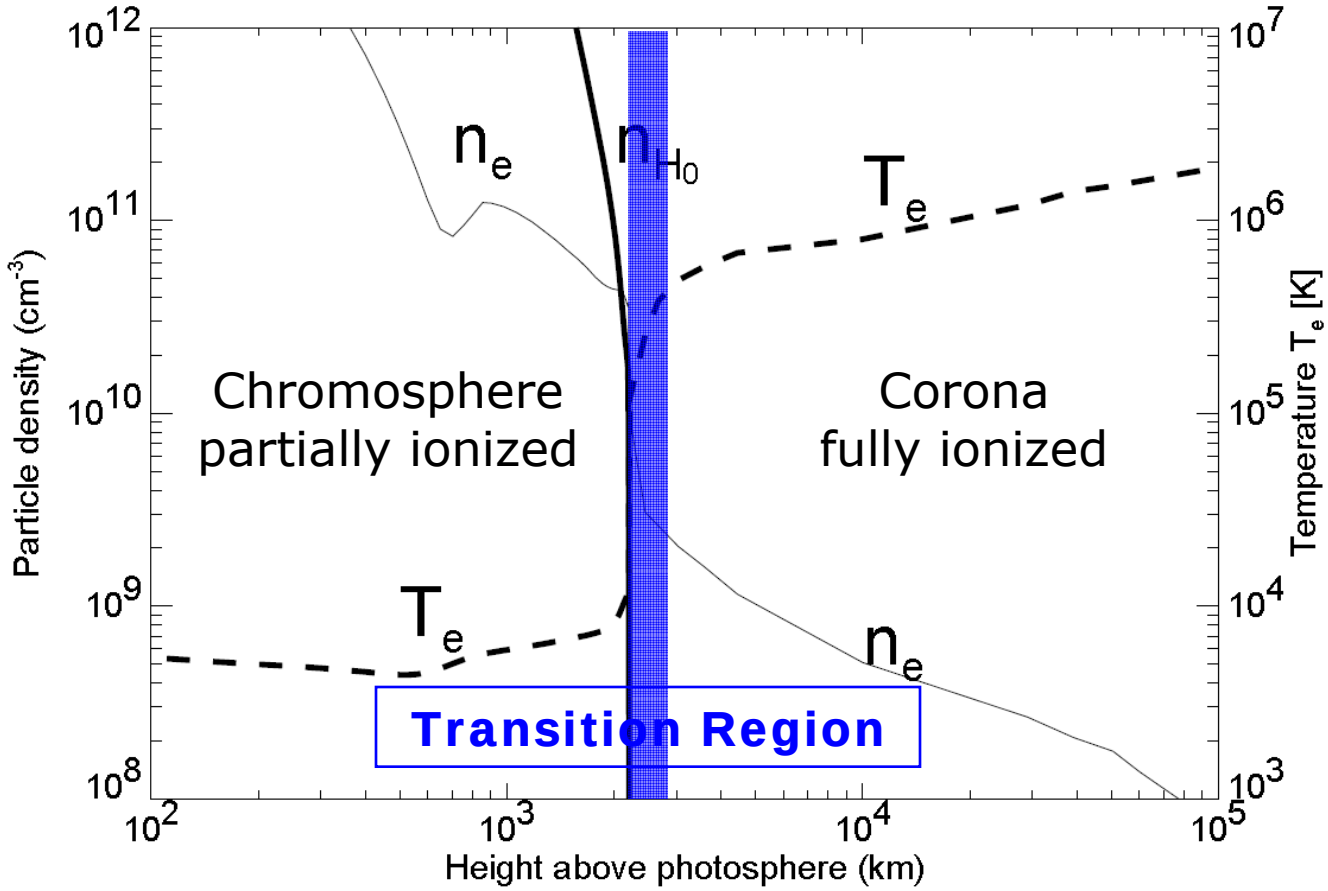
Fraction of ions in k state of ionization

Solar Spectrum

Quiet Sun
&
Flares
-
Gamma-rays
to
Radio



Chromosphere & Corona



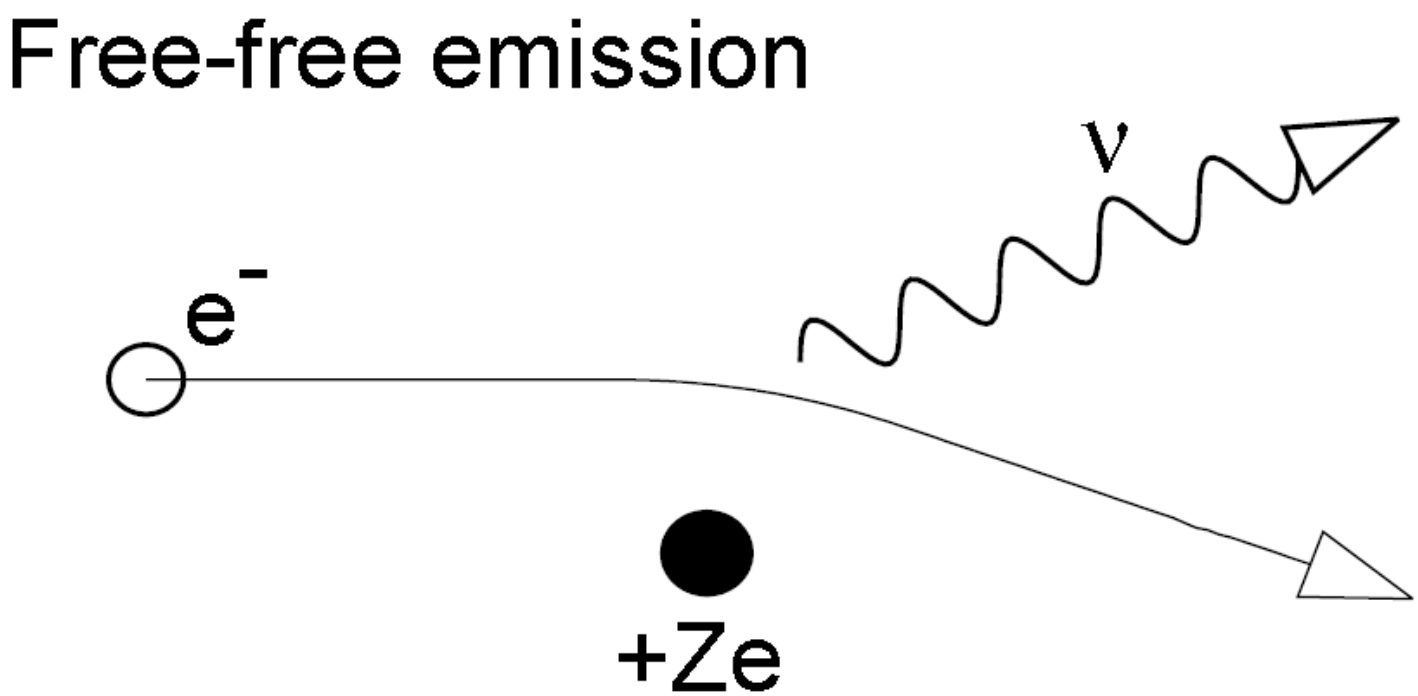
Chromosphere & Corona

- 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



Electron in hyperbolic orbit

Free-Free Emission
Thermal Bremsstrahlung

- Photon Spectrum

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

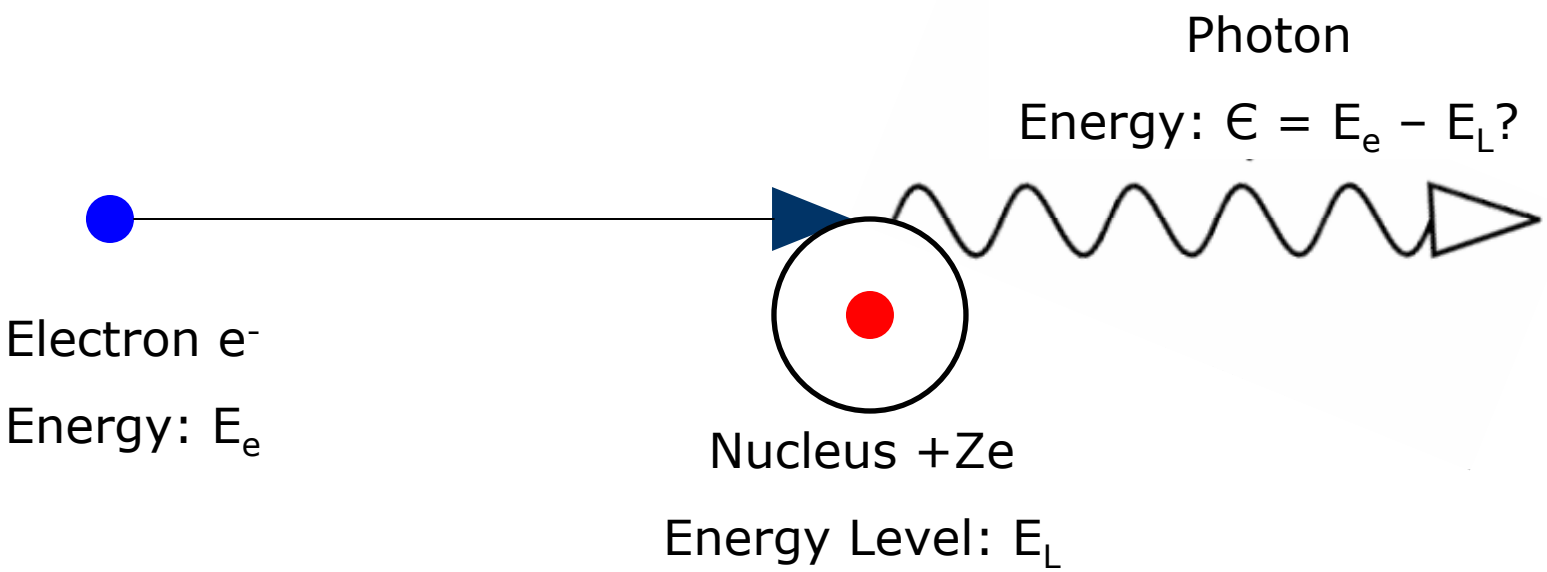
Units - keV s^{-1} cm^{-2} keV^{-1}

ϵ - photon energy = $h\nu$

n - electron and ion density

V - source volume

Free-Bound Emission
Recombination Radiation



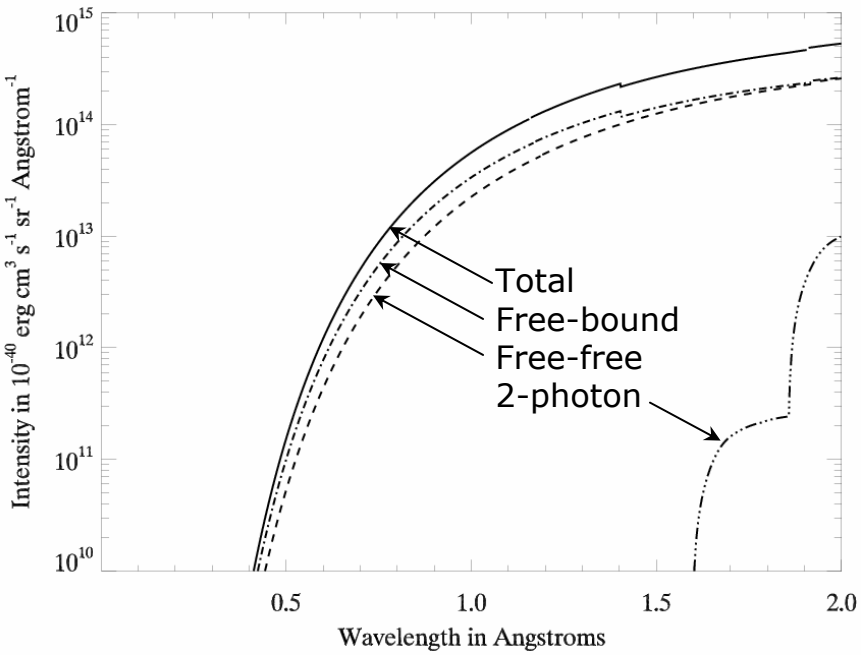
Continuum emission

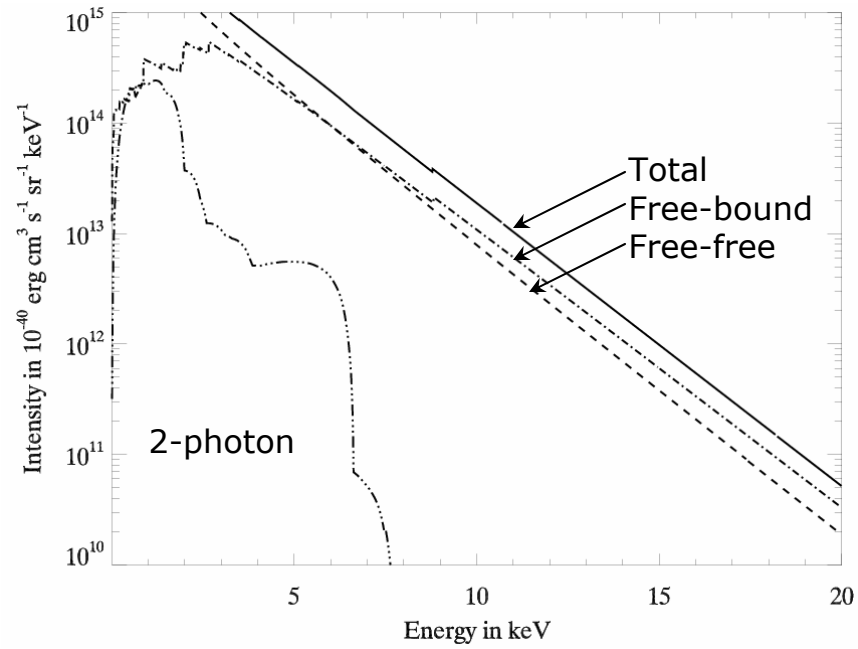
Spectral edges at atomic energy levels

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



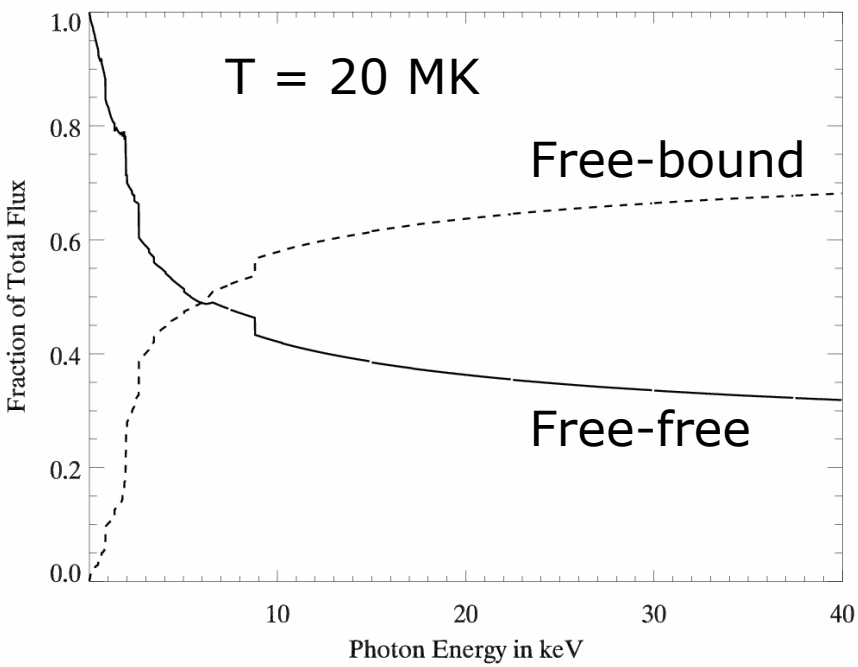


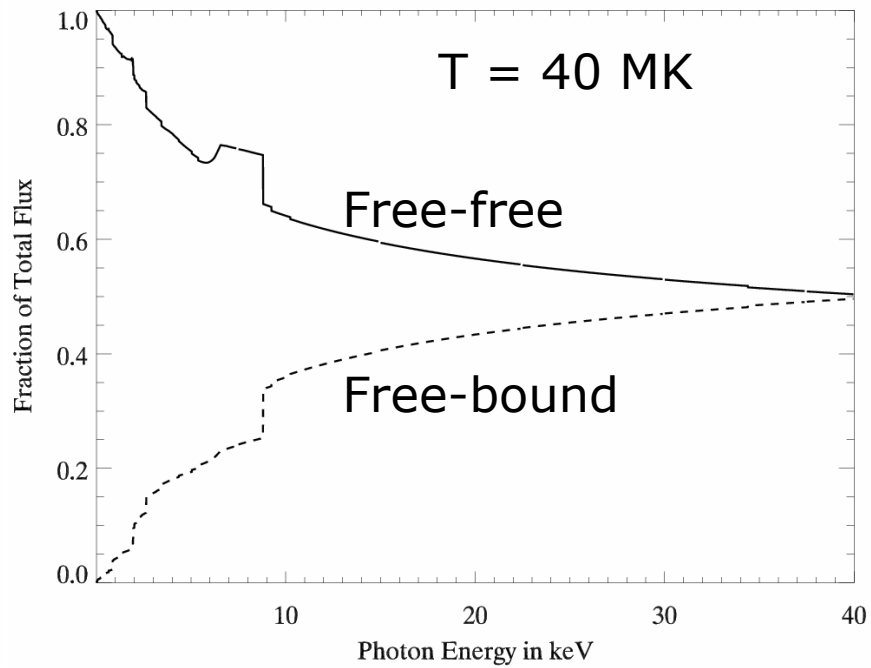
T = 20 MK Coronal Abundances

CHIANTI v. 5.2

Continuum Fractions
(CHIANTI v. 5.2)

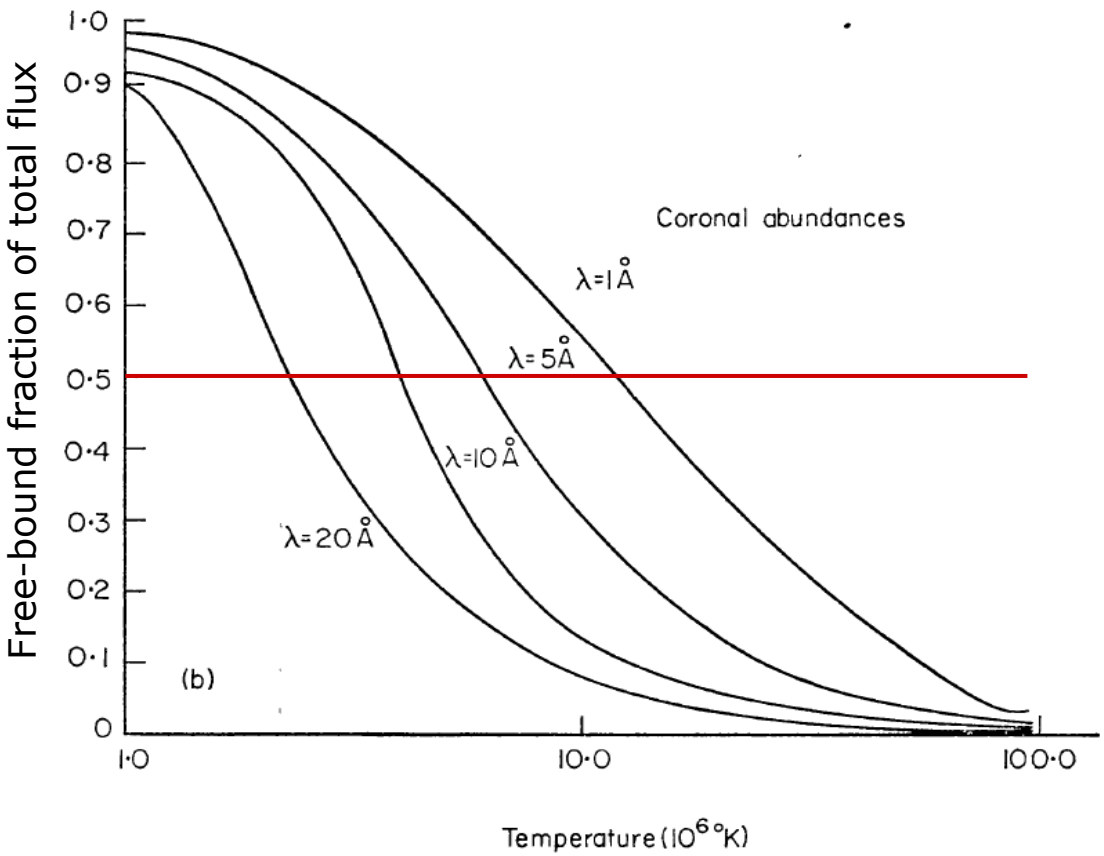
Coronal abundances & Mazzotta et al. ionization equilibrium



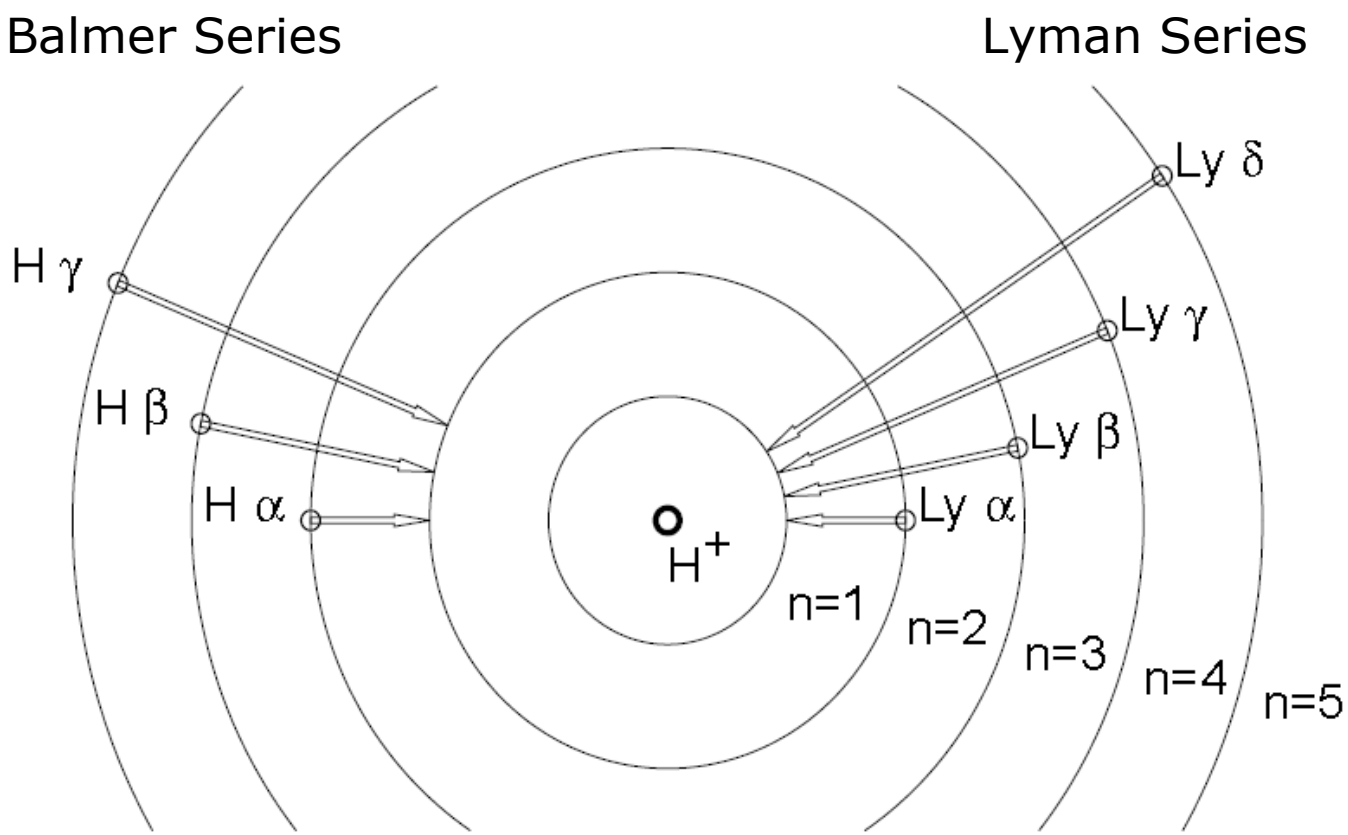


Free-Bound Fraction

Culhane, MNRAS, 144, 375, 1969.

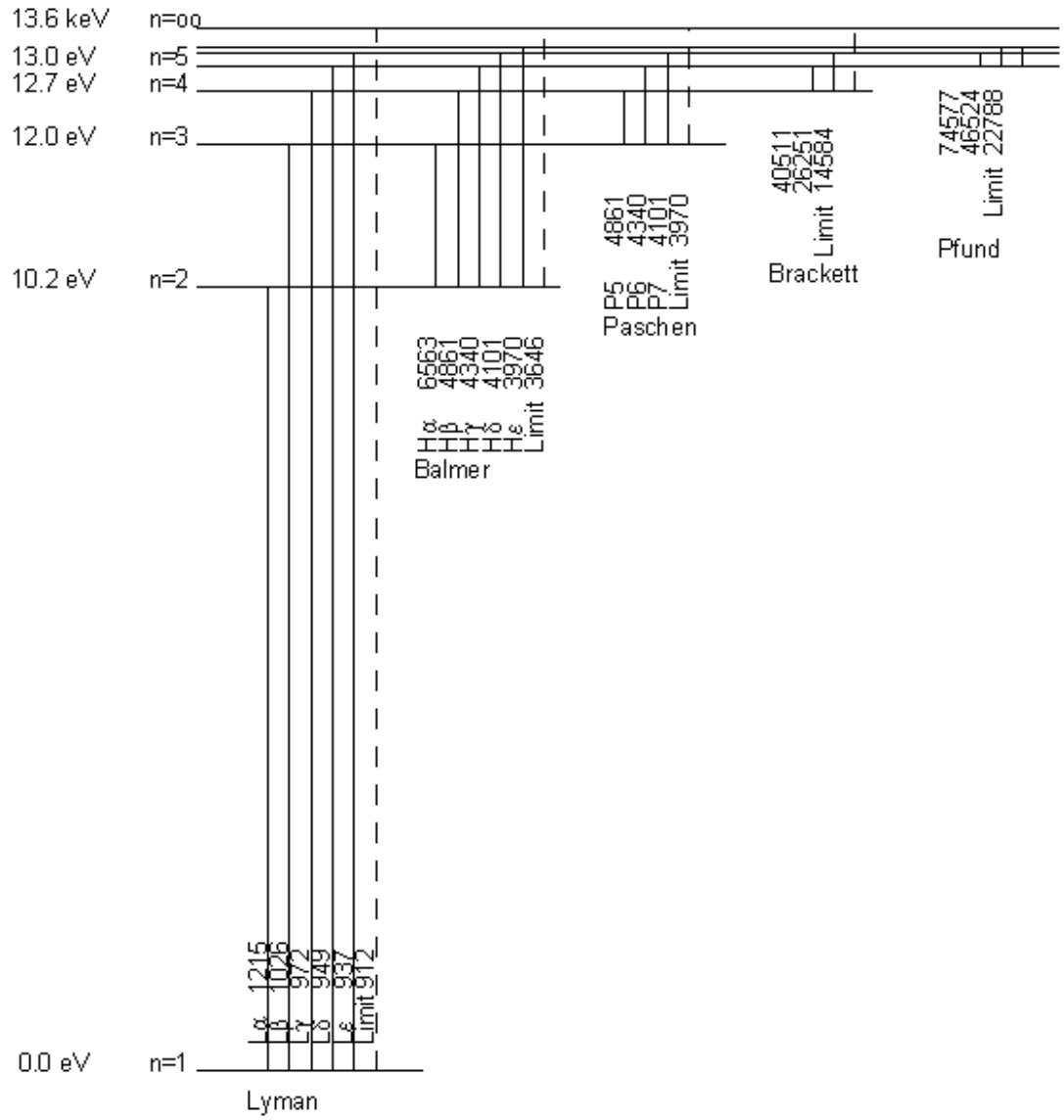


Line Emission
Hydrogen Atom



Hydrogen

Emission Lines



Quantum Numbers

- Principal quantum number

  $n = 1, 2, 3, 4\ldots$

  K, L, M, N,…

- Orbital angular momentum

  $l = 0, 1, 2, 3, 4, 5,\ldots$

  s, p, d, f, g, h,… where $l < n$

- Electron spin

  $s = ½$

- Projected angular momentum

  $m_l = l, l - 1, l - 2,\ldots -l$

- Projected electron spin

  $m_s = \pm ½$

Electron States

Shell	K	L			
n	1	2			
l	0	0	1		
	s	s	p		
m_l	0	0	-1	0	+1
m_s	±½	±½	±½	±½	±½
m	±½	±½	-1/2 -3/2	±½	+1/2 +3/2
Shell	K	L_1	L_2		

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

  $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 4p^6$

  "one s squared…"
- Neutral He & Fe XXV ground configuration

  $1s^2$

  "one s squared…"

Spectral Notation
Atomic or Ionic States

- Specification of ion state = $^{2S+1}L_J$

  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

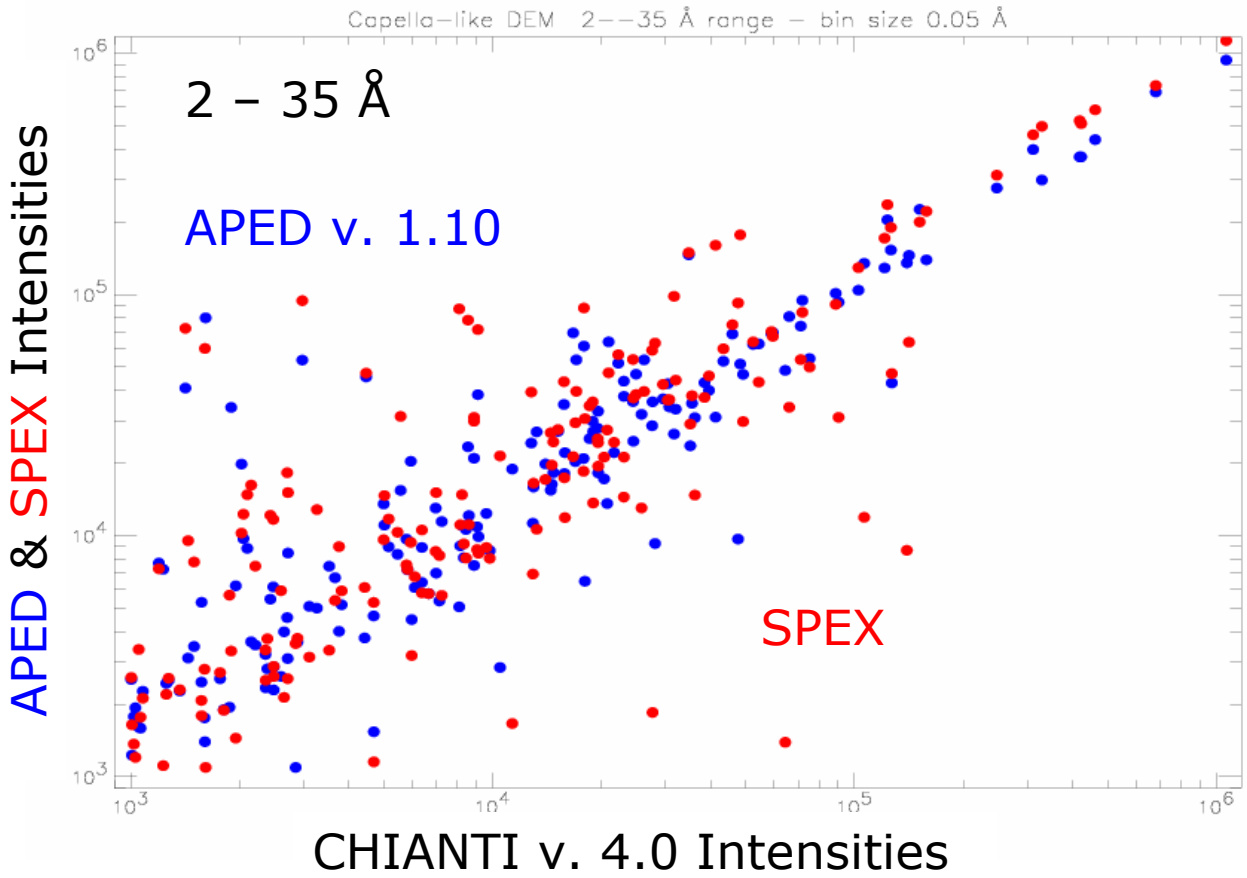
  = L + S

- 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")

Atomic Data Bases

- **Available Codes**
  - CHIANTI (v. 5.2)
  - ATOMDB - APEC/APED
    Astrophysics Plasma Emission Database and Code
    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)



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).

CHIANTI Spectral Synthesis Package

Line intensities calculation - click here for a short HELP - Send comments to chianti_help@halcyon.nrl.navy.mil

Wavelength (Å) Min. 0.1 Max. 20

Const. Density 1.00e+010

Ioniz. Fraction mazzotta_etal.ionec

All ions? - HELP no yes

All lines? - HELP no yes

ISOTHERMAL ? - HELP Yes No (DEM)

Log T (K): 7.3

Log EM (cm-5): 27

Photoexc.: NO

Units: ERGS

Protons: YES

Calculate intensities

Save/Restore

Quit

Calculate and plot a spectrum - click here for a short HELP -

keV [/Å] Min. 1.0 Max. 10

Bin HELP 0.001

FWHM HELP 0.1

Continuum? HELP No Yes

All lines? HELP no yes

Abundances HELP sun_coronal.abu

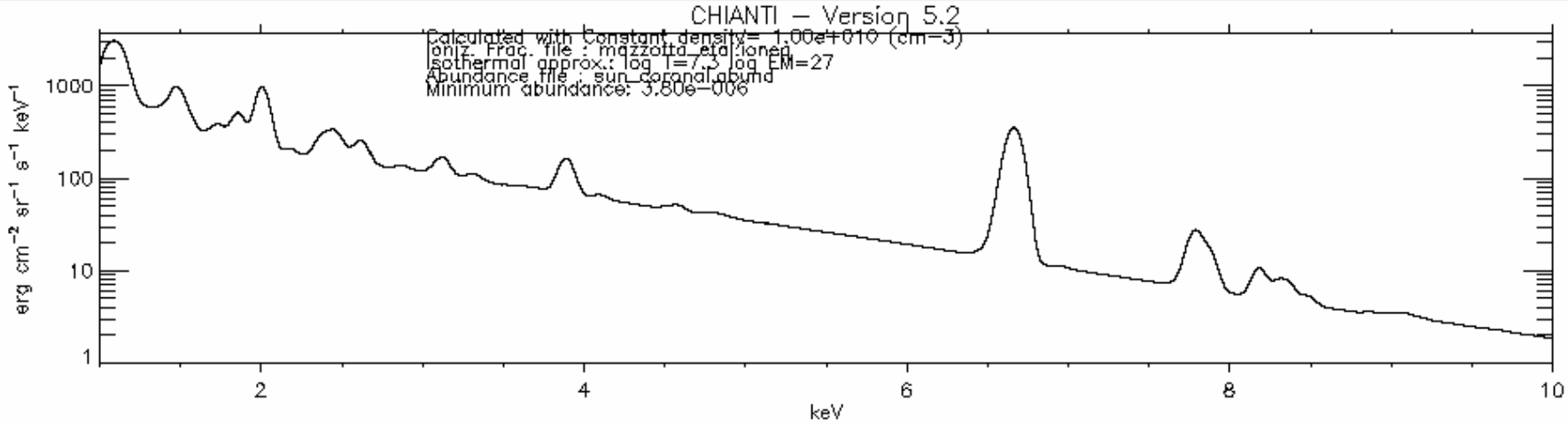
Min. Abund. HELP 3.80e

Eff. Area: NO HELP –

RESTORE spectrum

Units: ERGS

Calculate and plot



Labels? - HELP yes no

Min. - HELP 5.44e+0

X: 1.0000 10.0000

Y: 1.e0 3.72e+003

Zoom

Unzoom

Create PS file

Hardcopy

Save line details (latex)

Save line details (ascii)

Log [/Lin]

SAVE spectrum

Select lines with mouse

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
  → chromospheric evaporation

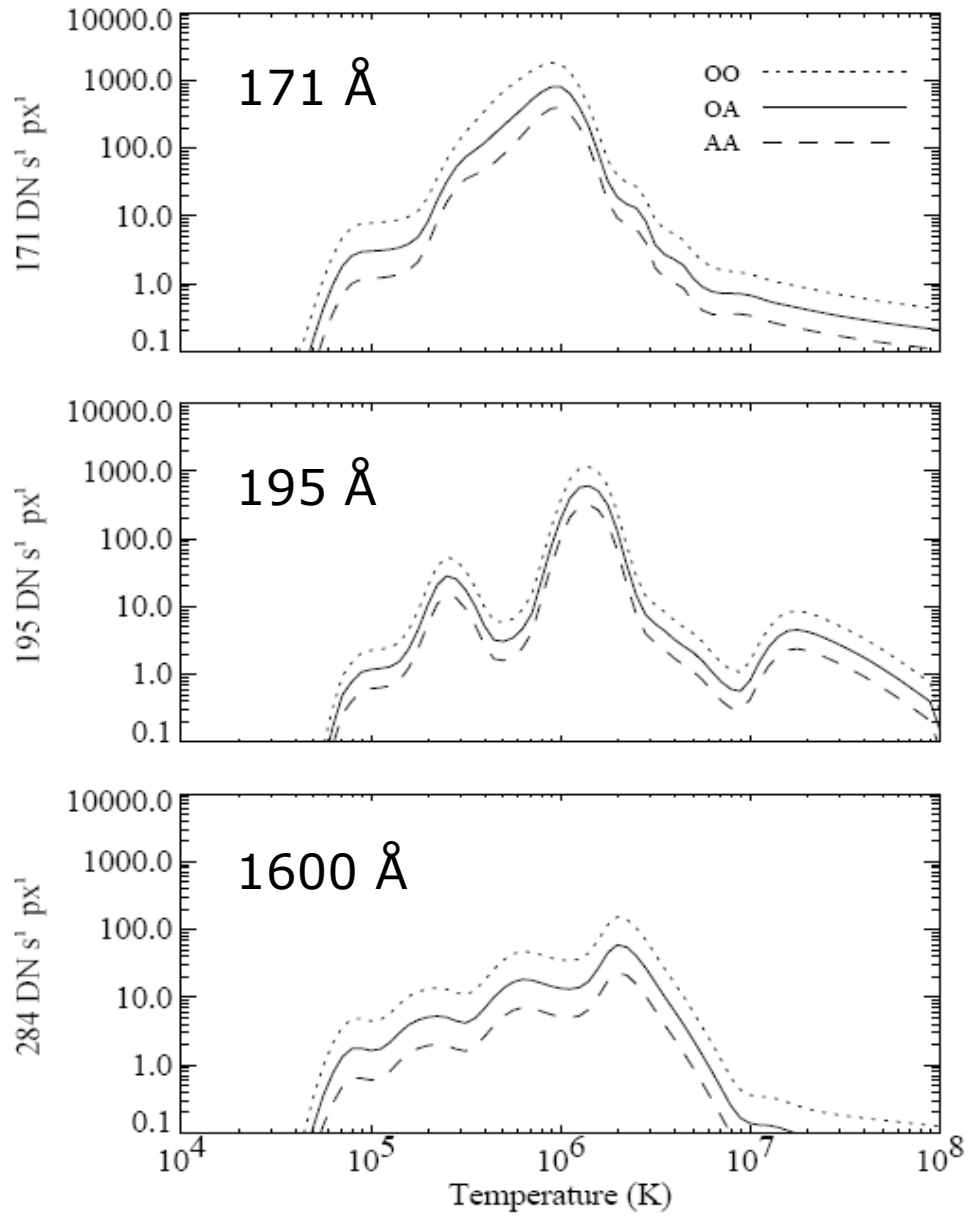
TRACE Spectral Bands

Wavelength (Å)	Emission	Bandwidth (Å)	Temperature (K)
171	Fe IX/X	6.4	$1.6-20 \times 10^5$
195	Fe XII/XXIV	6.5	$5.0-20 \times 10^5$, $1.1-2.6 \times 10^7$
284	Fe XV	10.7	$1.25-4.0 \times 10^6$
1216	H I Lα	84	$1.0-3.0 \times 10^4$
1550	C IV	30	$6.0-25 \times 10^4$
1600	UV cont, C I, Fe II	275	$4.0-10 \times 10^3$
1700	Continuum	200	$4.0-10 \times 10^3$
5000	White light	broad	$4.0-6.4 \times 10^3$

TRACE

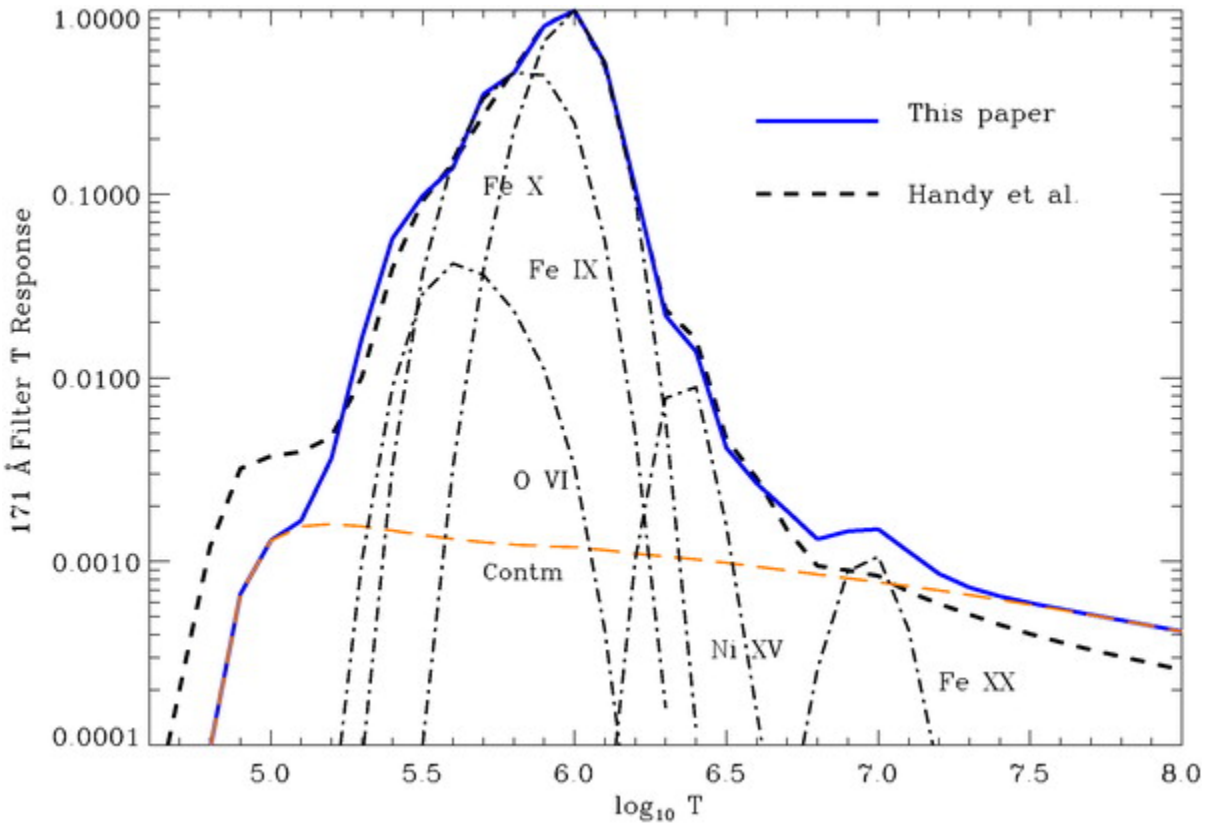
Temperature Coverage

EM = 10^{44} cm^{-3}



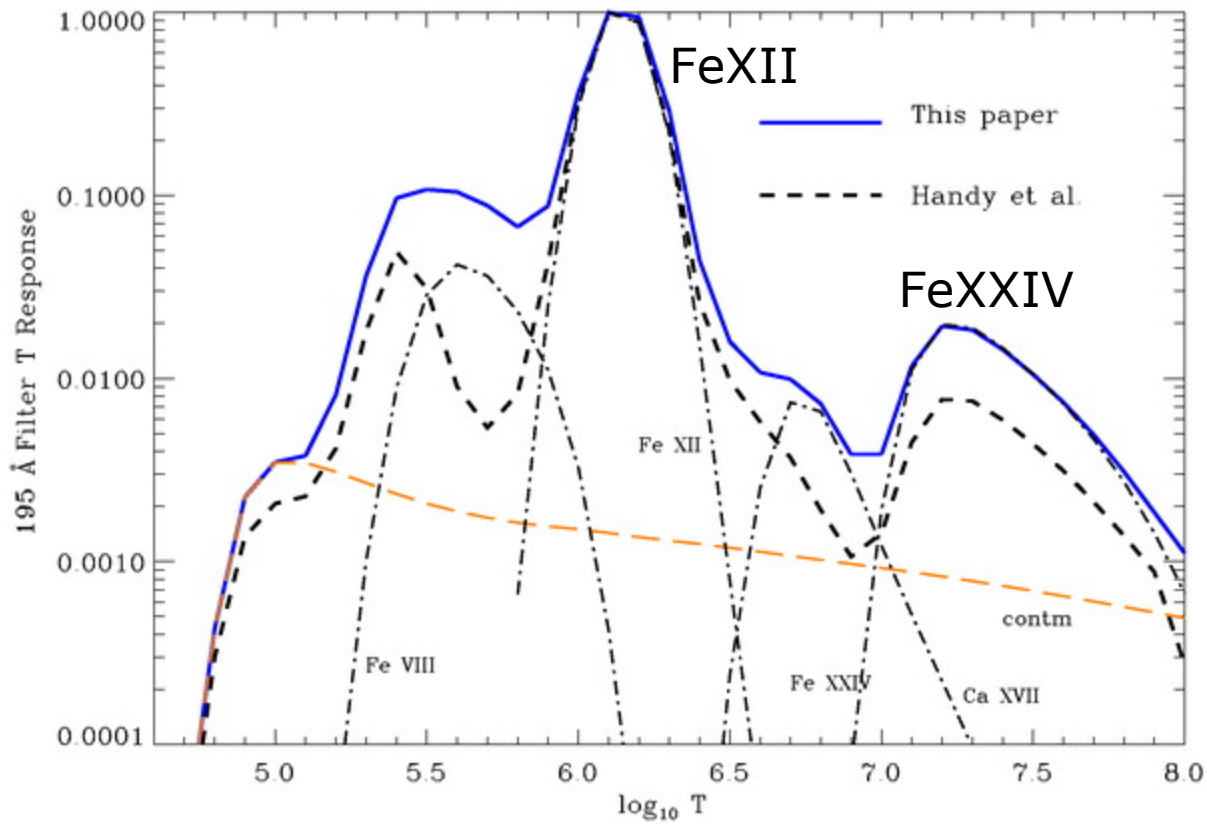
Handy et al. Solar Phys., 187, 229, 1999.

TRACE & EIT
171 Å Filter Response



Phillips et al. ApJ, 626, 1110, 2005.

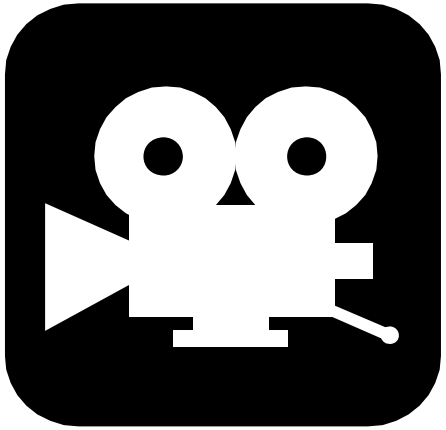
TRACE & EIT
195 Å Filter Response



Phillips et al. ApJ, 626, 1110, 2005.

RHESSI – EIT - TRACE Movie

X1.5 Flare on 21 April 2002

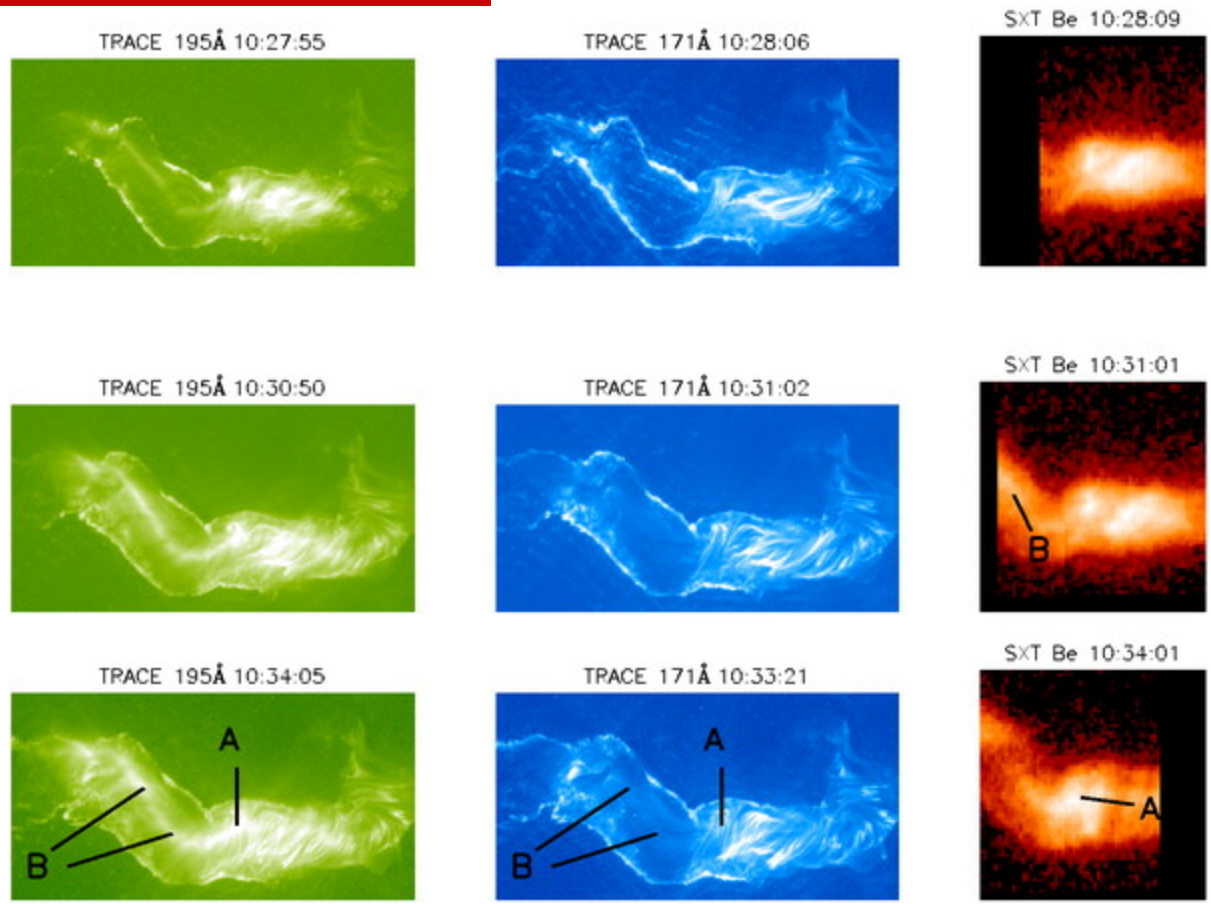


Click to show movie

High-Temperature Component

Bastille Day Flare
14 July 200?

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

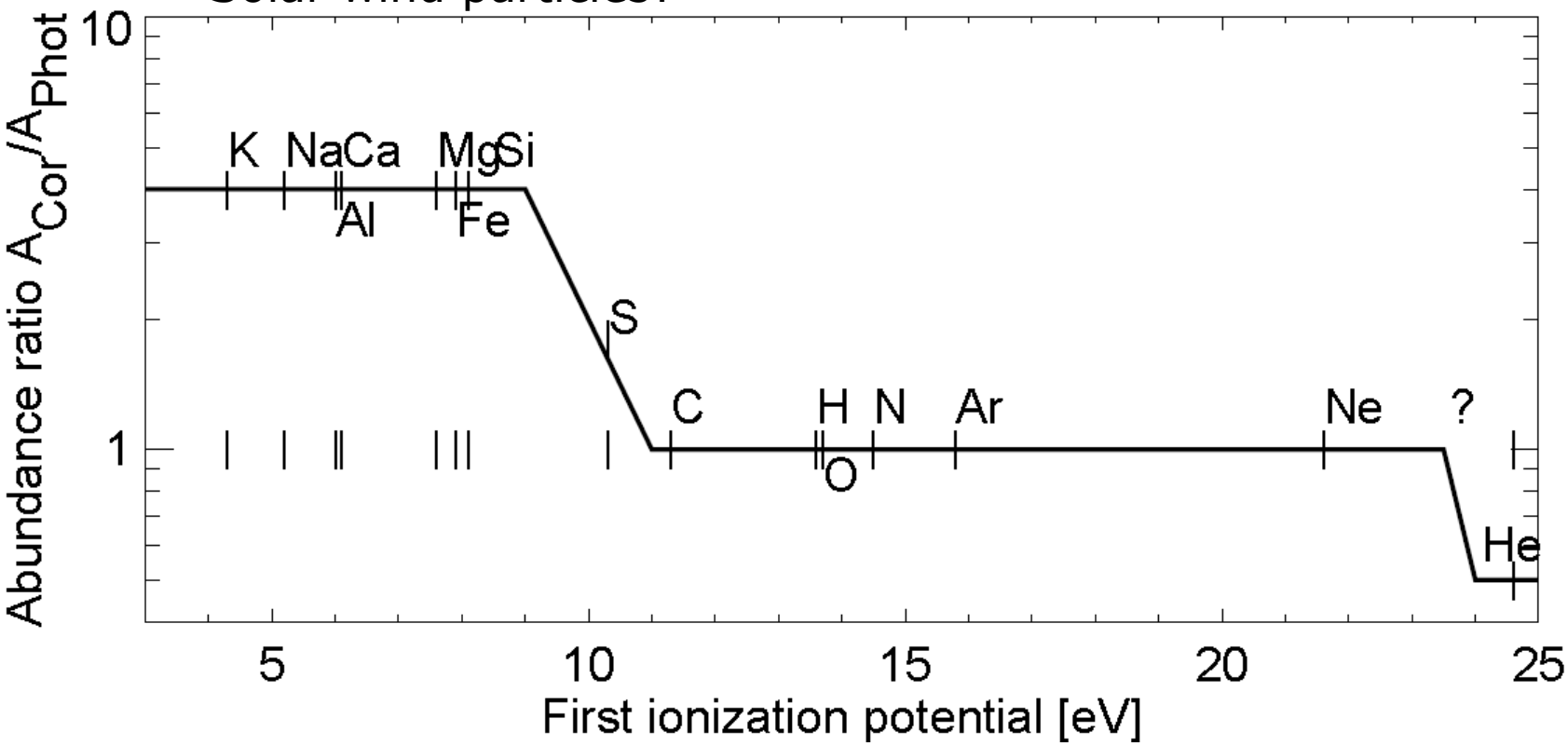


FIP Effect

- 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?



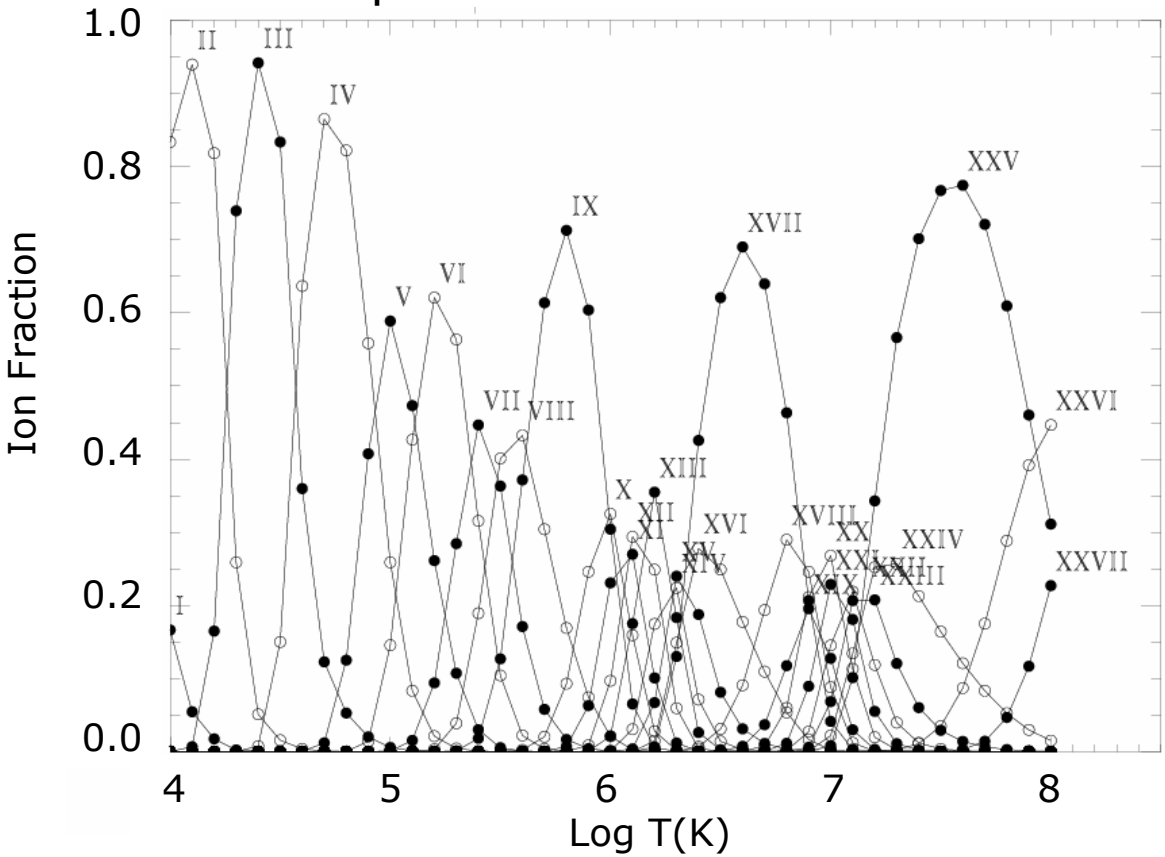
Feldman & Widing 2003

Feldman - Flares

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

Fe Ionization-Recombination Equilibrium

Ionization equilibrium for Fe – Mazzotta et al.



Ions with Complete Outer Shells

- Fe IX
- Fe XVII
- Fe XXV

are more stable,

so higher fraction

Highly Ionized Iron - FeXXV

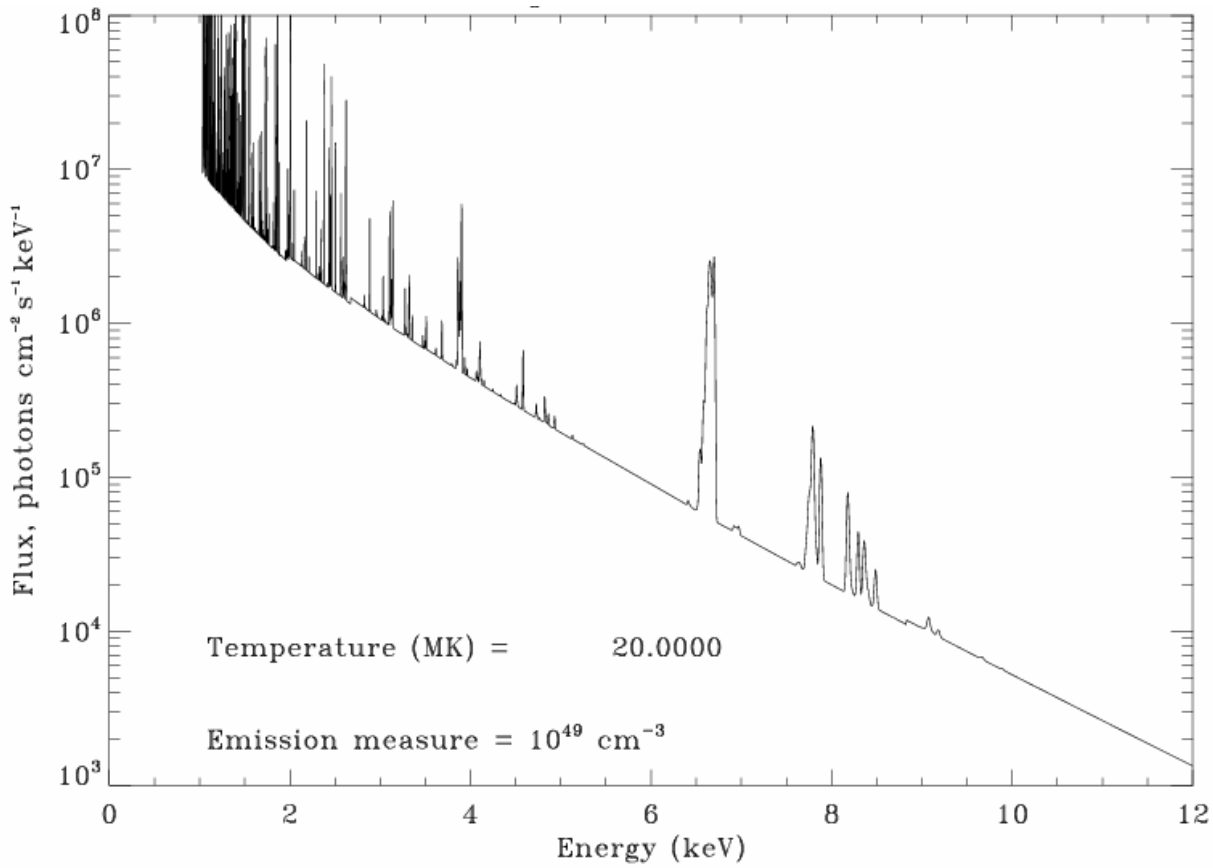
- Ion - Fe^{+24}
- Spectrum - FeXXV
- 2 electrons remaining in K shell
- "helium-like"
- Ground state
  $1s^2$ ("one s squared") $^1S_0$ ("singlet S zero")
- Transitions between levels give emission lines

Phillips, "The Solar Flare 3.8-10 keV X-Ray Spectrum," ApJ, 605, 921, 2004.

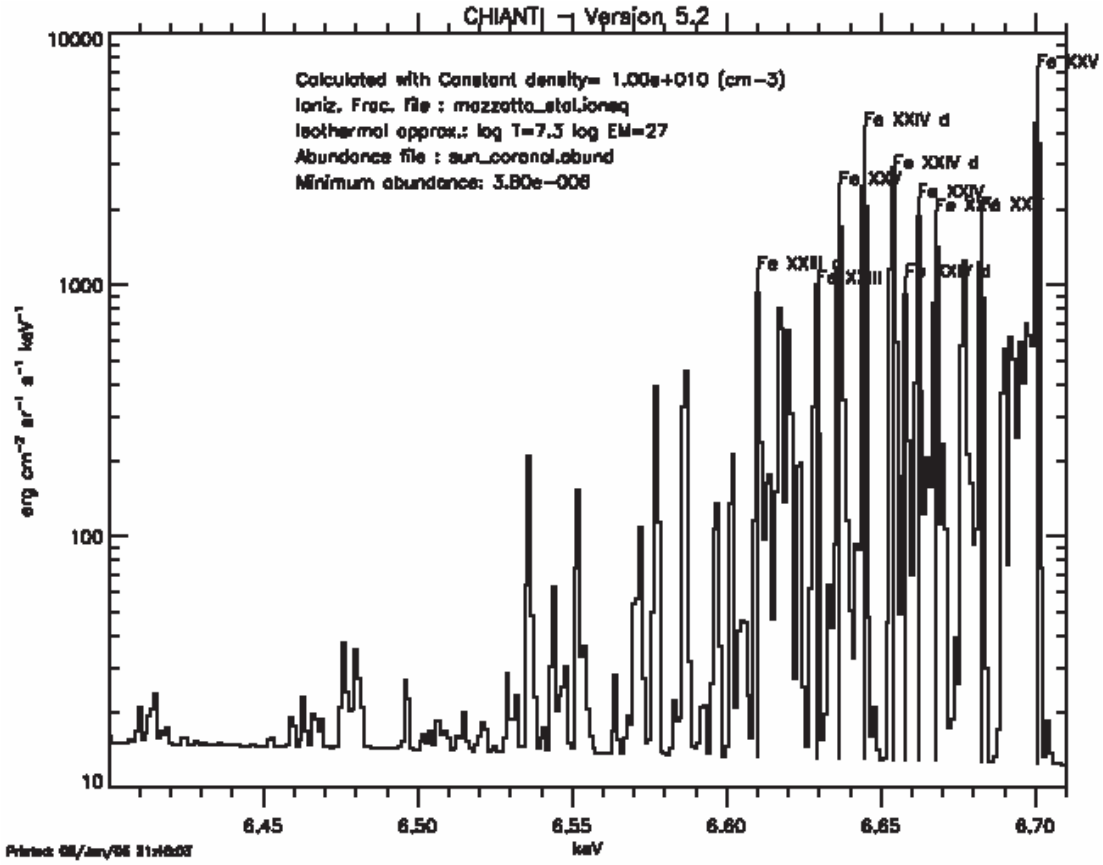
Fe-line Complex (~6.7 keV)

- 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

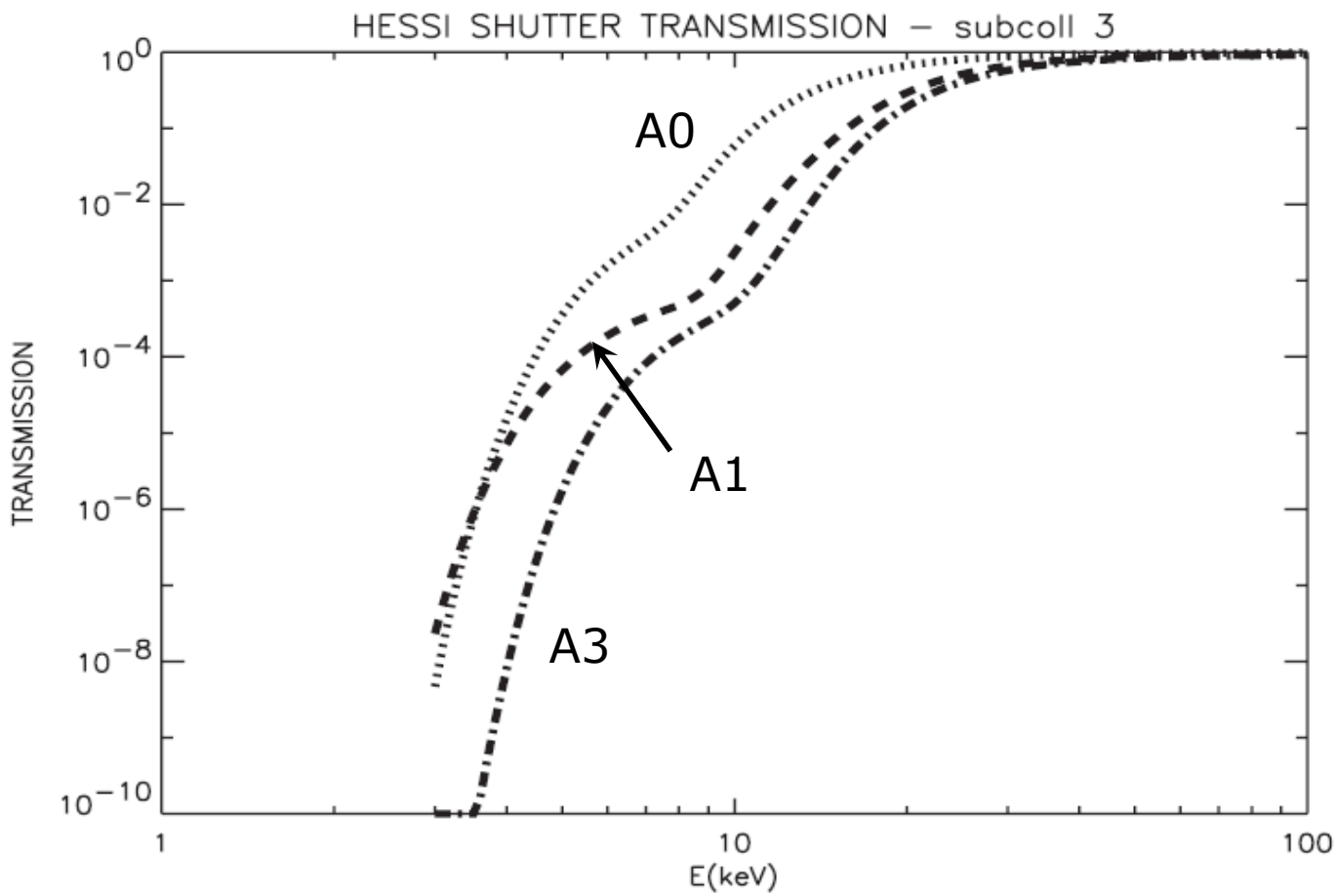
CHIANTI Spectrum
T = 20 MK Coronal Abundances



CHIANTI Spectrum
Fe Line Complex near 6.7 keV

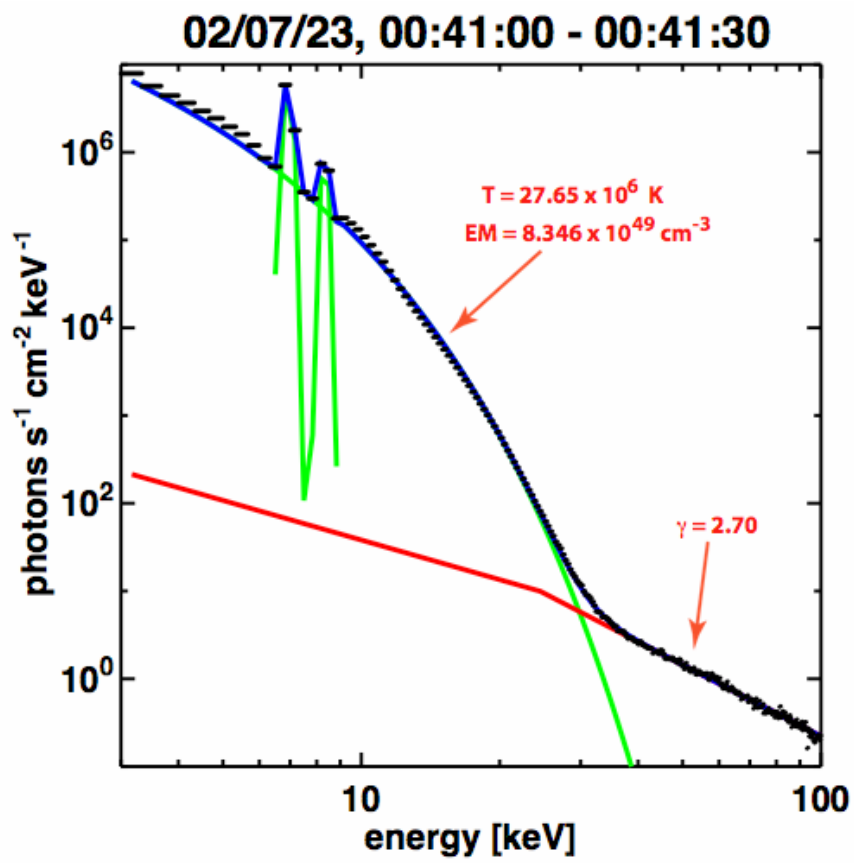


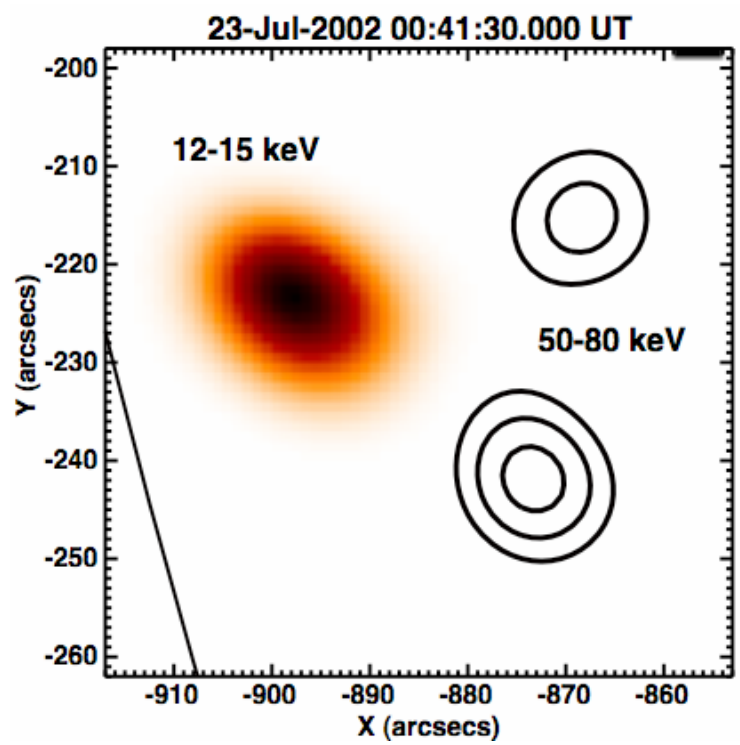
RHESSI Sensitivity



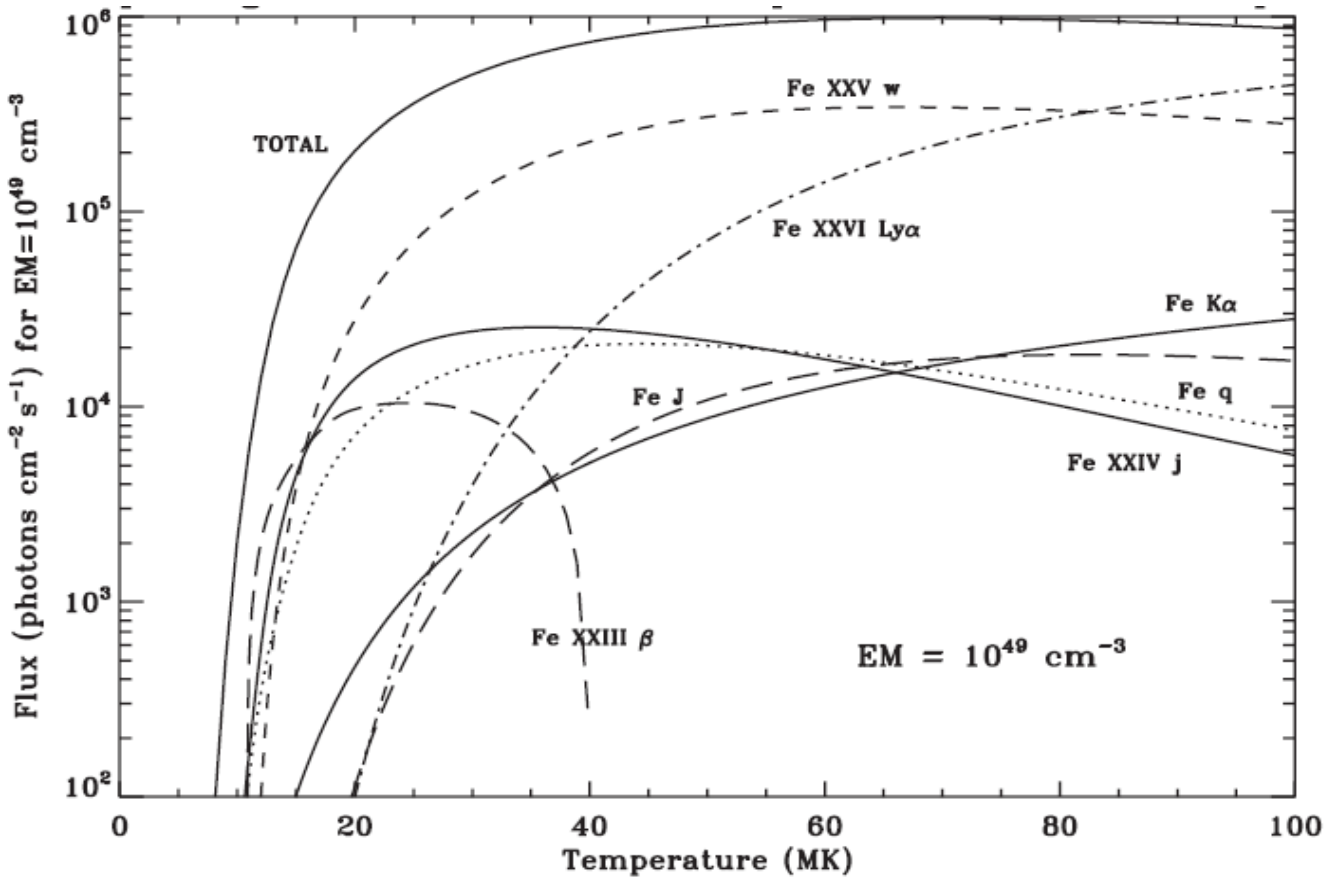
RHESSI Imaging Spectroscopy

Caspi & Lin, 2005

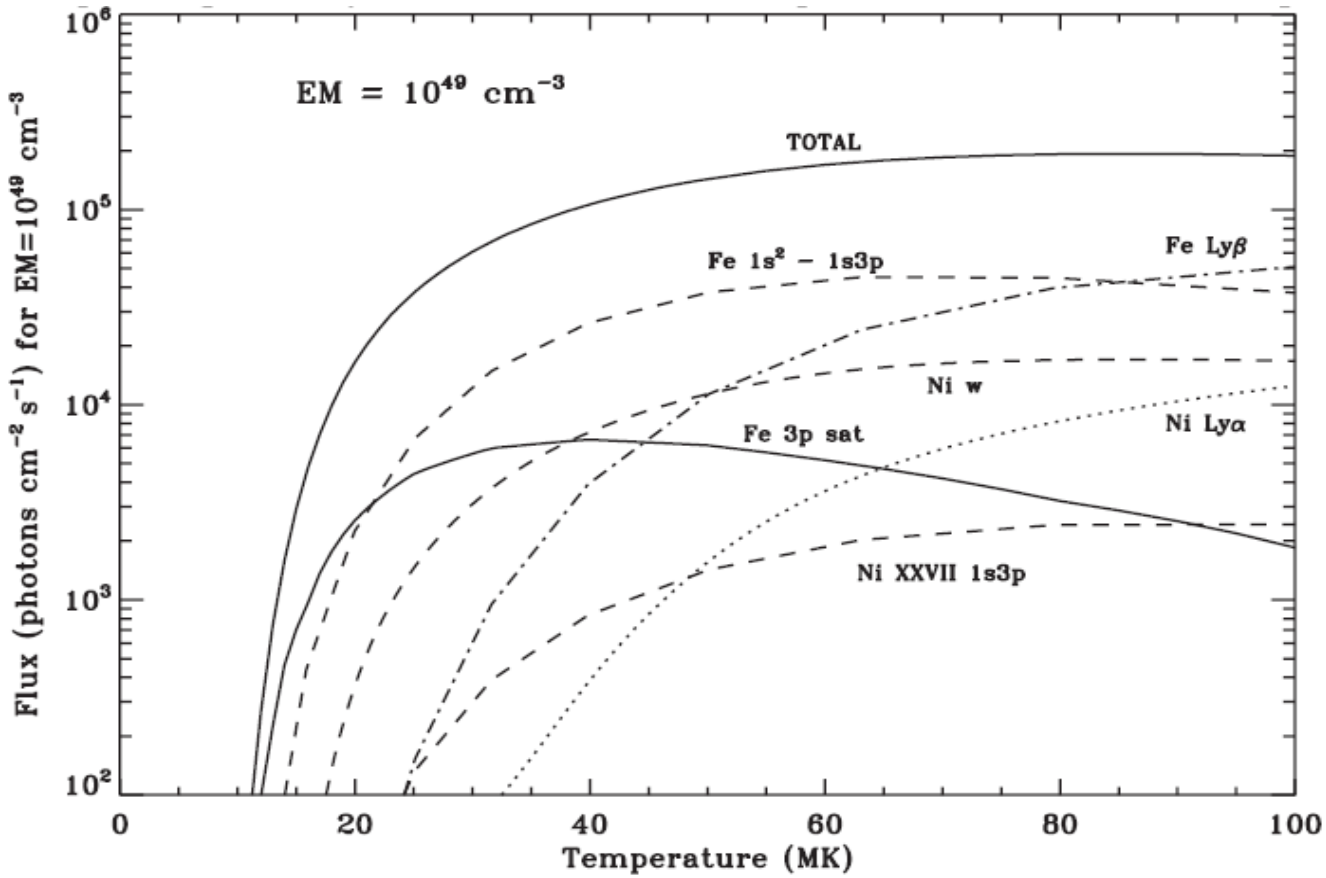




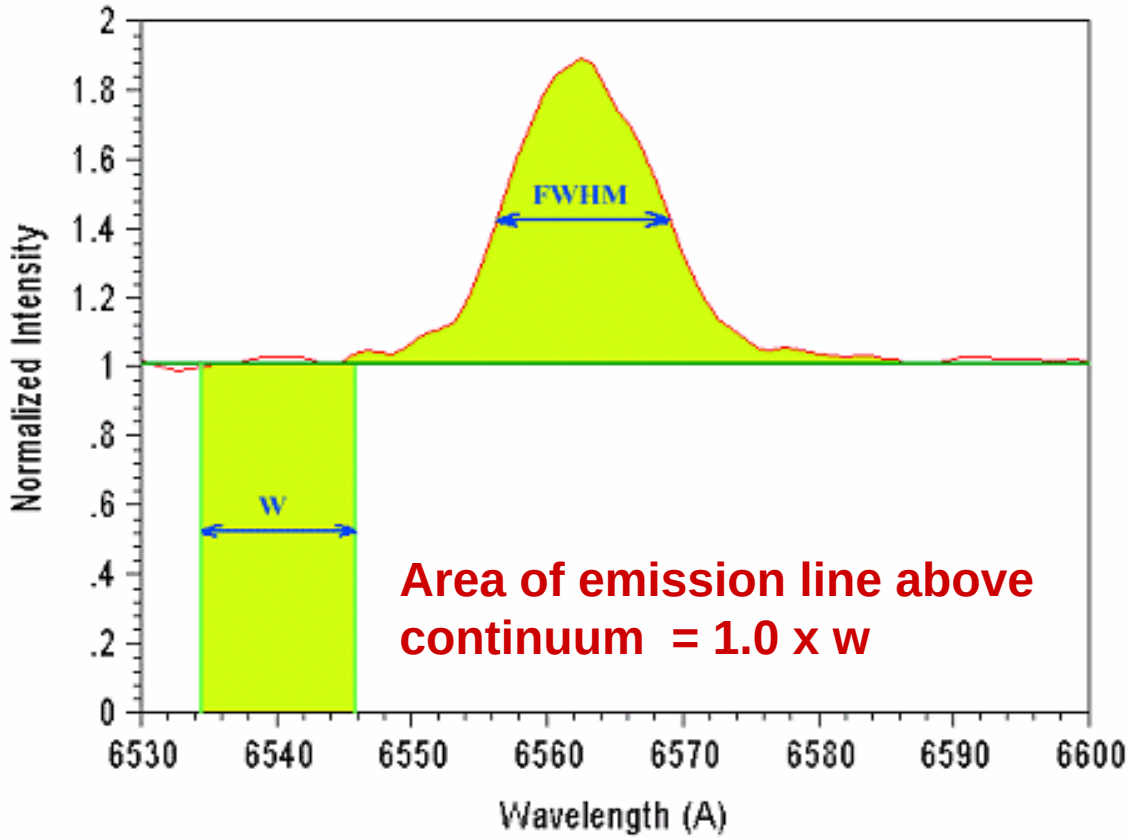
Fe-line Complex ~6.7 keV



Fe / Ni-line Complex ~8 keV



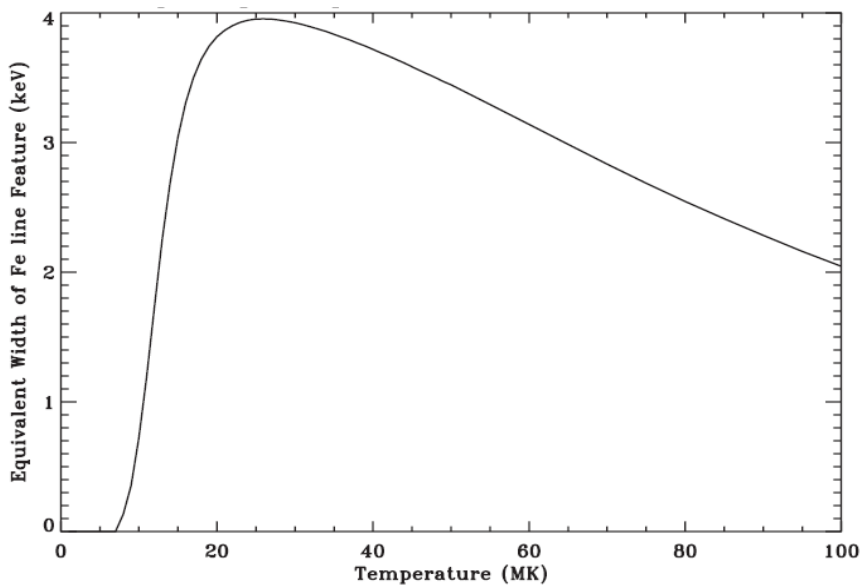
Equivalent Width Definition



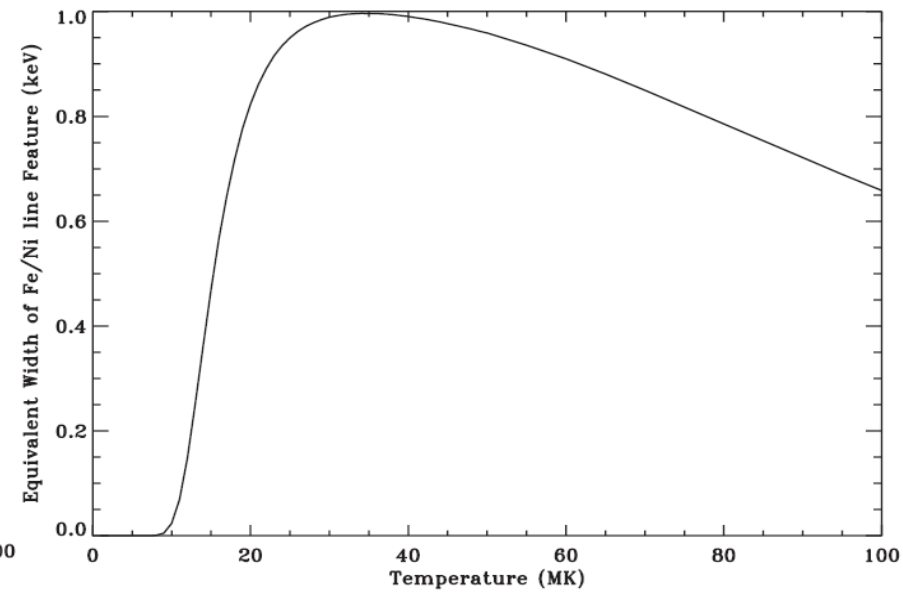
Area of emission line above continuum = 1.0 x w

Fe & Fe-Ni Line Complexes Equivalent Widths vs. Temperature

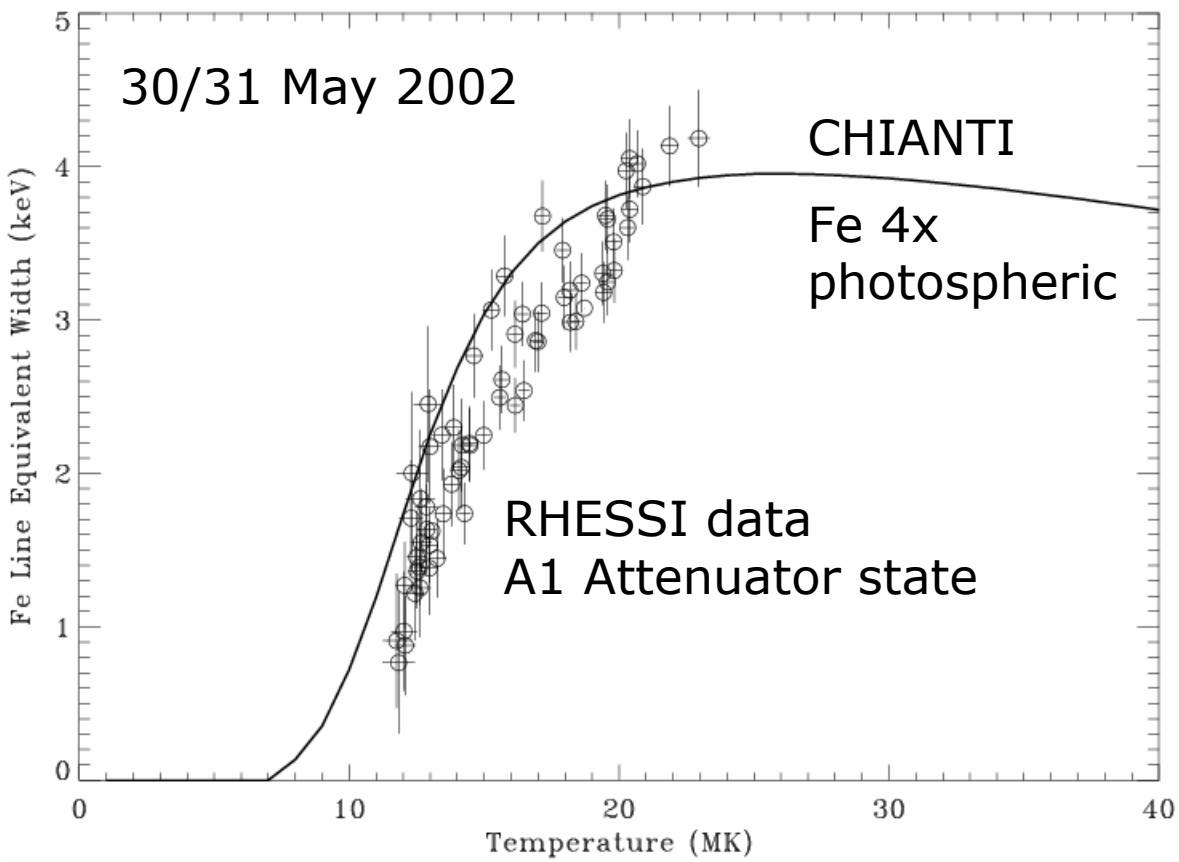
Fe complex at ~6.7 keV



Fe-Ni complex at ~8 keV

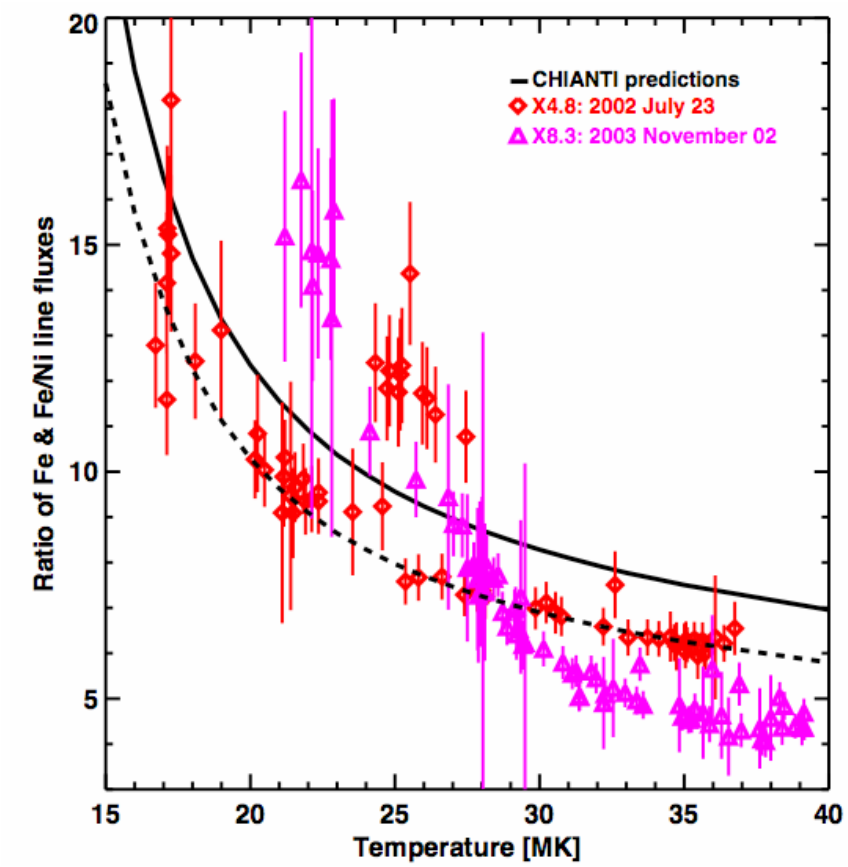


Fe Line Complexes
Equivalent Width vs. Temperature



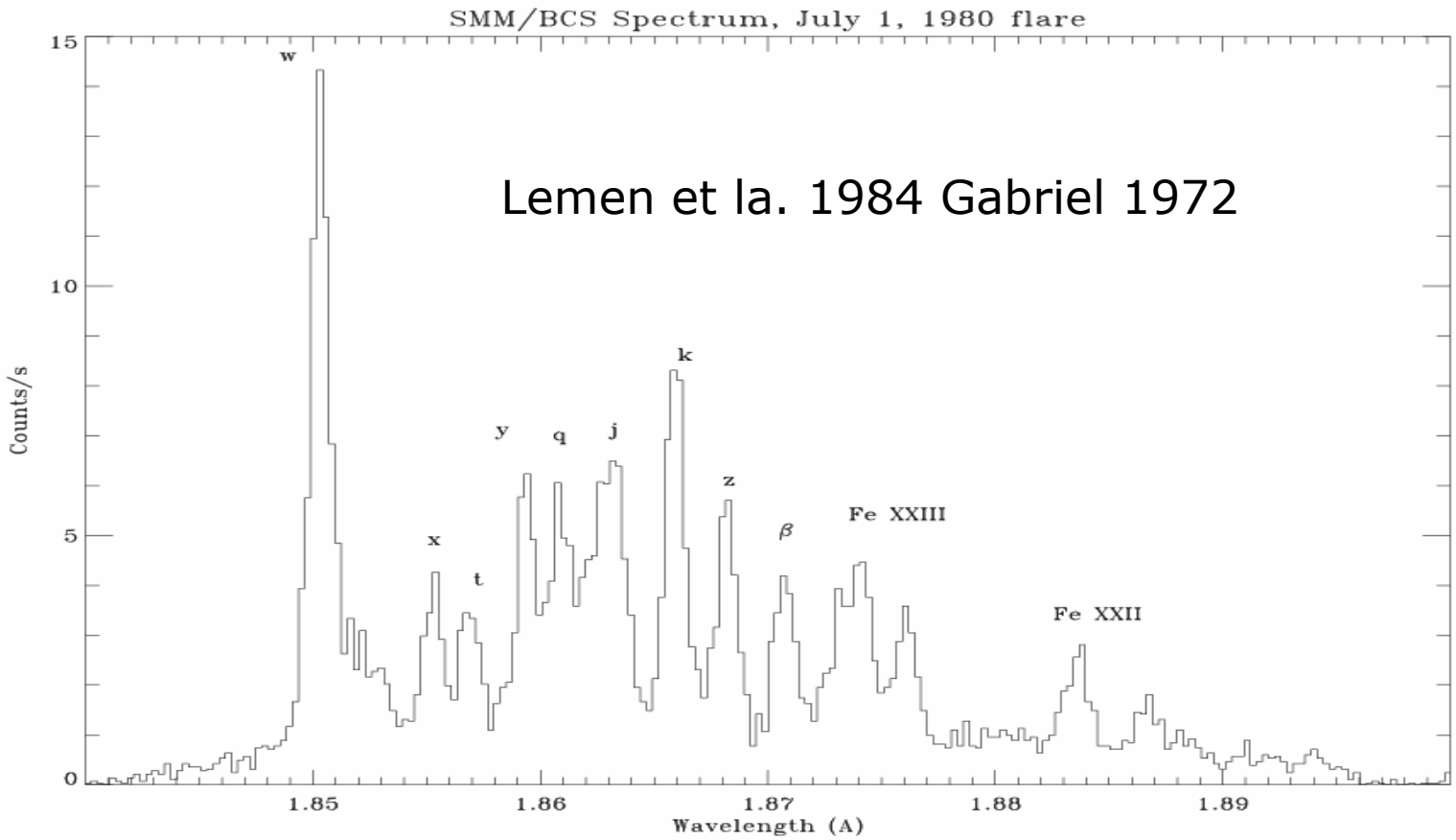
Flux Ratio vs. Temperature

Caspi & Lin, 2005



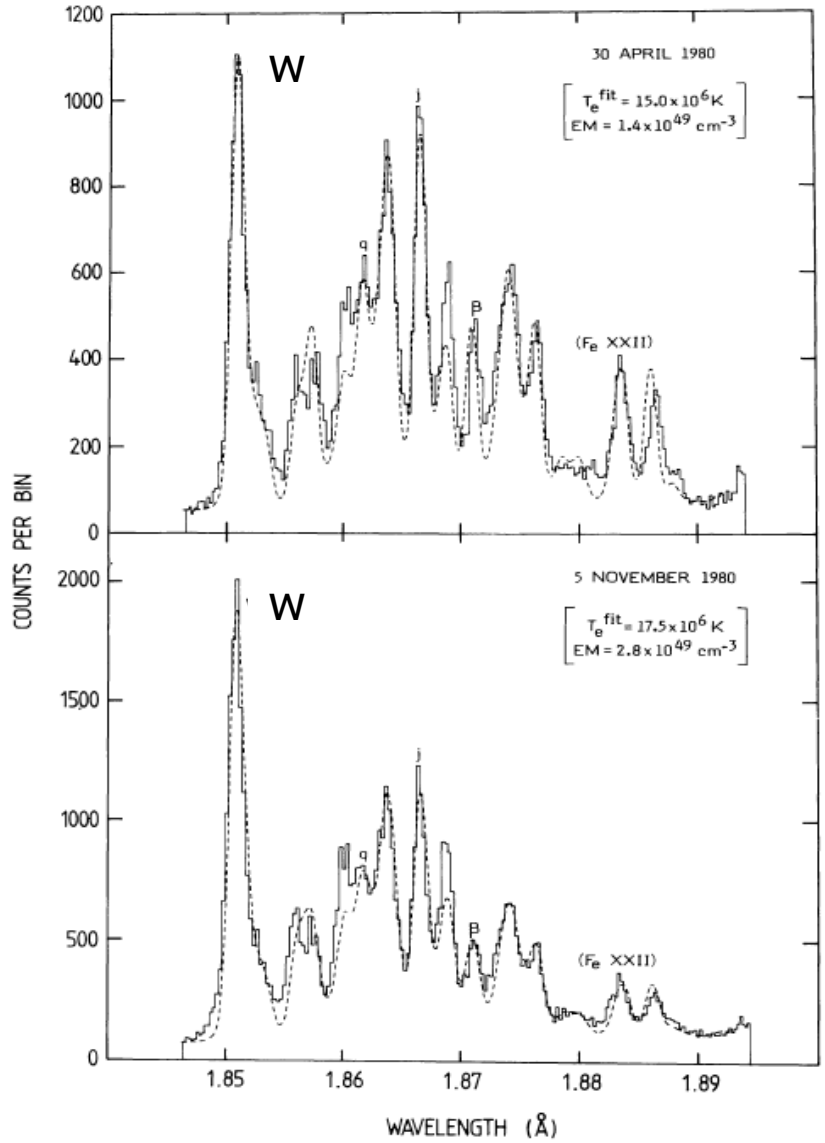
Blue shifts – flare dynamics

SMM/BCS Spectrum
Fe XXV lines and satellites



SMM / BCS Fe Spectra

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



Lemen et al., A&A, 135, 313 (1984).

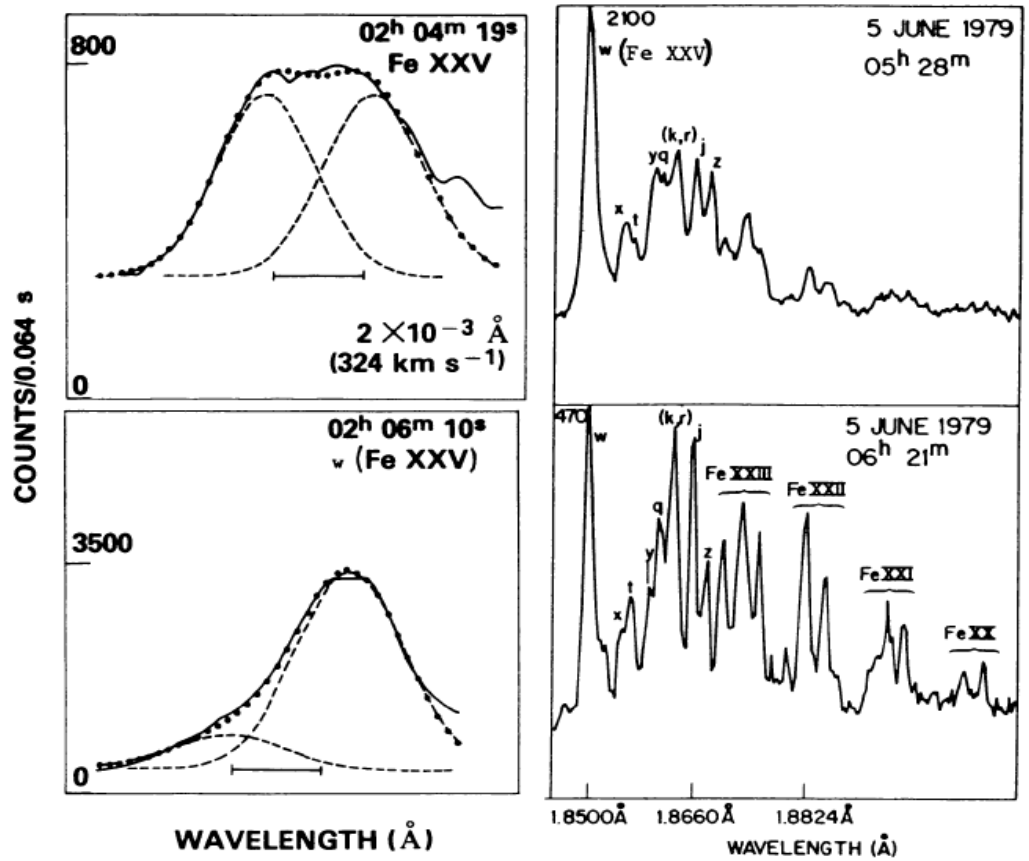
Blue Shifts and Line Broadening

P78

SOLFLEX

Bragg Crystal Spectrometer

FeXXV



Doschek, 1990, ApJS, 73,117, 1990

Blue Shifts and Line Broadening

SMM/BCS

CaXIX

Doschek, 1990, ApJS, 73,117, 1990

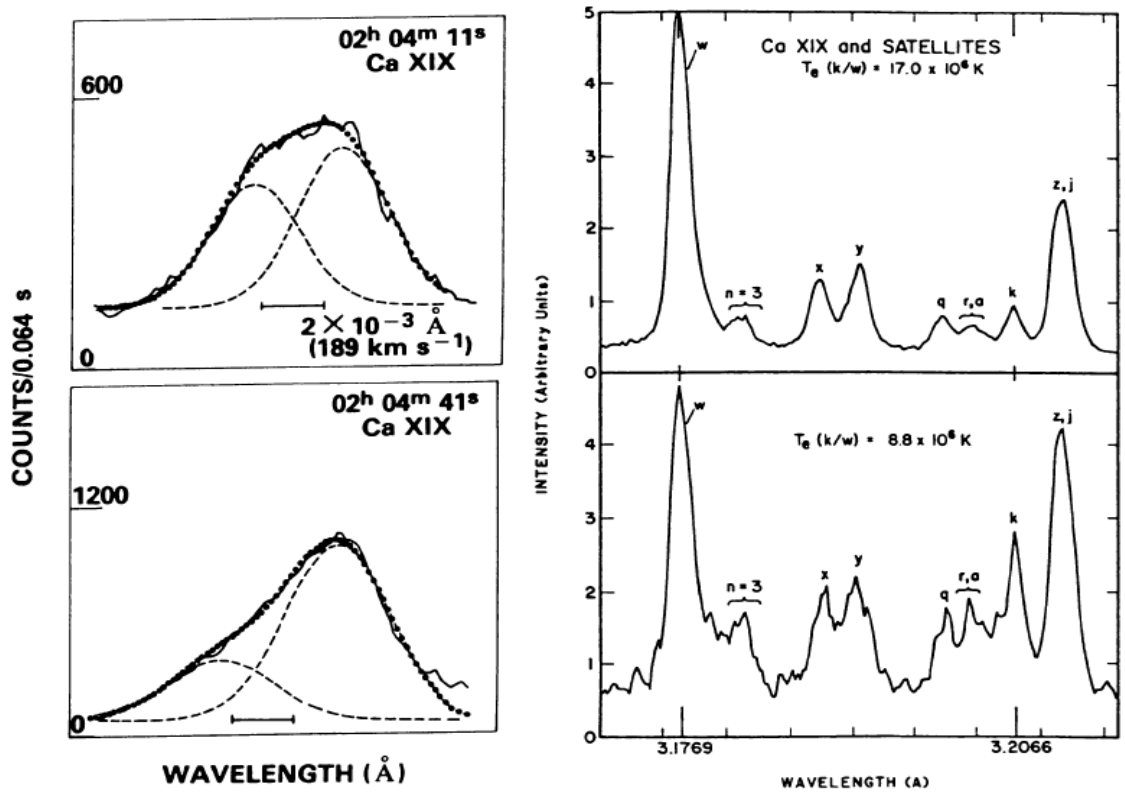


FIG. 2.—Calcium spectra of solar flares. The ratio k/w is used to determine temperature.

Blue Shifts and Line Broadening

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

Multithread Model

(Warren, ApJ, 637, 522, 2006.)

- 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.

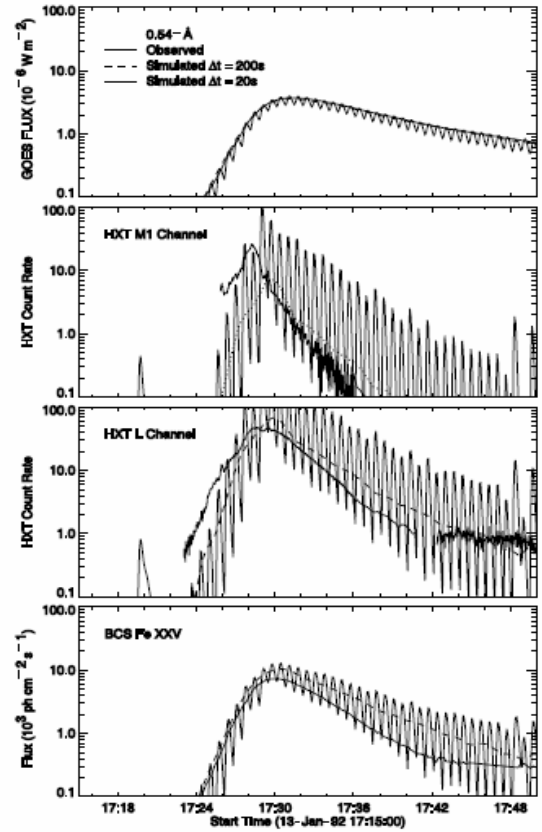
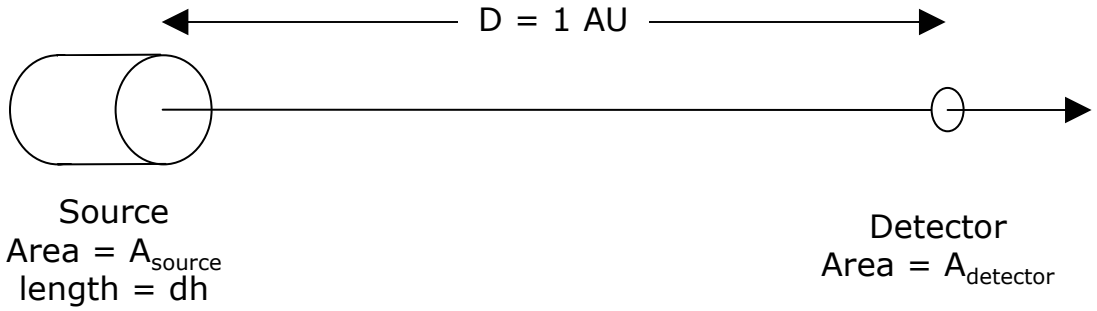


FIG. 8.—Light curves for emission formed at high temperatures for relatively gentle heating (200 s) and impulsive heating (20 s).

Emission Measure Demystified



Column Emission Measure

$$CEM = \int n_e \, n_H \, dh \; [cm^{-5}]$$

Volume Emission Measure

$$VEM = \int n_e \, n_H \, dV \; [cm^{-3}]$$

$$VEM = \int_{Asource} CEM \, dA$$

$$VEM = A_{source} \, CEM \; cm^{-3}$$

Photon Flux at Earth

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

Flux(CEM27, λ)

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

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

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

(Note that the detector area cancels out.)

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

Column to Volume EM

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

FVEM49(λ) = FCEM27(λ) 10^{49} / (A_{source} 10^{27})

= $10^{(49 - 27)}$ D^{-2} SICEM27(λ) photons cm^{-2} s^{-1} $Å^{-1}$

Source area cancels out.

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

FVEM49(λ) = $10^{(49 - 27 - 26.352)}$ SICEM27(λ) photons cm^{-2} s^{-1} $Å^{-1}$

= $10^{-4.352}$ SICEM27(λ) photons cm^{-2} s^{-1} $Å^{-1}$

= 4.45 10-5 SICEM27(λ) photons cm^{-2} s^{-1} $Å^{-1}$

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

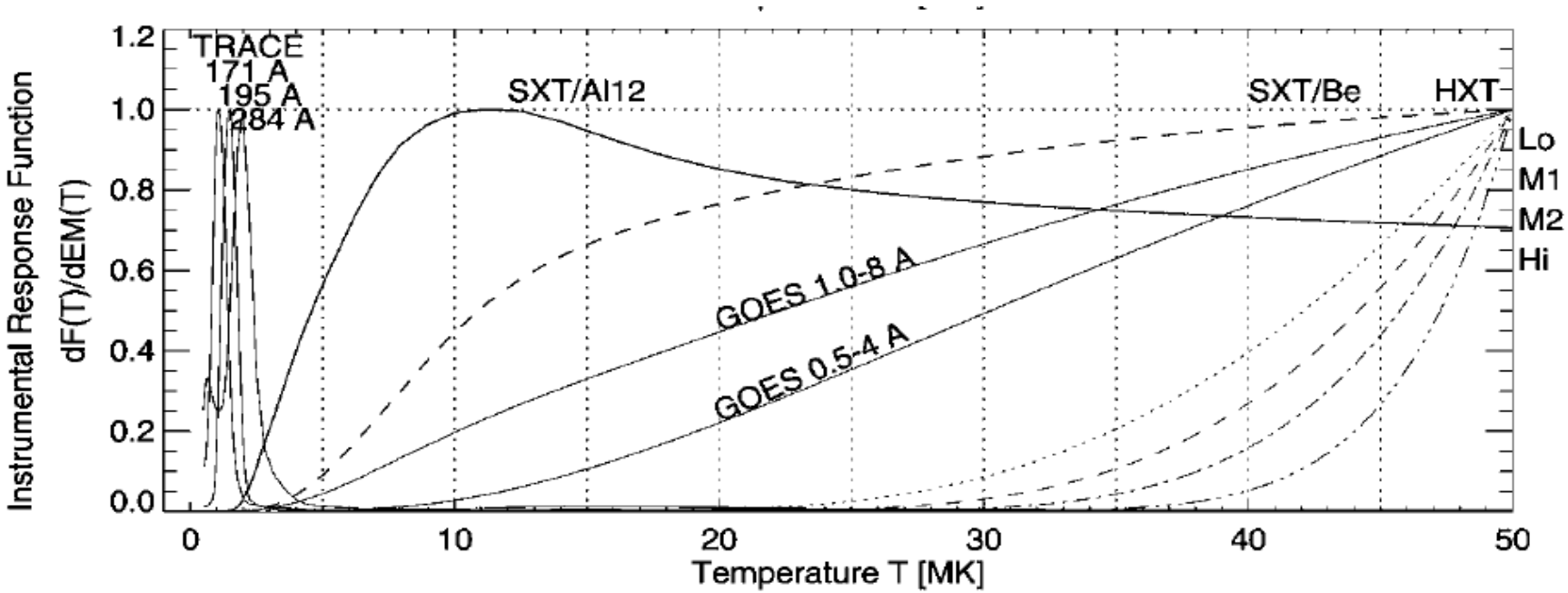
= SICEM 22.648(λ) photons cm^{-2} s^{-1} $Å^{-1}$

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

DEM Analysis

Aschwanden & Alexander, Sol. Phys. 204, 93, 2001

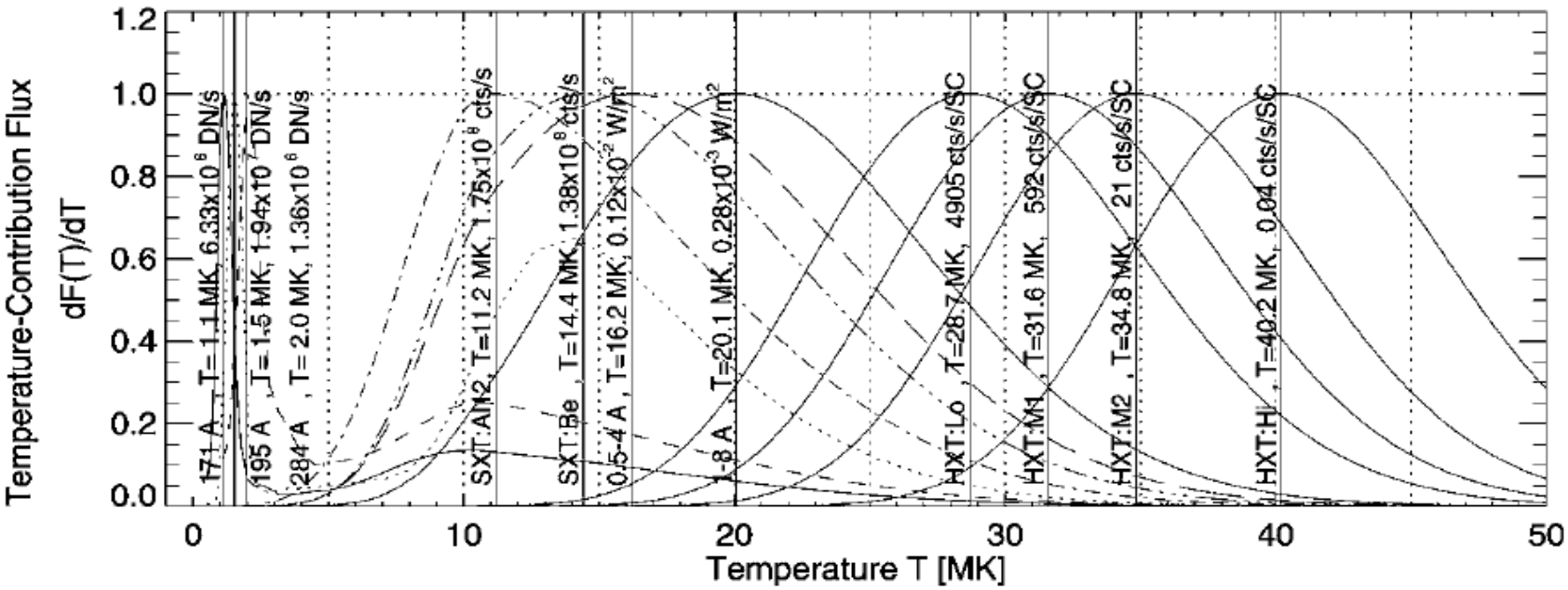
Instrument response (dF/dEM) vs. Temperature



DEM Analysis

Aschwanden & Alexander, Sol. Phys. 204, 93, 2001

Normalized G(T) functions

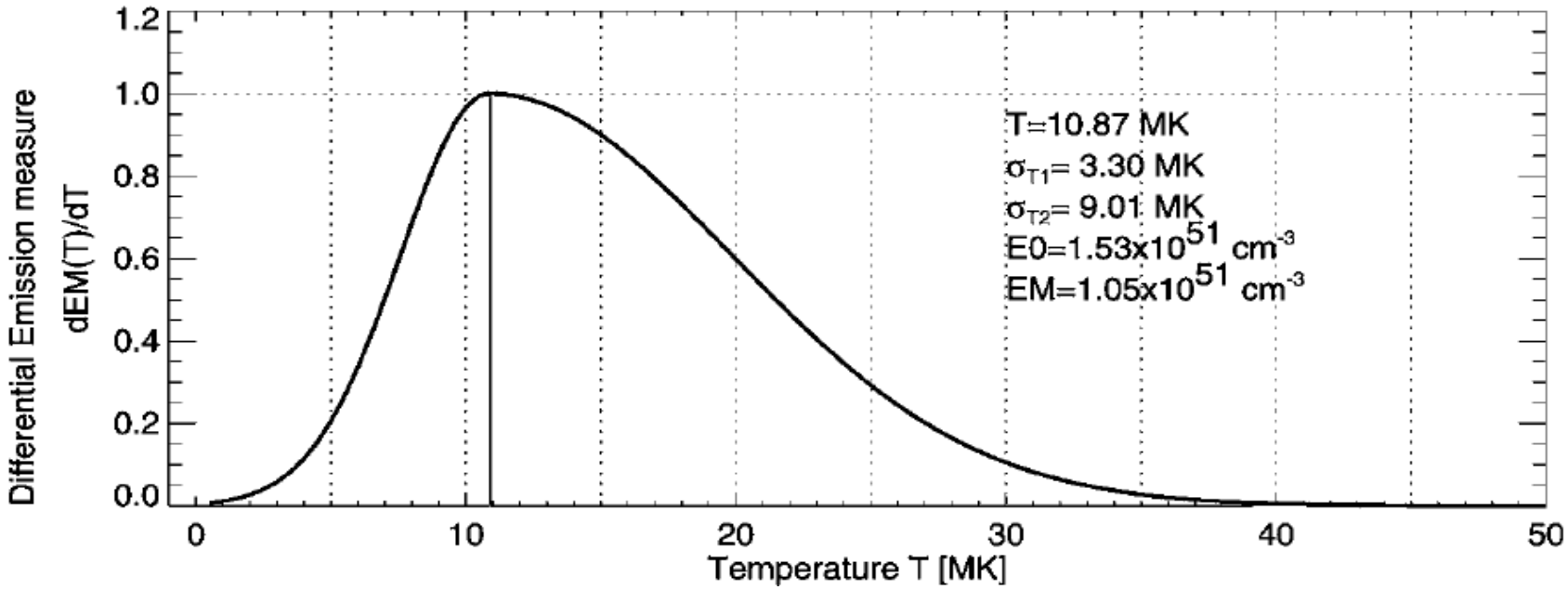


DEM Analysis

Aschwanden & Alexander, Sol. Phys. 204, 93, 2001

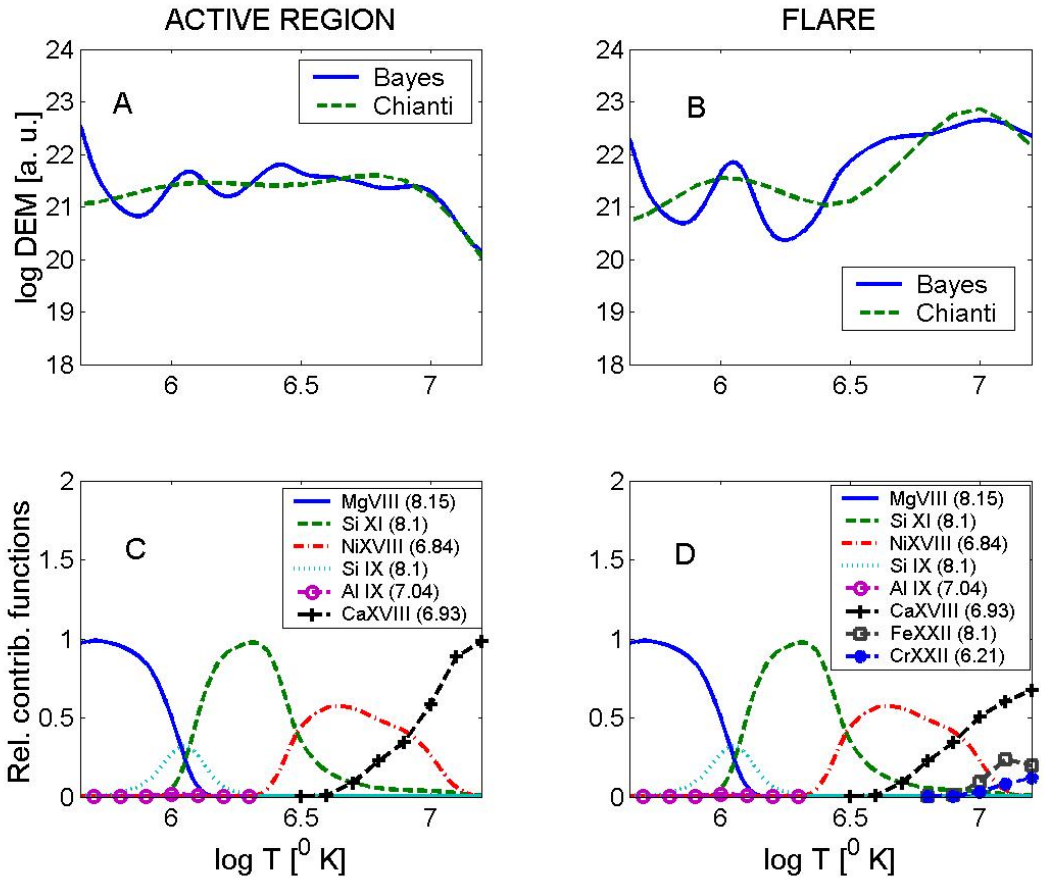
Bastille Day event – 14 July 2000

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

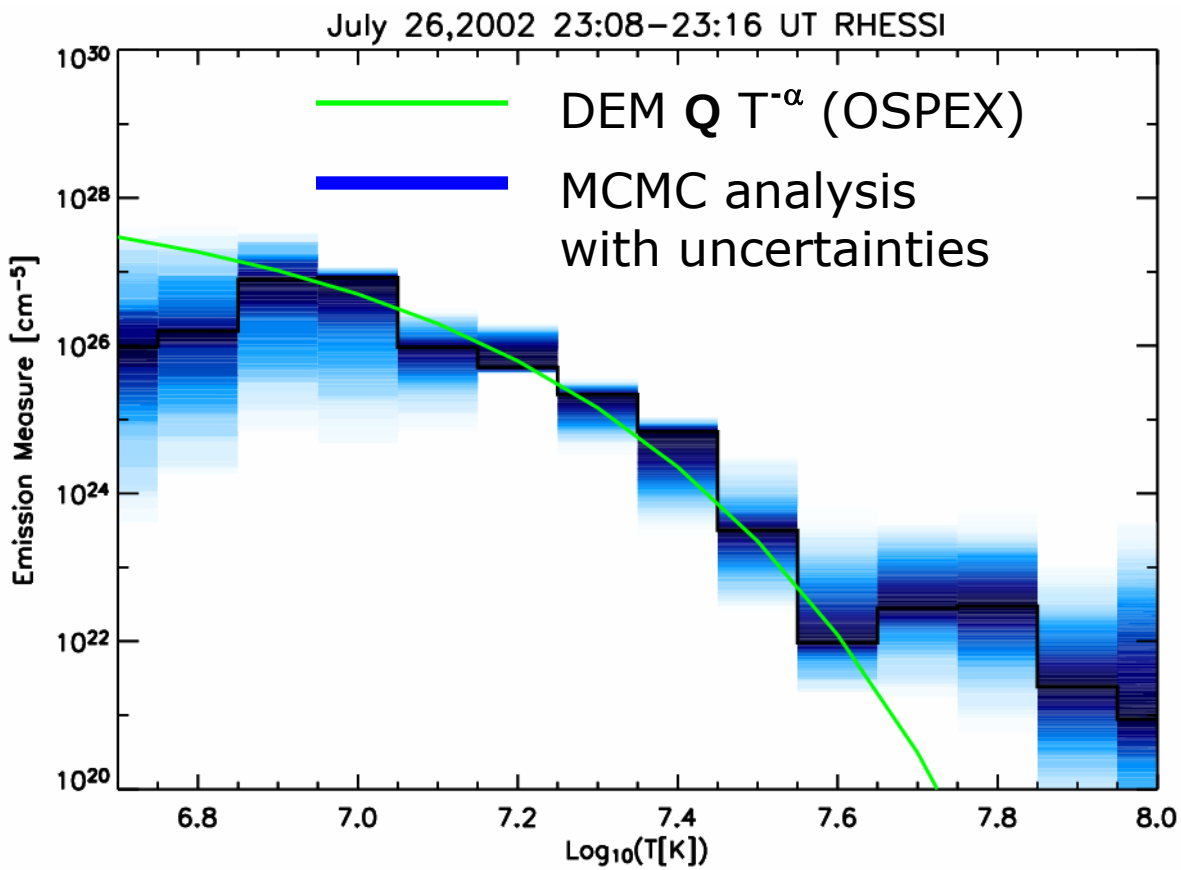


CORONAS-F

DEM for the active region and the flare 28.12.2001

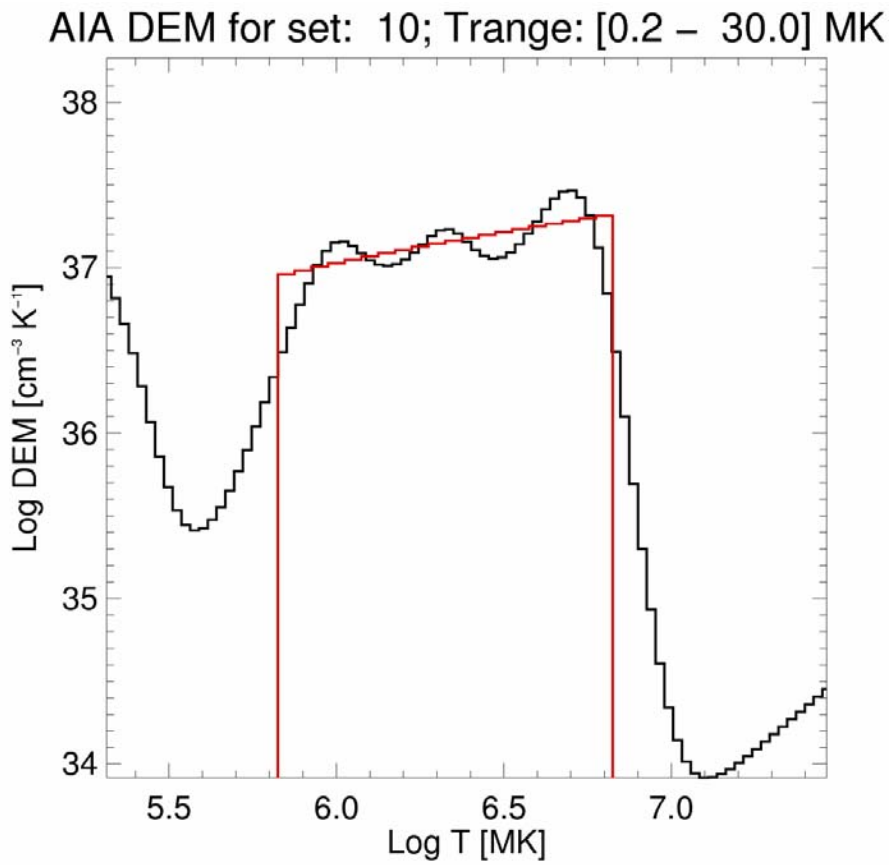


Markov-Chain Monte Carlo (MCMC) DEM Analysis (Liwei Lin, SAO)



DEM Analysis Limitations

Sylwester



Deal or No Deal!
Thermal or Nonthermal

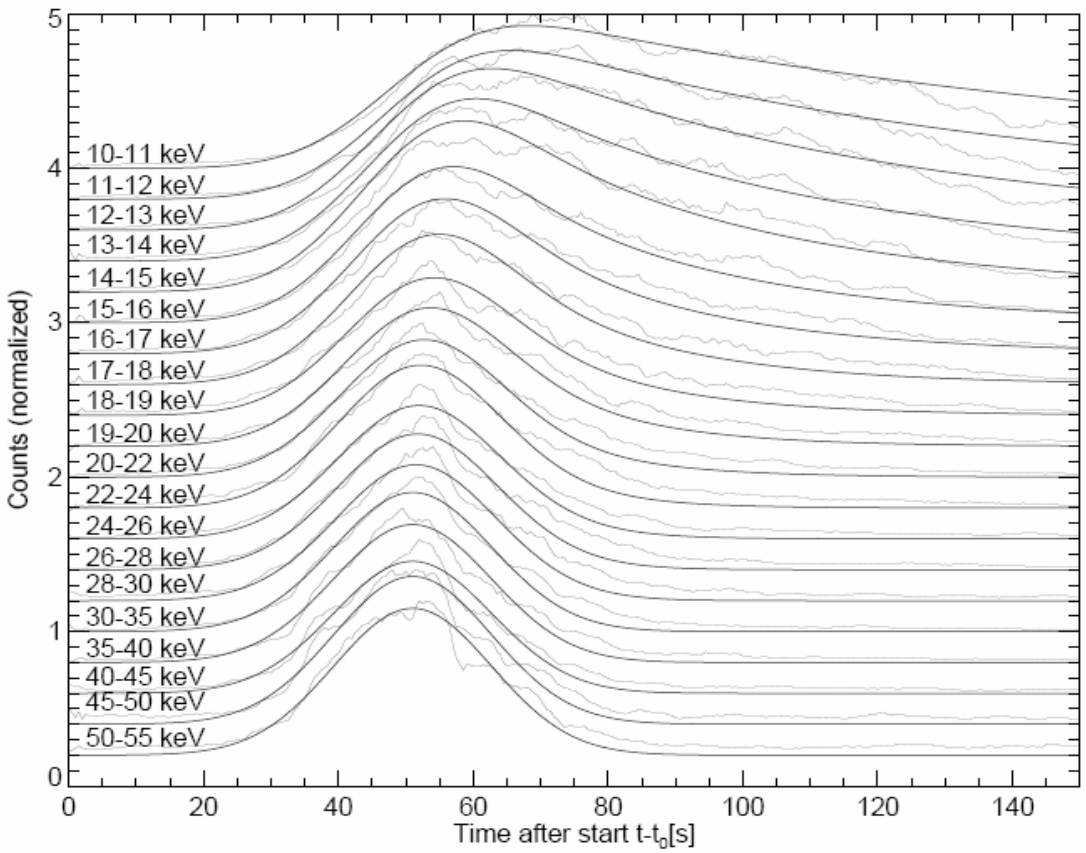
The standard mythology

- 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!

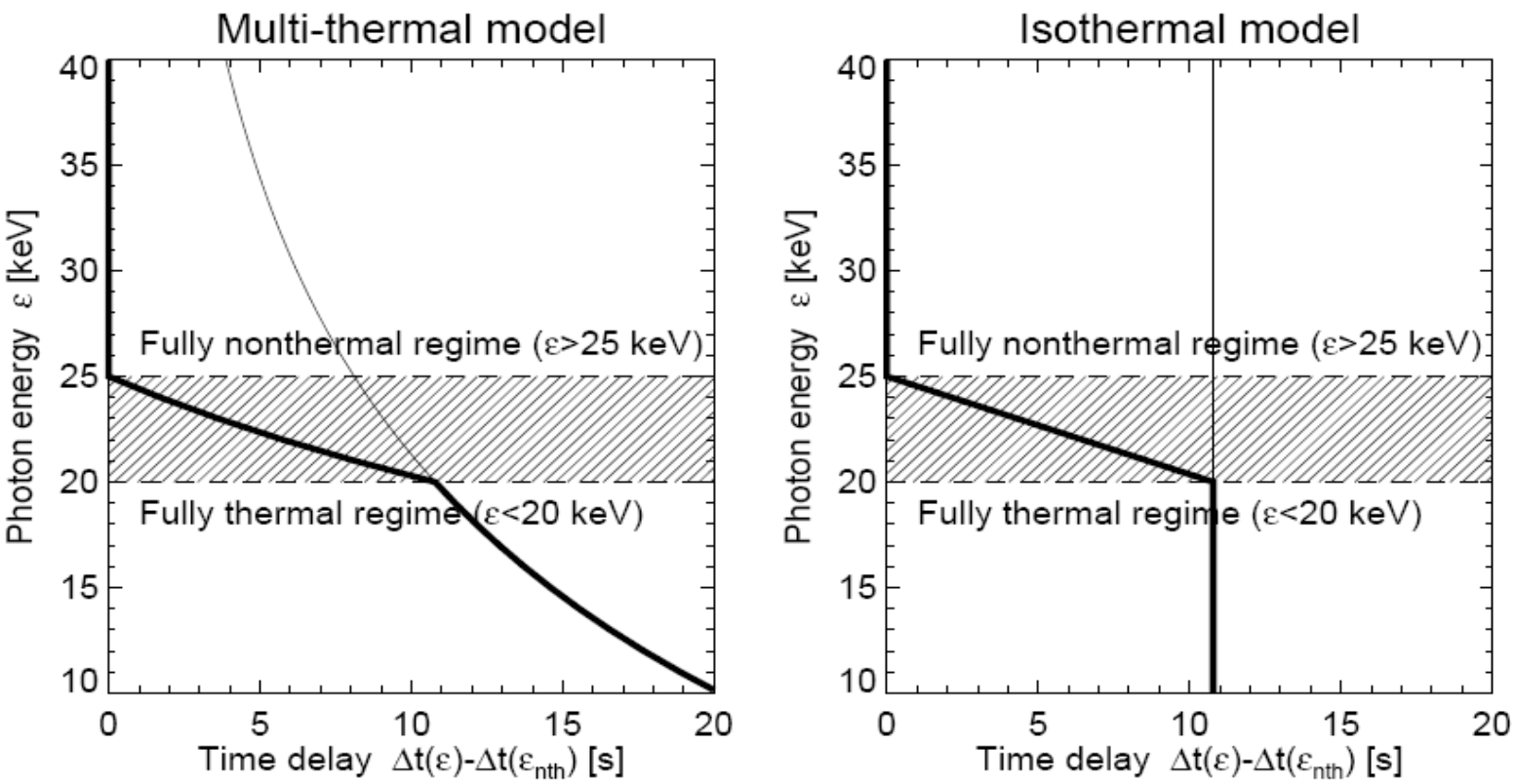
Energy Dependent Time Delays

Aschwanden, 2006, preprint



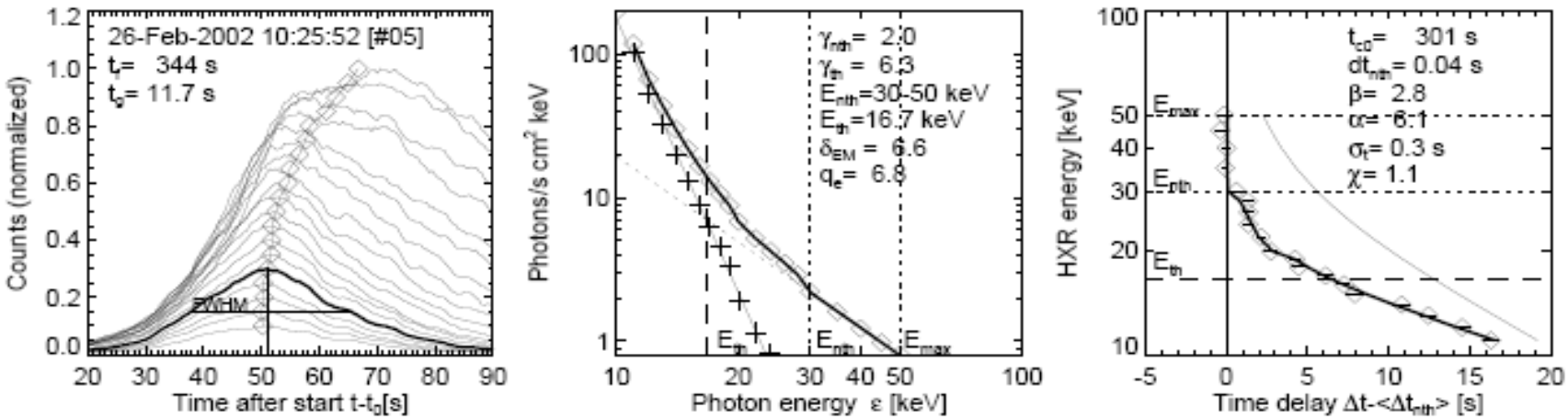
Energy Dependent Time Delays

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

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

EM – emission measure

T - temperature

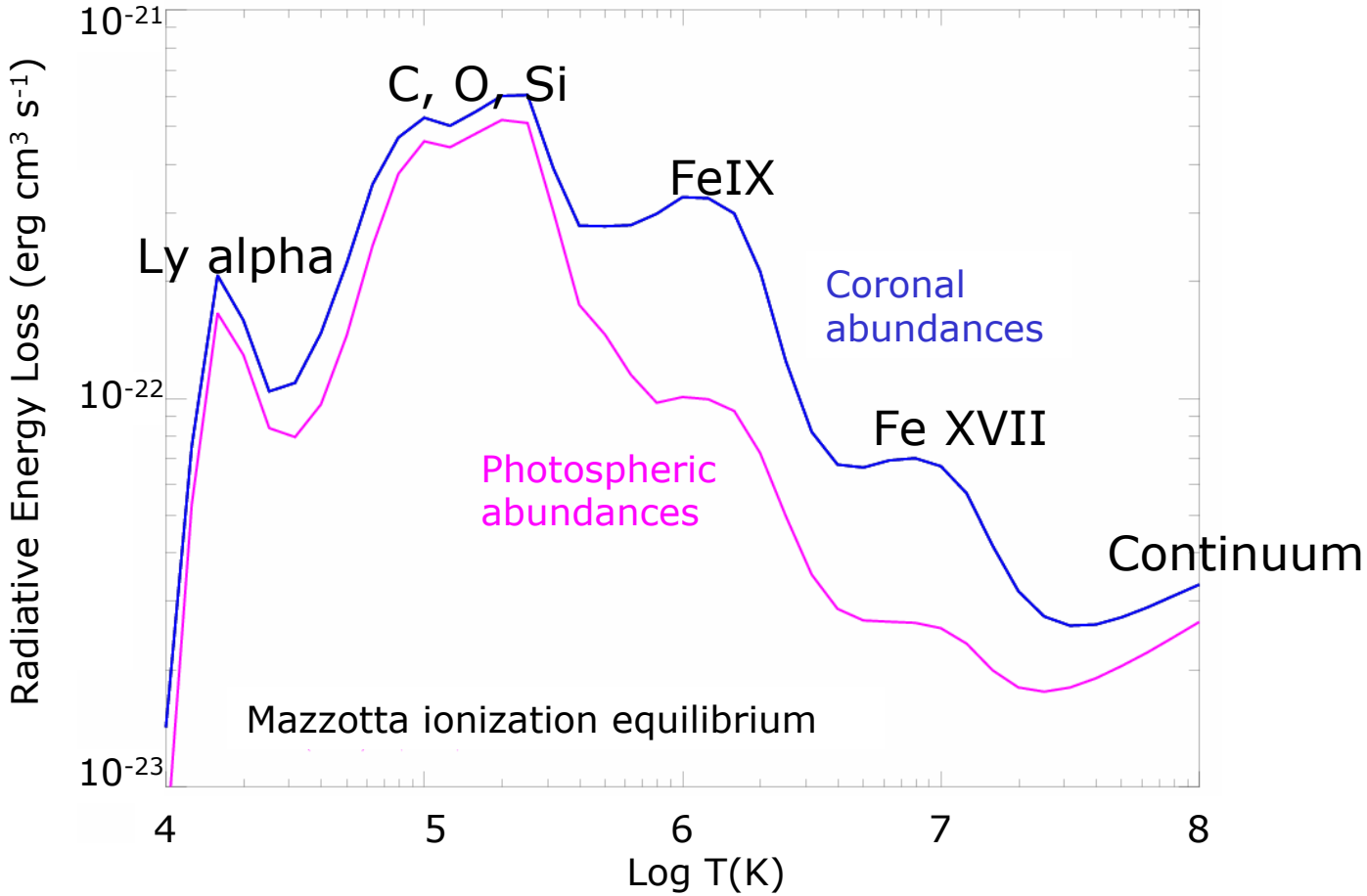
$f_{rad}(T)$ - radiative loss function

- Total radiated energy from the flare plasma

$$L_{total} = \Sigma[\ L_{rad}(t)\ *Dt\ ]\ \text{erg}$$

Sum is over the duration of the flare

CHIANTI Radiative Loss Function



Thermal Energy

Thermal energy of plasma

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

n_e – electron density in cm^{-3}

V – volume of emitting plasma in cm^3

$V_{apparent}$ – volume from image

f - filling factor (assumed to be 1)

k_B – Boltzmann's constant

T – temperature (from GOES and RHESSI)

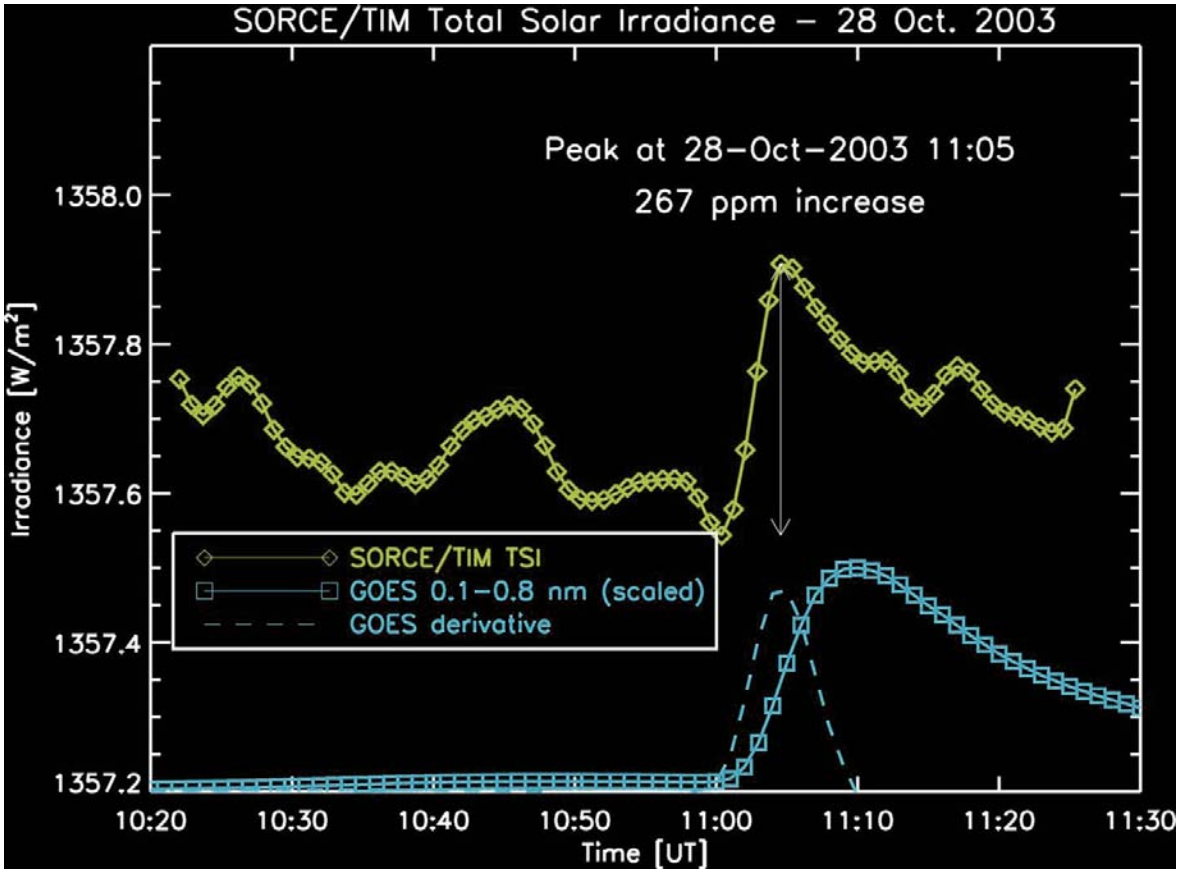
$EM = n_e^2\ V$ – emission measure in cm^{-3} (from GOES and RHESSI)

$V = f\ V_{apparent} \sim f\ A^{3/2}$

A - source area from image

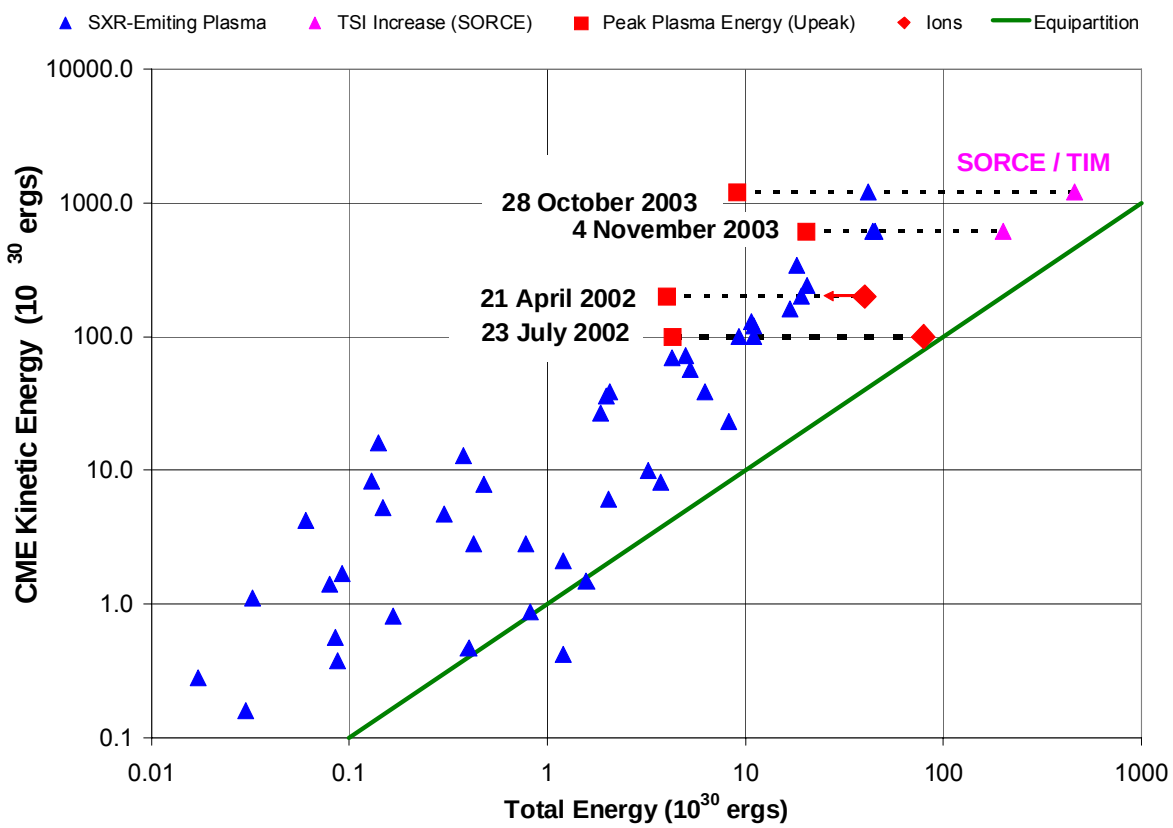
Increase in Total Solar Irradiance

X17 flare on 28 October 2003



CME vs Flare Energies

Dennis et al. 2006



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 2nd 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