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Atomic Data: its role in interpreting data

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STFC Introductory Course on Solar-Terrestrial Physics
Armagh, Sept. 2007

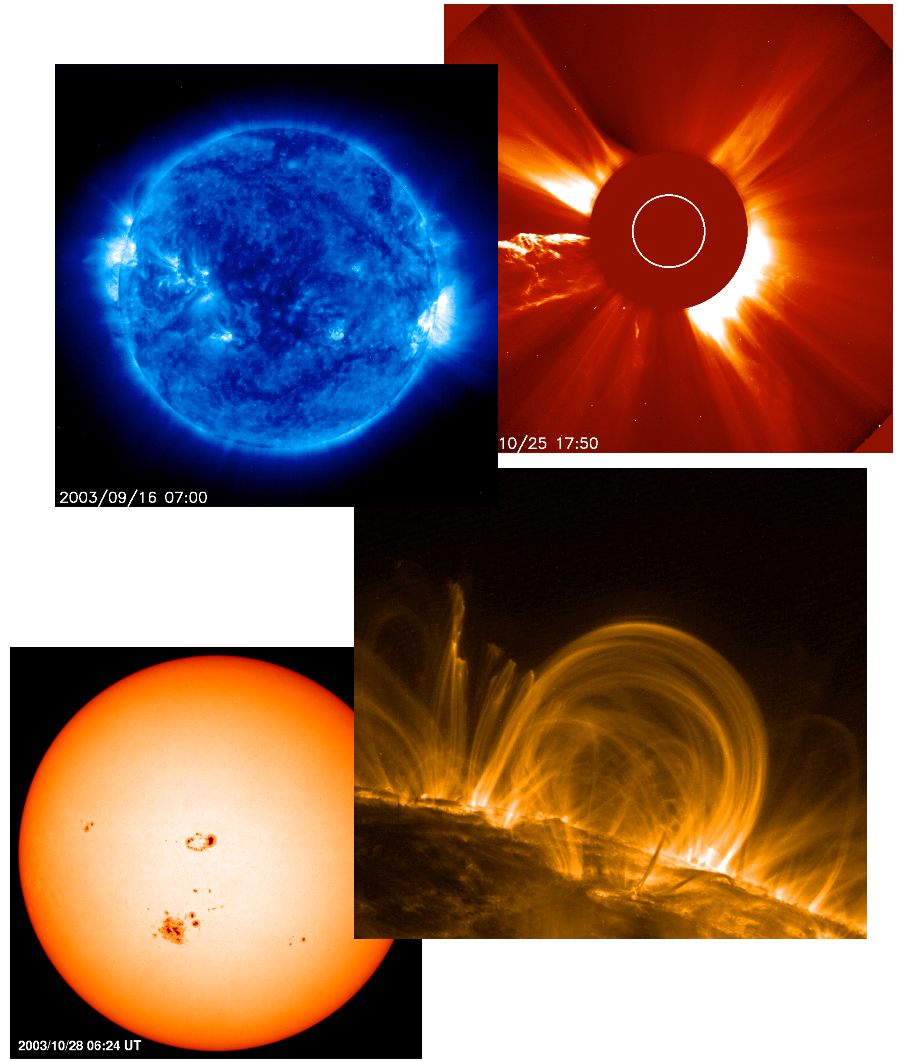
Overview

- **Ultraviolet radiation**
- Atomic physics in the Sun’s atmosphere
- Application to Hinode/EIS
- Limitations of imaging instruments
- Using atomic data in theoretical models

Satellites

- Golden age of solar physics…
  - **SOHO**, 1995-
  - **TRACE**, 1998-
  - RHESSI, 2002-
  - **Hinode**, 2006-
  - **STEREO**, 2006-
- Still to come…
  - **SDO**, 2008
  - **Solar Orbiter**, 2015-17

All missions except RHESSI have UV instrumentation



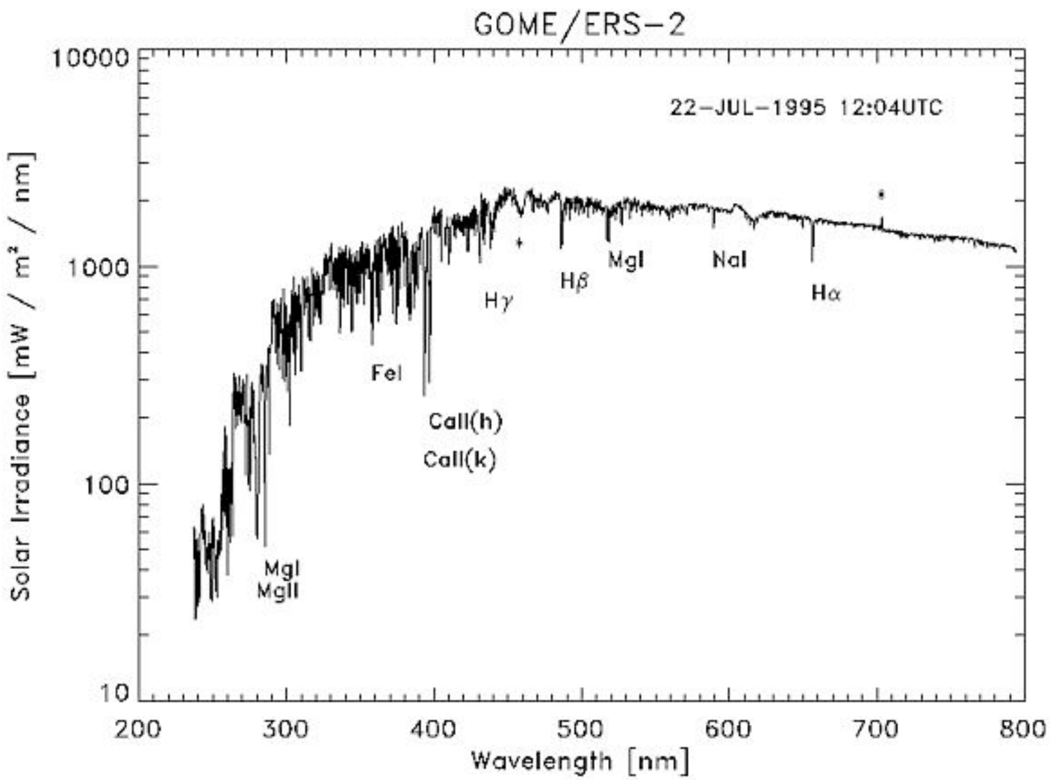
Ultraviolet Radiation

- Extends from 10 to 380 nm
- 99 % of UV that reaches Earth's surface is > 315 nm (UV-A)
- UV-B radiation (200-315 nm) is absorbed by oxygen molecules to produce ozone
- Variation of extreme UV radiation modifies size of the Earth's ionosphere

- UV radiation below 200 nm provides excellent diagnostic possibilities for the Sun's transition region and corona (T > 20,000 K)
  - requires satellite-based instrumentation

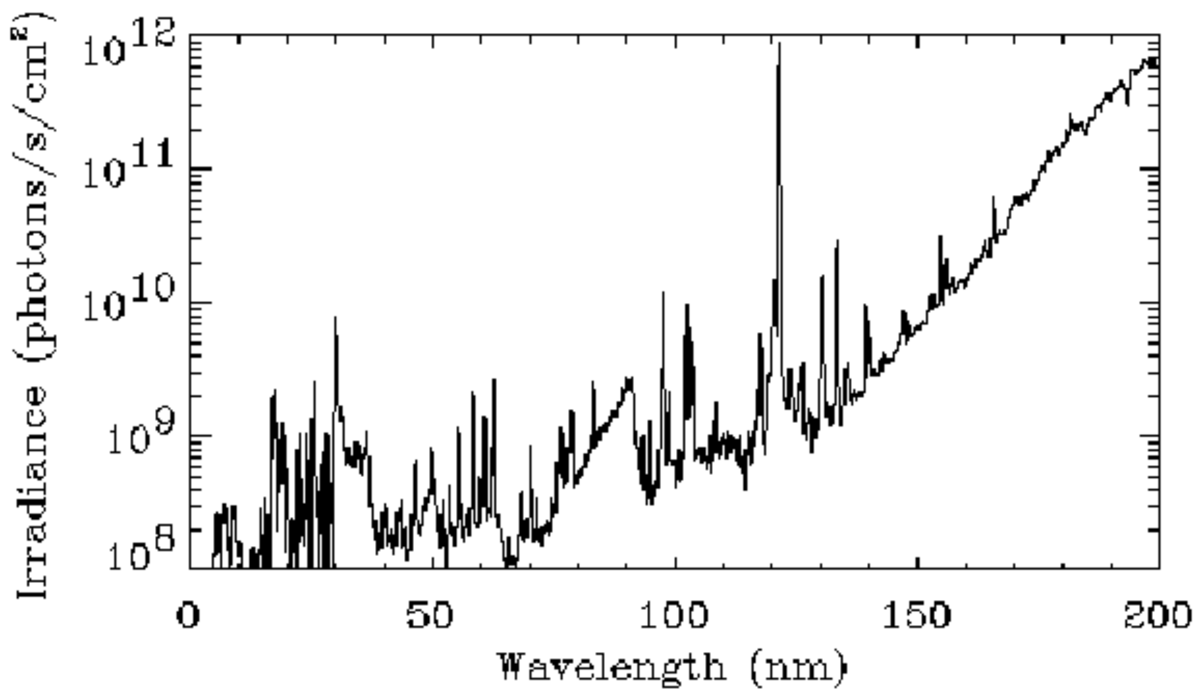
Solar Visible Spectrum

- Shows *continuum* (≈ blackbody 5800 K) and *absorption* lines

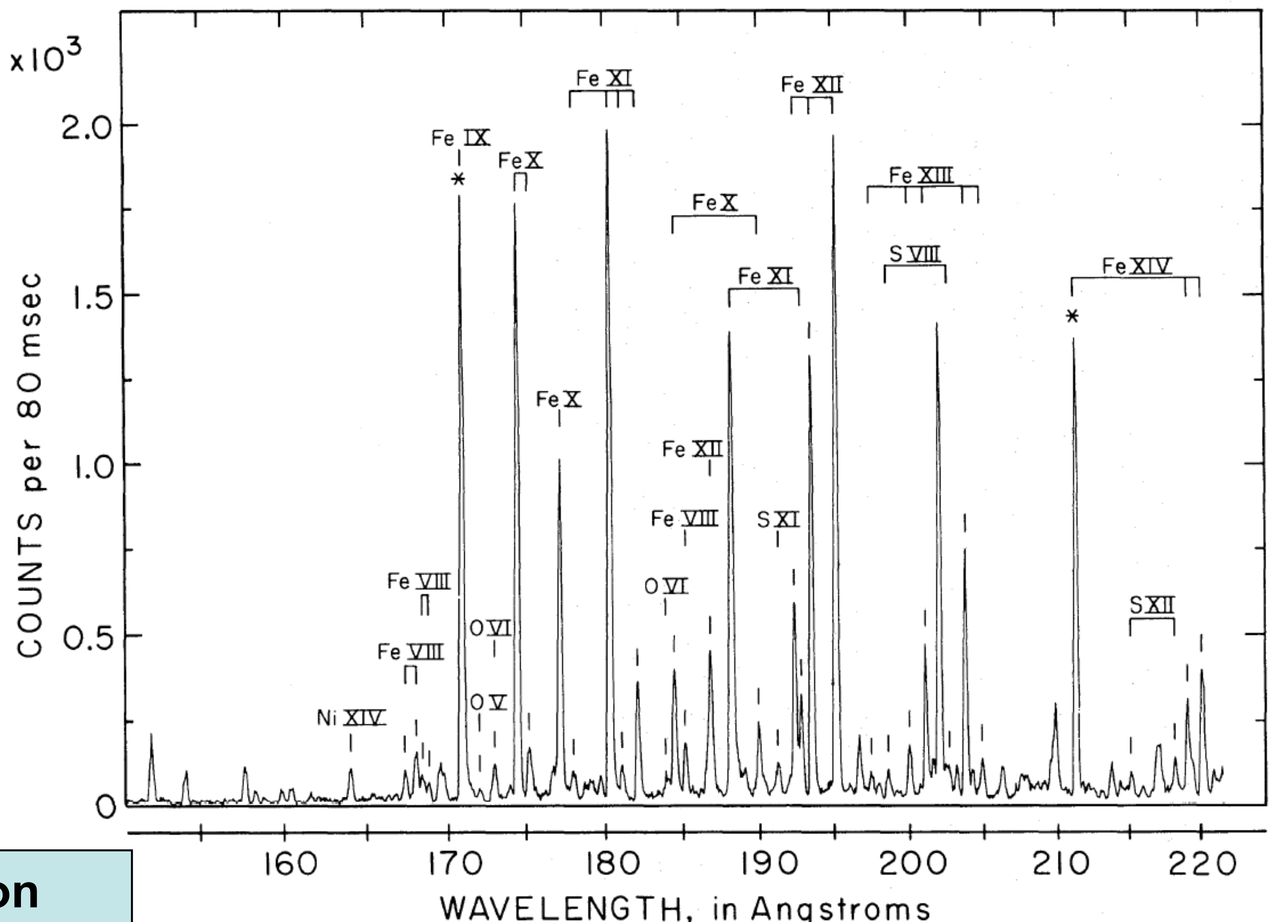


Solar Ultraviolet Spectrum

- In the UV, continuum emission disappears and spectrum dominated by *emission lines*
- The 'quiet' solar atmosphere emits most radiation at UV wavelengths



UV spectrum

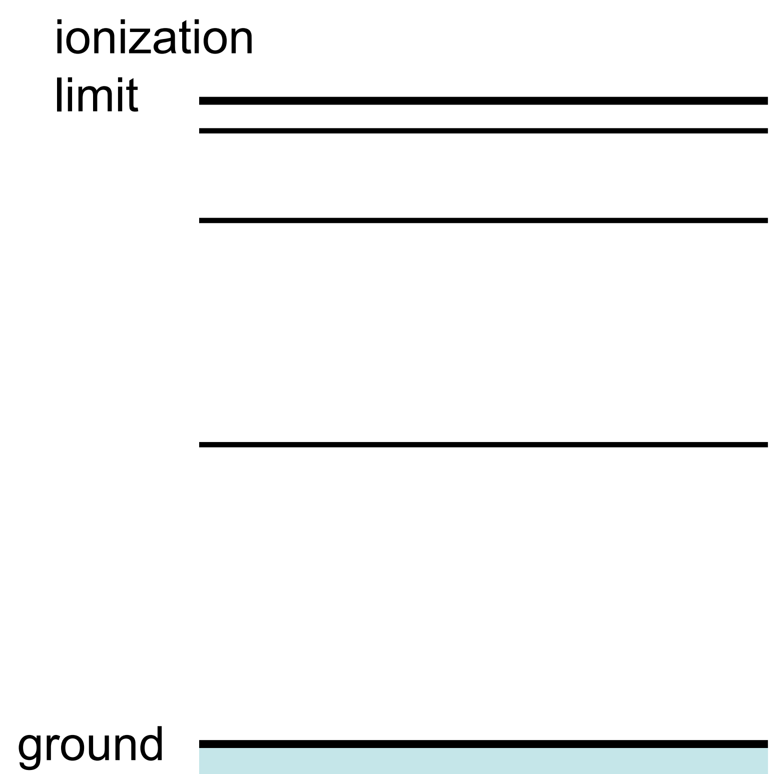


Notation
1 nm=10 Å
Fe XII=Fe^{+11}

Malinovsky & Heroux (1973)

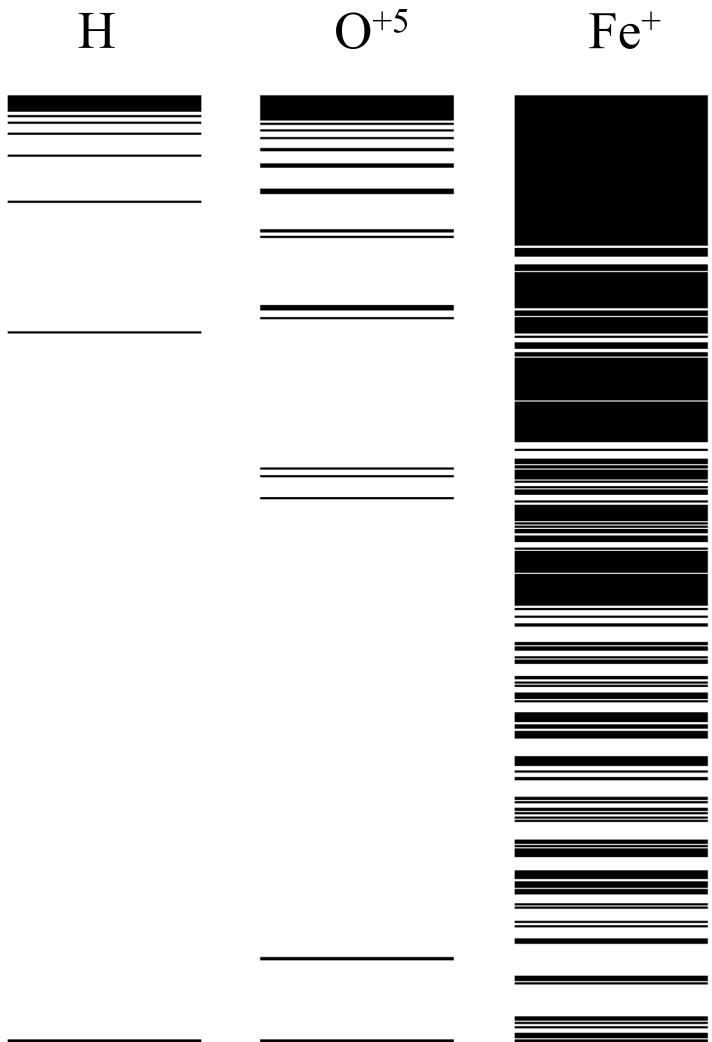
Why do we see lines? – Atomic structure basics

- Quantum physics leads to electrons orbiting the nucleus lying in discrete orbitals
- Energy levels can be labelled by integers, E_i
- Lowest level is *ground level*
- Higher levels become squashed together, merging into ionization limit



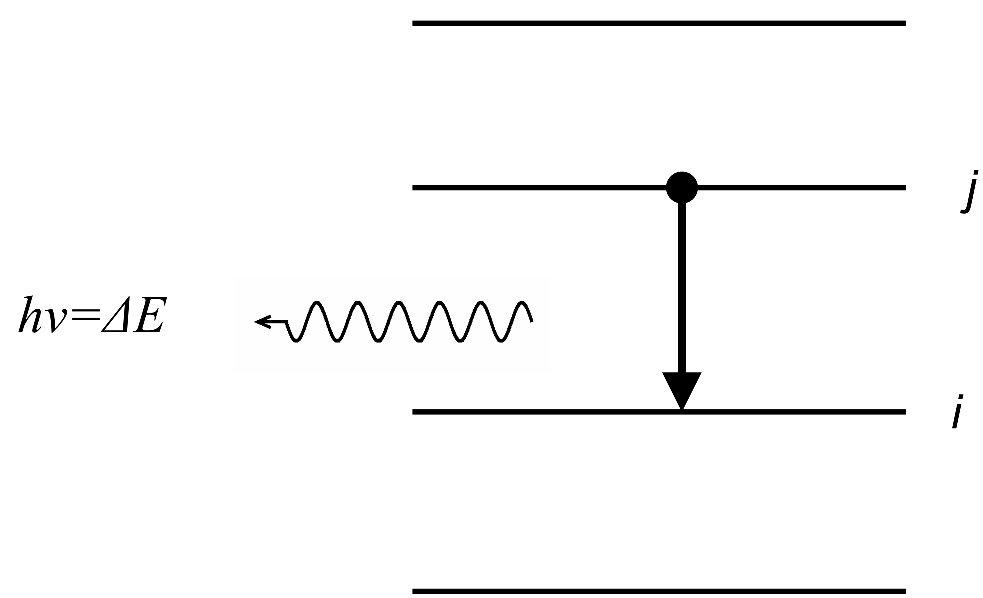
Level structure

- Hydrogen has simple structure (Rydberg level series)
- Li-like O^{+5} has 3 electrons, yet series remains simple
- Large ions such as Fe^{+} have very complex level structure

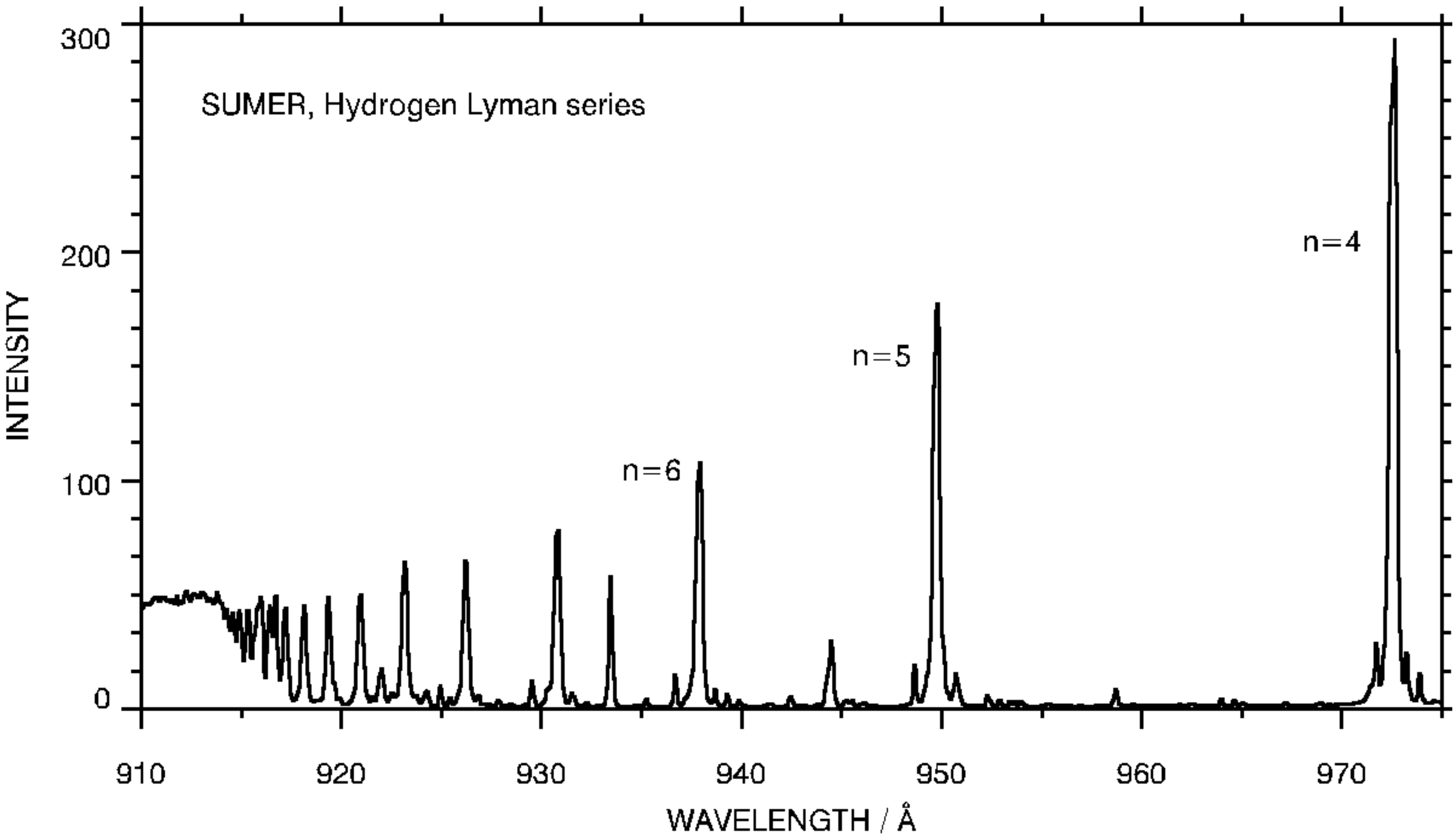


Atomic Transitions

- Emission lines arise from transitions between ion levels
- Photon energy = $E_j - E_i$



Hydrogen Spectrum



Remote sensing of the Sun in the UV

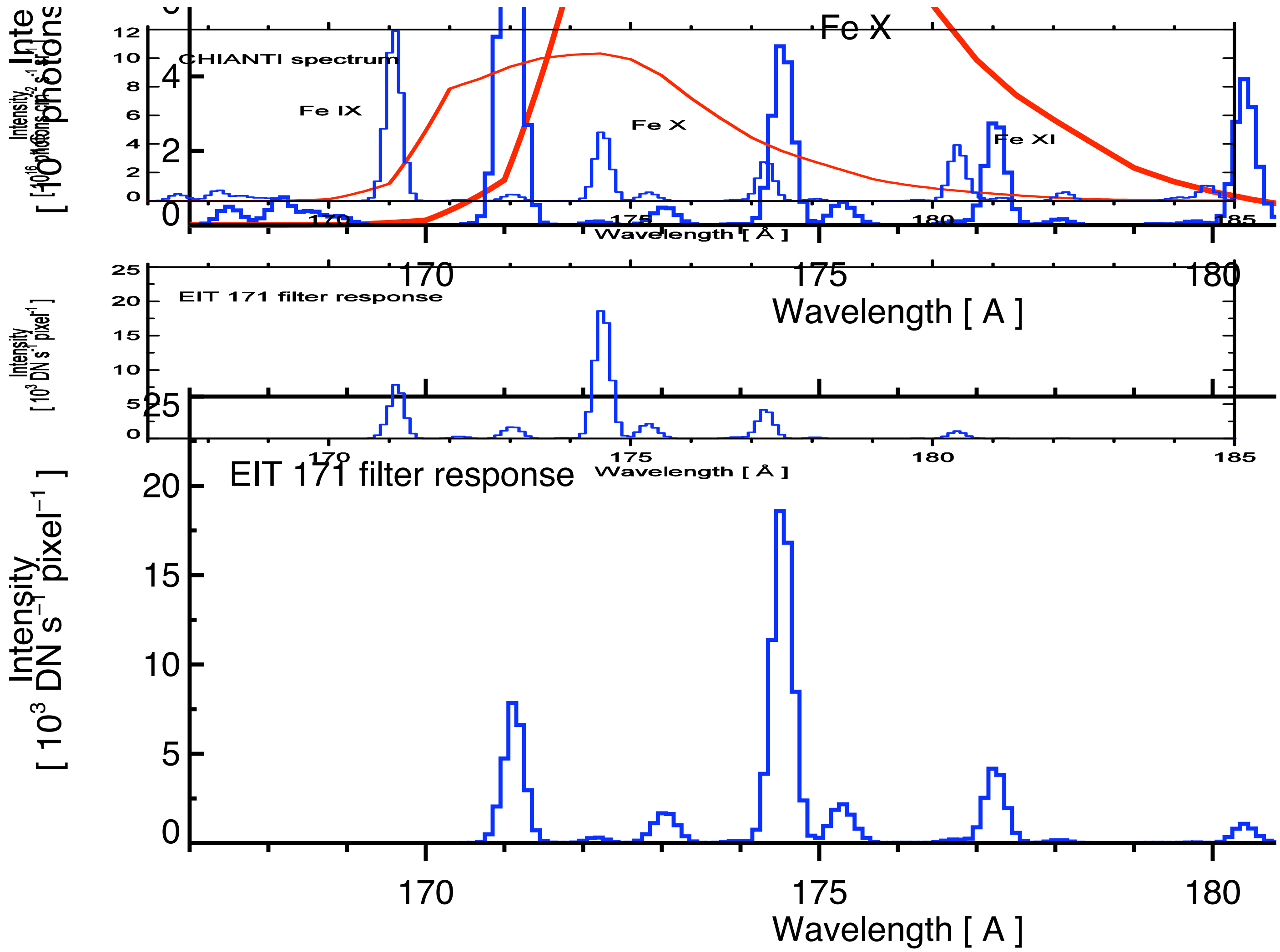
- Two approaches

- *Filtergrams*
  - Filter out a small portion of the spectrum, and take X-Y images

- *Spectroscopy*
  - Throw out one of the spatial dimensions to obtain wavelength resolution

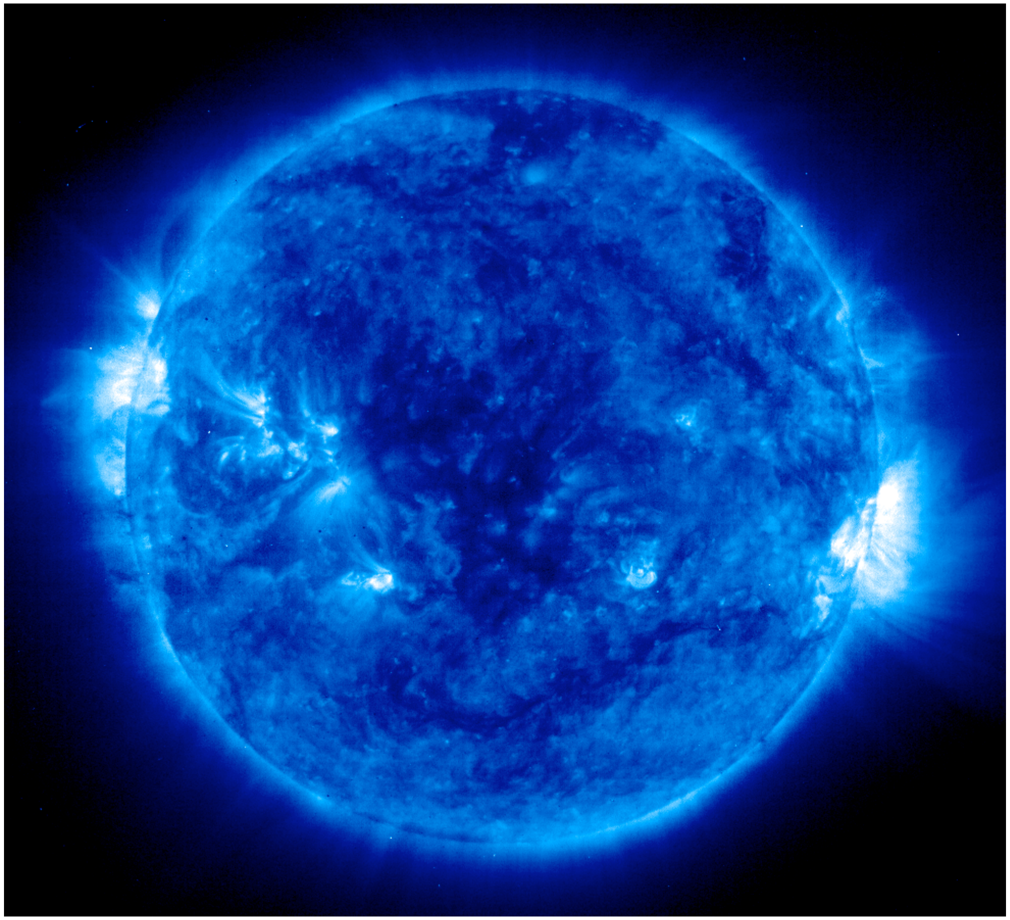
Filtergram Example: SOHO/EIT

- EIT Fe IX/X 173 filter lets through only radiation around 173 Å



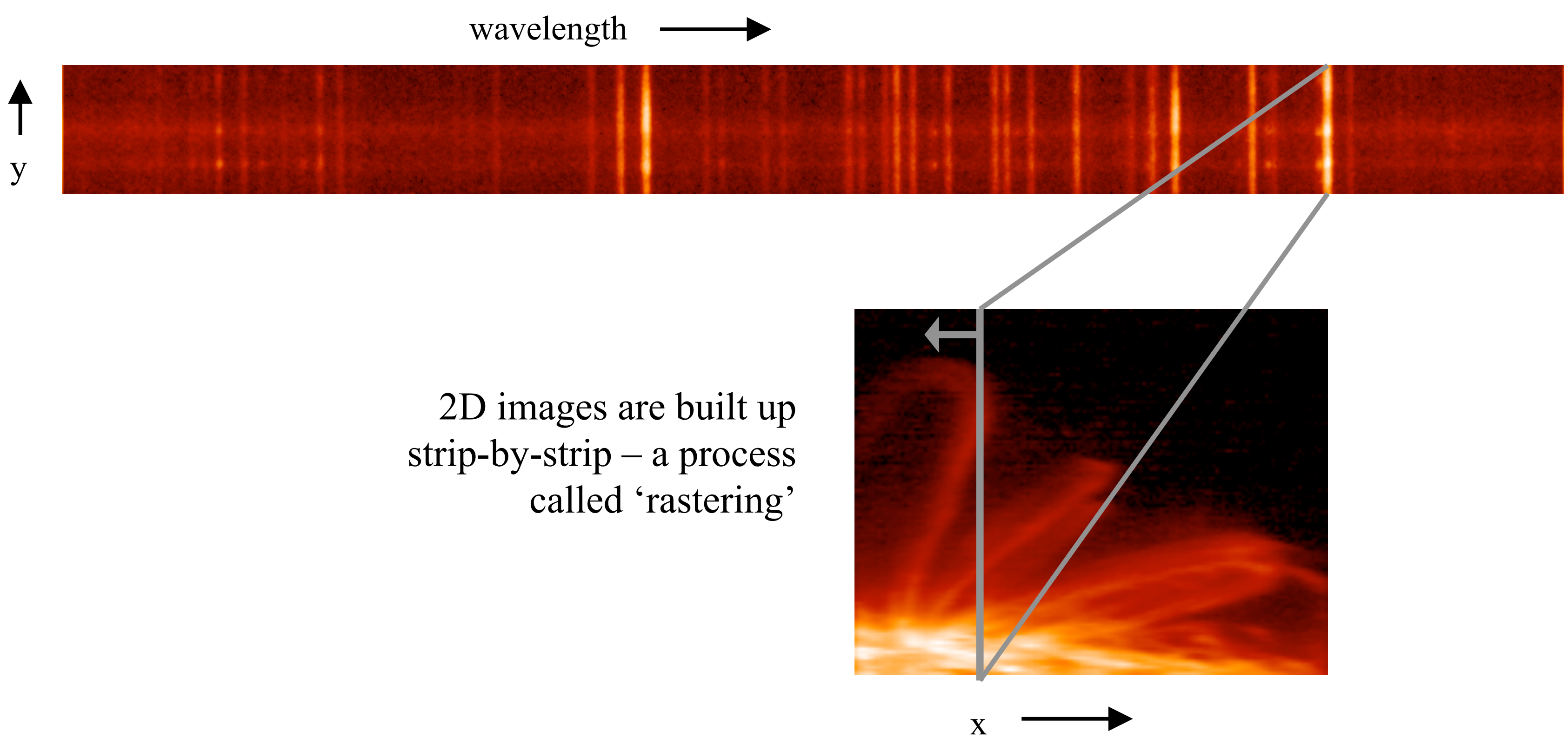
Filtergram Example: SOHO/EIT

- Radiation corresponds to ≈ 1 million K (EIT Fe IX/X 173 filter)

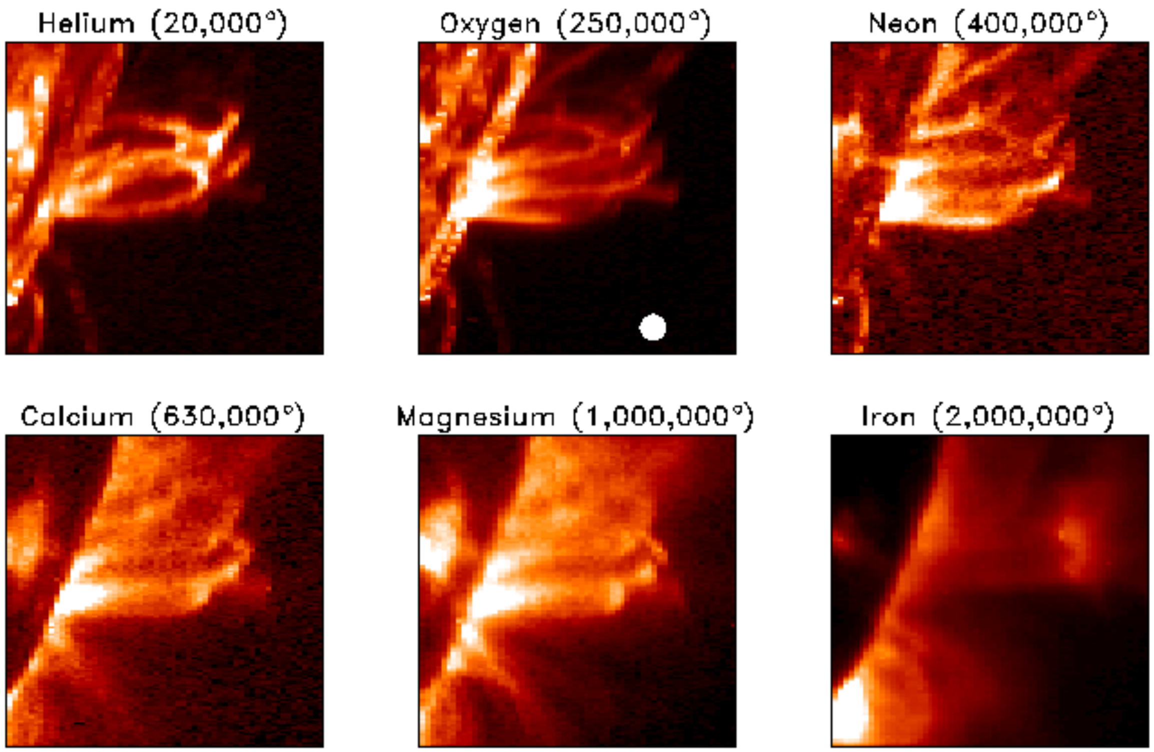


Spectroscopy Example: SOHO/CDS

- 2D images are built up by repeated exposures at neighbouring positions



CDS Images



SOHO/CDS 23-Mar-1998
Loops of gas at different temperatures observed near the solar limb

Imaging vs. Spectroscopy

	Advantages	**Disadvantages**
Filtergrams (Imaging)	High time cadence; easy to analyse	Ambiguous interpretations
Spectroscopy	Detailed plasma information: temperature, density, emission measure, abundances, velocities	Rasters can be slow; difficult to analyse; useful lines often weak

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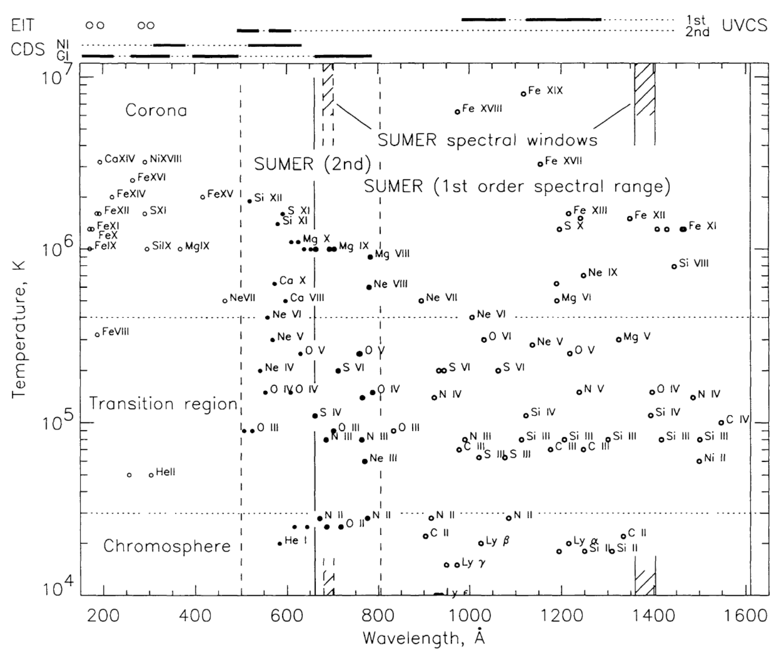
Complexity of Sun’s atmosphere

- A ‘soup’ of several hundred ions of many elements permeated by free electrons
- Ions produce several thousand emission lines at UV wavelengths
- Not in thermodynamic equilibrium



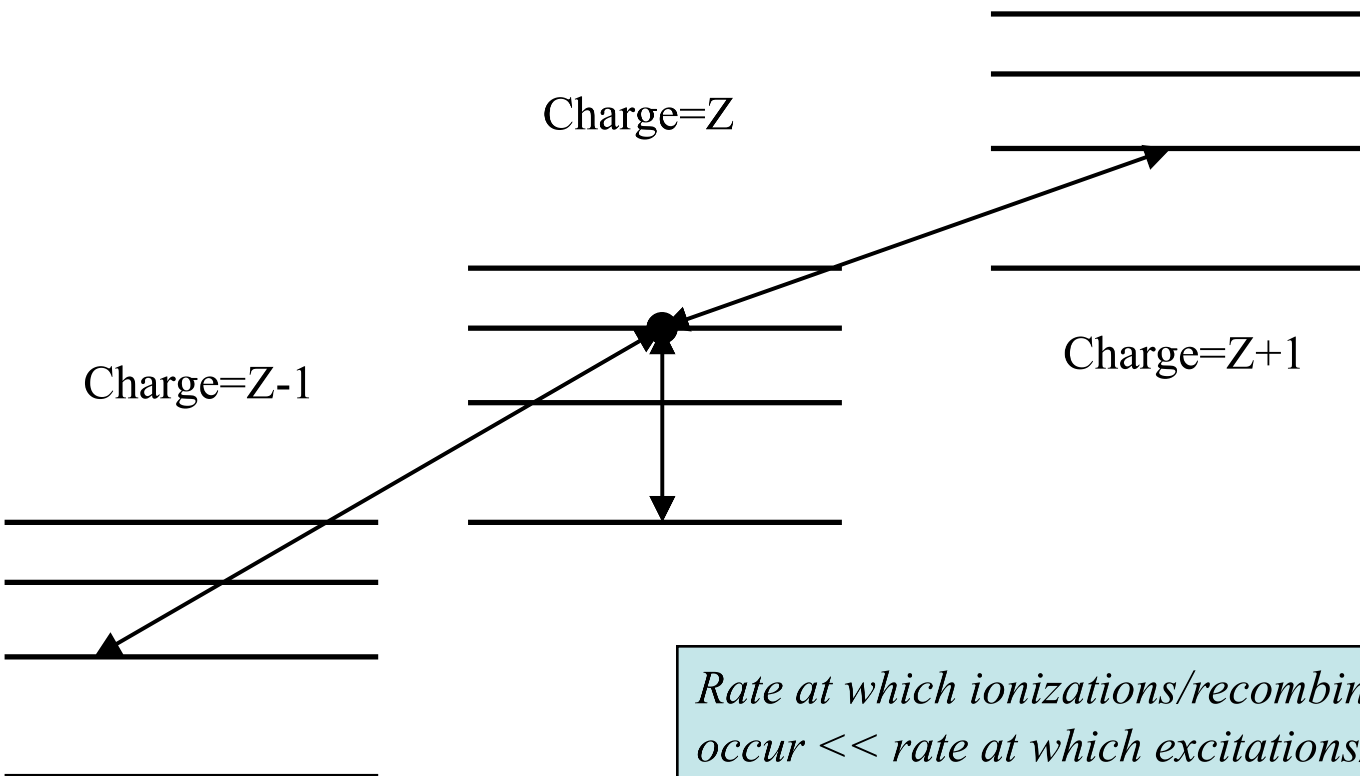
To make sense of observations need some simplifying approximations

Key approximation 1

- Only collisions of ions with **electrons** are important
- An electron collision can lead to:
  - **excitation** of level within ion
  - **ionization** of ion (removal of bound electron)
  - **recombination** of ion (capture of free electron)

Key Approximation 2

- **Ionization** balance separate from **level** balance

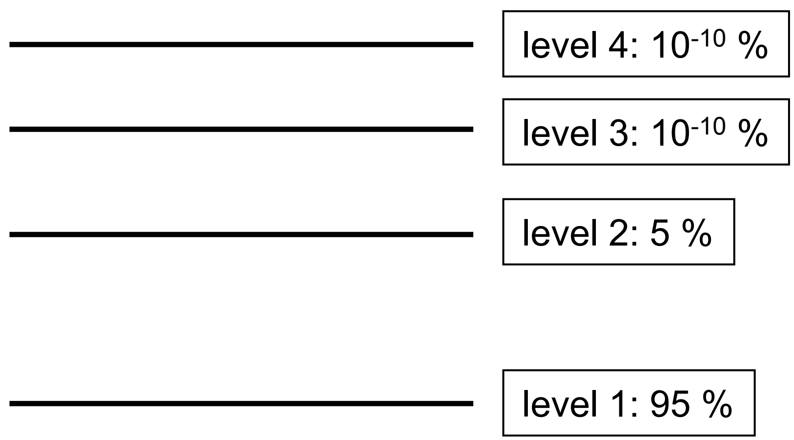


Rate at which ionizations/recombinations occur << rate at which excitations/decays occur

Key Approximation 3

- Only relevant atomic processes for **level balance** are
  - electron excitation/de-excitation
  - spontaneous radiative decay

- Low coronal density (10^8-10^{10} electrons cm^{-3}) means collisions are rare
- Typically it takes ~ 1 s to excite a level, but it decays in ~ 10^{-10} s
- Most ions have electrons in the lowest energy levels



Key Approximation 4

- Coronal plasma is **optically thin**
  - once emitted, photons are not re-absorbed

- The number of photons counted by instrument directly represents the number of photons emitted by the plasma

Emissivity and intensity

- Define the *emissivity*

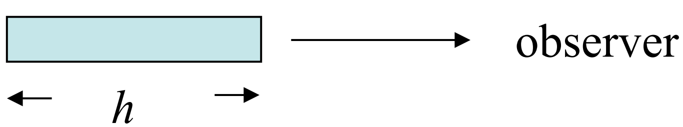
$$\varepsilon_{ij} = E_{ij} N_j A_{ji}$$

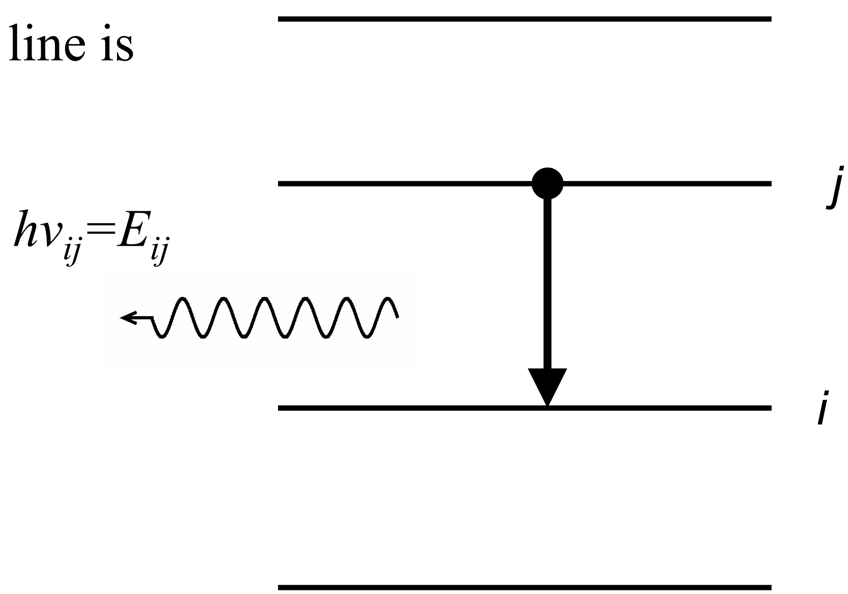
- E_{ij} is the energy for the transition; N_j is the population of level j; A_{ji} radiative decay rate (a constant)

- The *predicted intensity* of an emission line is

$$4\pi I = \int \varepsilon_{ij} dh$$

- h is the column depth





Emissivity

- The **emissivity** of an emission line is given as

$$\varepsilon_{ij} = E_{ij} N_j A_{ji}$$

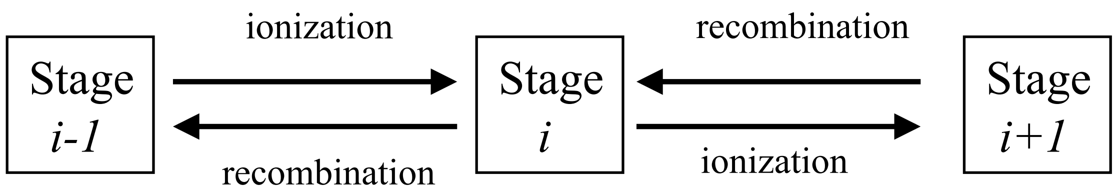
- this is re-written as (using Fe XII as example)

$$\varepsilon_{ij} = E_{ij} \frac{N_j}{N(\text{Fe XII})} \underbrace{\frac{N(\text{Fe XII})}{N(\text{Fe})}}_{F(T)} \underbrace{\frac{N(\text{Fe})}{N(\text{H})}}_{Ab(\text{Fe})} \underbrace{\frac{N(\text{H})}{N_e}}_{0.83} N_e A_{ji}$$

- $N_j/N(\text{Fe XII})$ is written as n_j, and $\sum n_j=1$

<u>*Approximation 2*</u> *→ F(T) and n_j can be separately calculated*

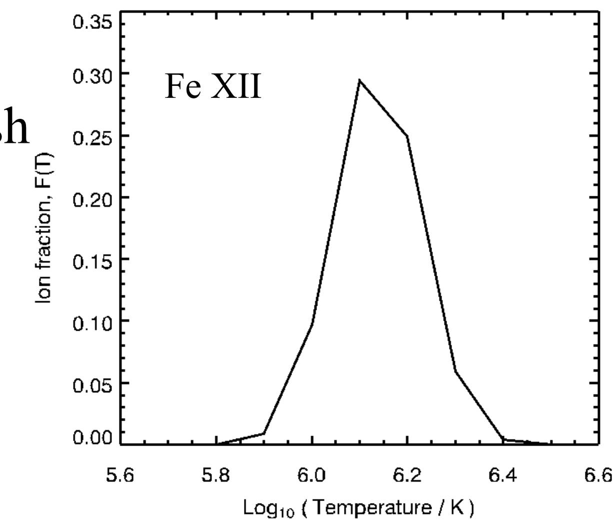
Ionization Balance



- Solving for all ionization stages, *i*, gives the **ionization fraction**

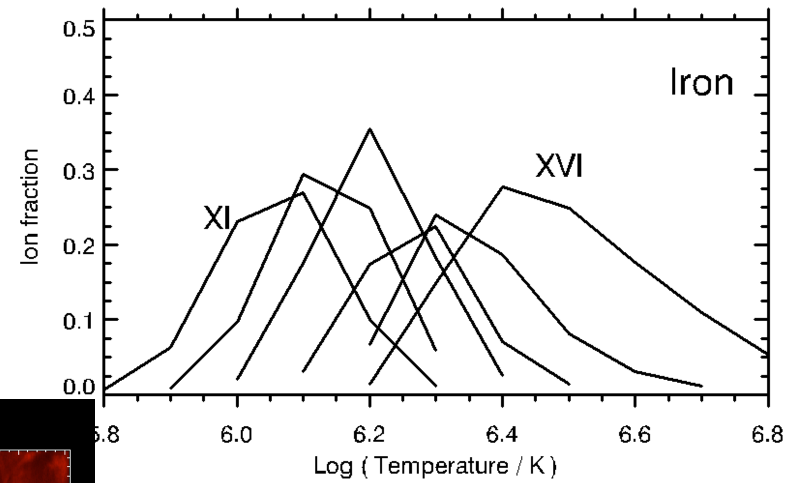
$$F_i(T) = \frac{N^i}{\sum_j N^j}$$

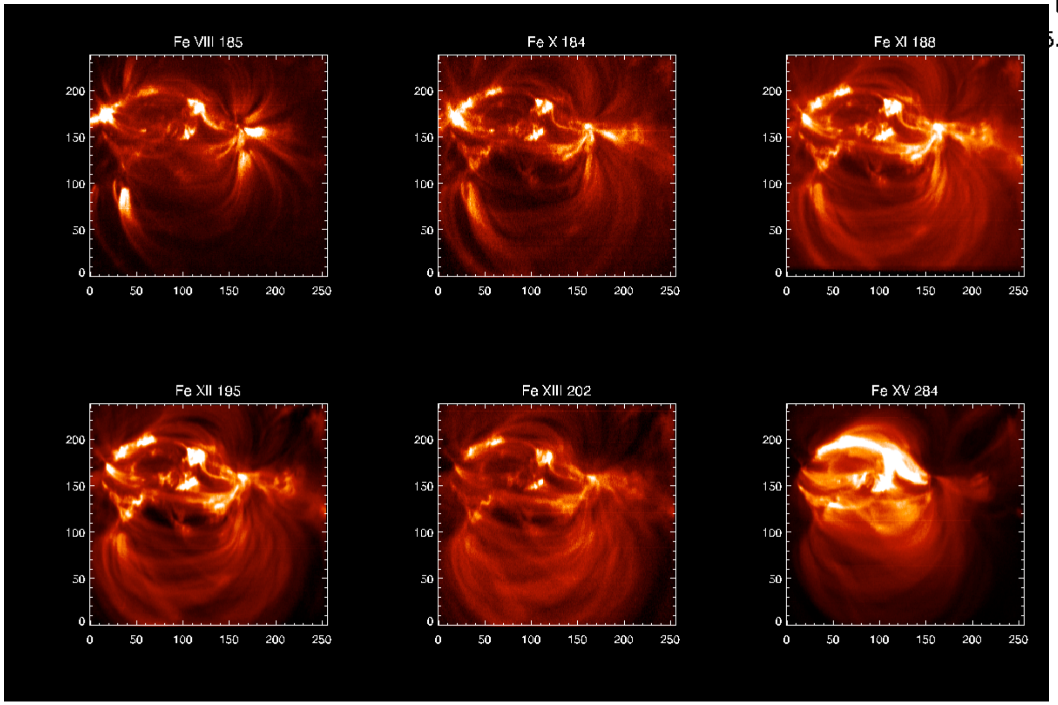
- Tables of updated ionization fractions are publish
  - Bryans et al. (2006, ApJS)
  - Mazzotta et al. (1998, A&A)
  - Arnaud & Raymond (1992, ApJS)
  - Arnaud & Rothenflug (1985, A&AS)



Ionization balance – temperature diagnostics

- Ions are generally formed over narrow temperature range
- Observing several consecutive ions allows detailed temperature structure to be seen





Level Balance Equations

$$n_i \sum_{j \neq i} \alpha_{ij} = \sum_{j \neq i} n_j \alpha_{ji}$$

(leaving level *i* = entering level *i*)

- α_{ij} is the rate at which transitions $i \rightarrow j$ occur
- solar corona: α contains (i) radiative decay rates (A_{ji}), (ii) electron excitation/de-excitation rates (q_{ij})

$$\alpha_{ij} = \begin{cases} N_e q_{ij} & (i < j) \\ A_{ij} + N_e q_{ij} & (i > j) \end{cases}$$

Level Balance Equations

- To solve the level balance equations requires atomic data

- *Energy levels* (E_j)
- *Radiative decay rates* (A-values)
- *Electron excitation rates* (q_{ij})

- Typical atomic models have 20-100 levels

- There are > 100 different ions relevant to corona, so a lot of atomic data required!

The CHIANTI database

- The first database to make atomic data generally available to solar physicists
- Collaboration between UK, US and Italy
  - K. Dere, E. Landi, H. Mason, G. Del Zanna, M. Landini, P. Young
- First released in 1996, regularly updated
  - currently on version 5.2
- Provides all atomic data necessary for modelling coronal spectra
- Freely available

www.chianti.rl.ac.uk

CHIANTI data files

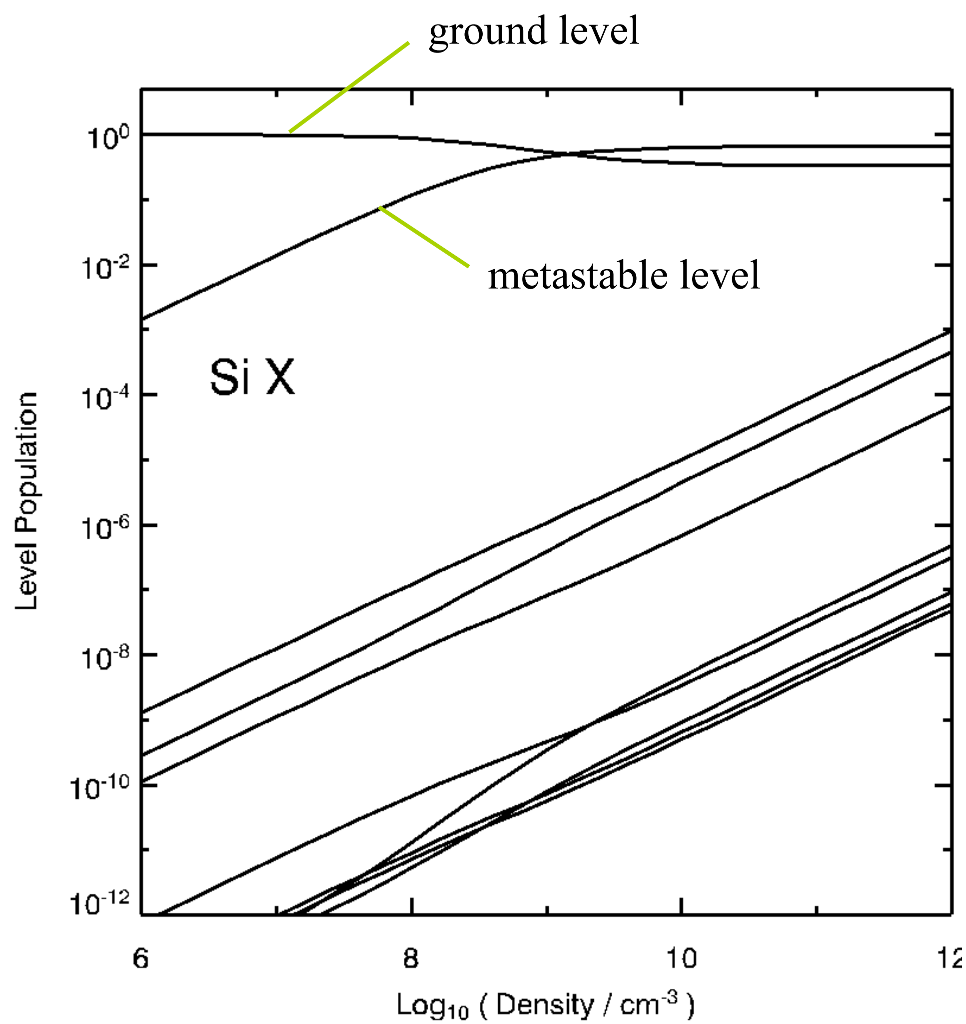
- CHIANTI is found within *Solarsoft*
  - $SSW/packages/chianti
- For each ion there is a directory, e.g., dbase/fe/fe_12
- 3 main files for each ion, e.g.,

fe_12.elvlc	Energy levels (E_i)
fe_12.wgfa	Radiative decay rates (A_{ji})
fe_12.splups	Electron collision data (q_{ij})

- Each is a text file, containing the atomic data for deriving level populations

CHIANTI: level populations

- Central purpose of CHIANTI is to calculate the level populations (n_j)
- Populations (and thus emissivities) are most strongly affected by electron density



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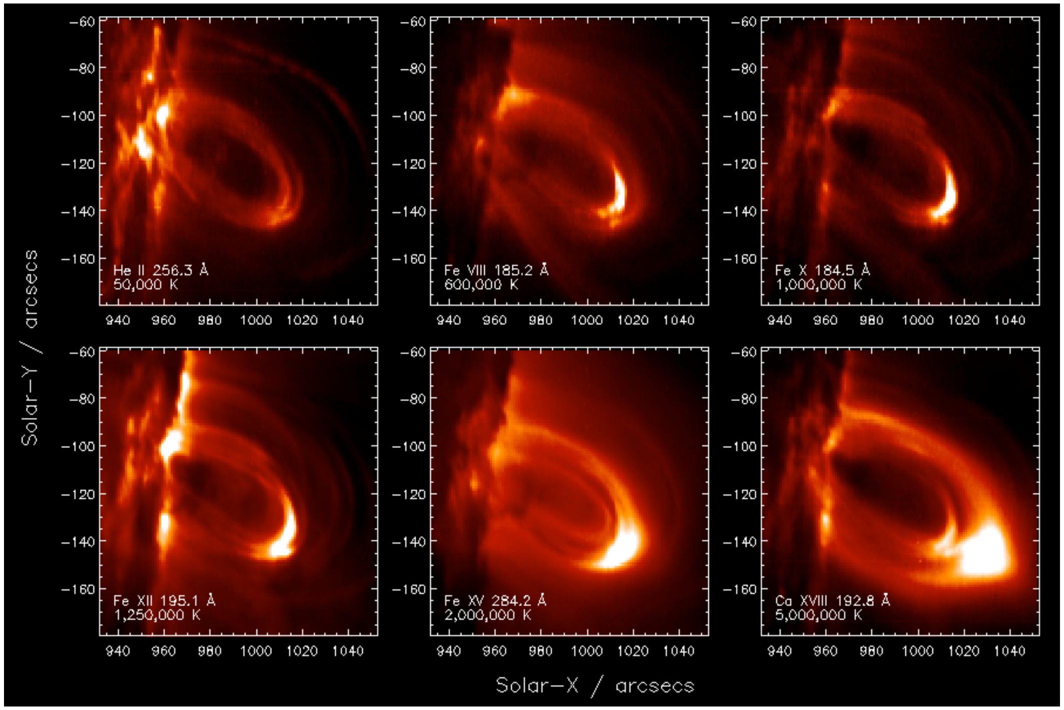
Hinode

- Japan/USA/UK mission
- Follow-up to *Yohkoh*
- 3 scientific instruments
  - X-ray imager (XRT)
  - EUV spectrometer (EIS)
  - Optical telescope (SOT)
- Launched 2006 Sep 23
- Mission aim:
  - Study the connections between fine magnetic field elements in the photosphere and the structure and dynamics of the entire solar atmosphere.

EUV Imaging Spectrometer

- UK-led instrument (PI: Louise Harra, MSSL)
- Spectra in 170-211 Å and 246-292 Å wavelength ranges
- Field-of-view: 9 x 8.5 arcmin²
- Spatial scale: 1 arcsec pixels
- Spectral scale: 0.023 Å pixels

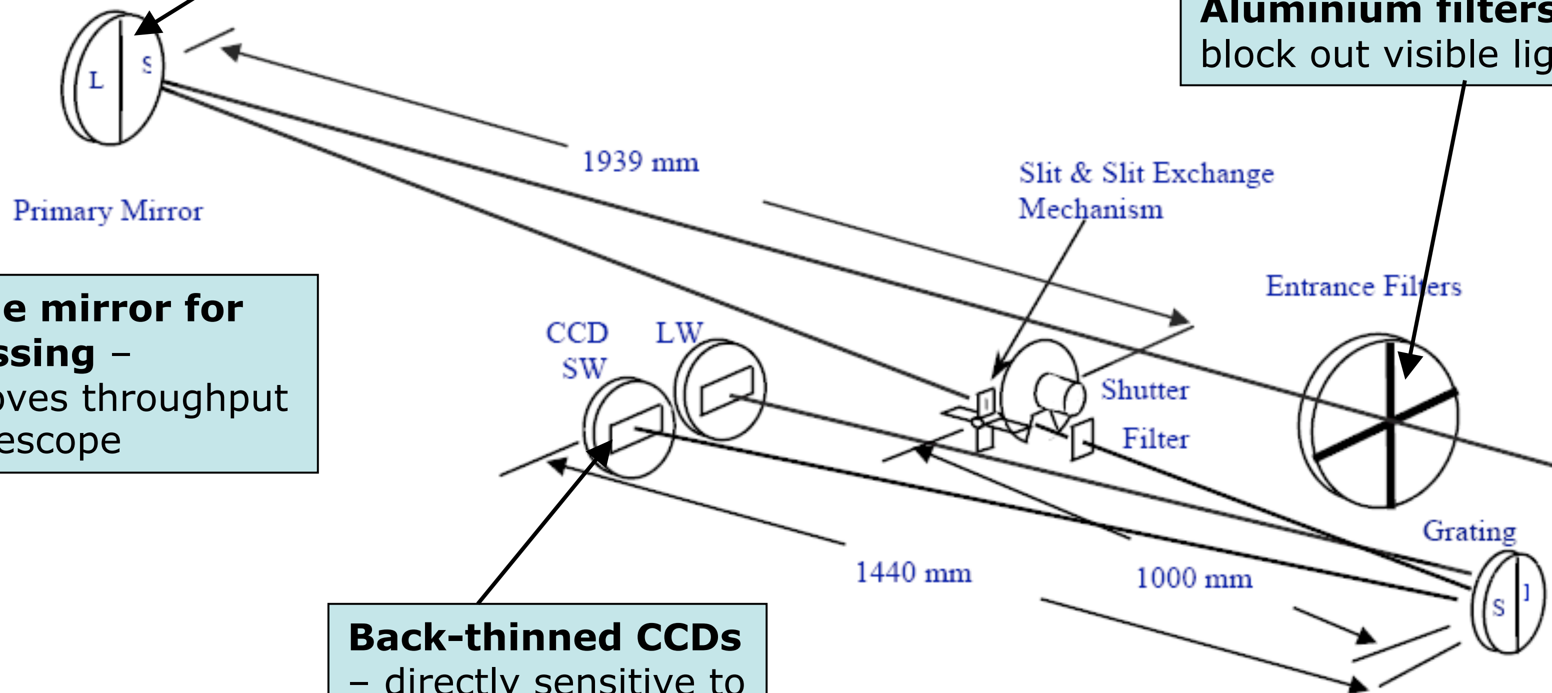


EIS: Technical Aspects

Multilayer coating – gives high reflectivity in EUV

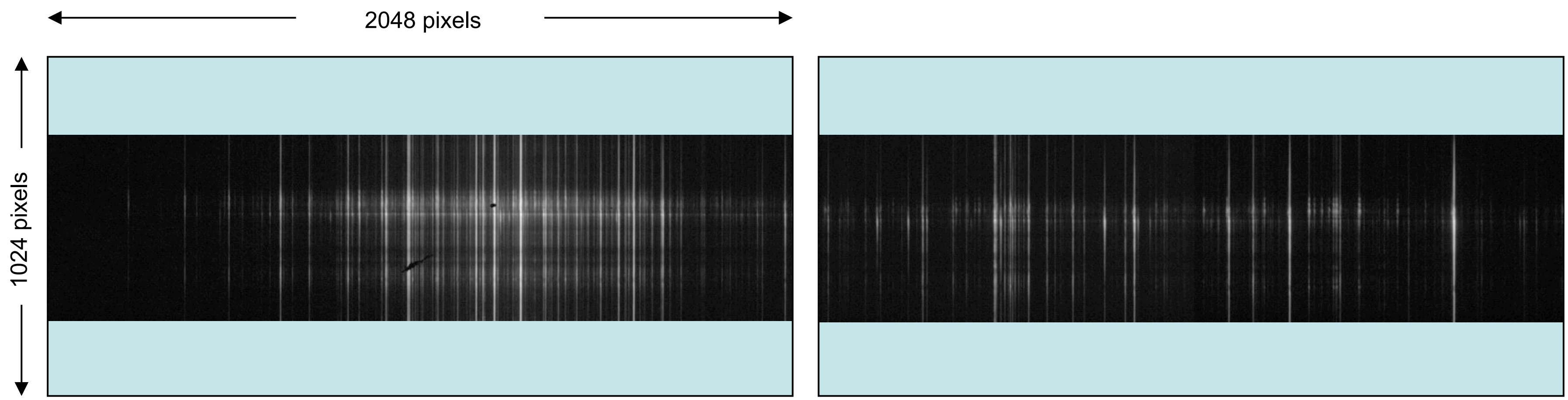
Aluminium filters – block out visible light

Single mirror for focussing – improves throughput of telescope



Back-thinned CCDs – directly sensitive to EUV radiation

What does data look like?

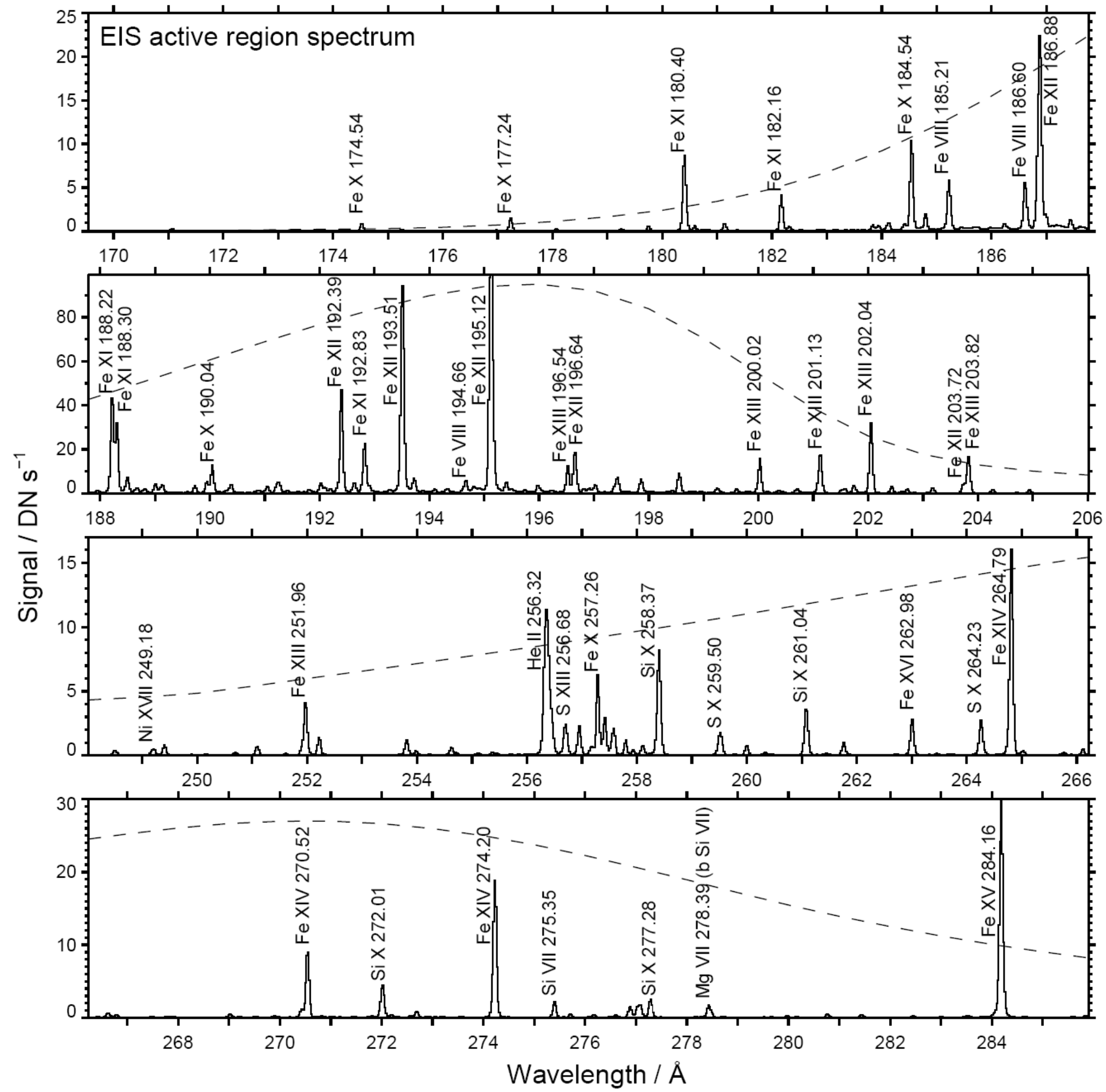


CCD-B
Short wavelength
170-211 Å

CCD-A
Long wavelength
246-292 Å

The EIS spectrum

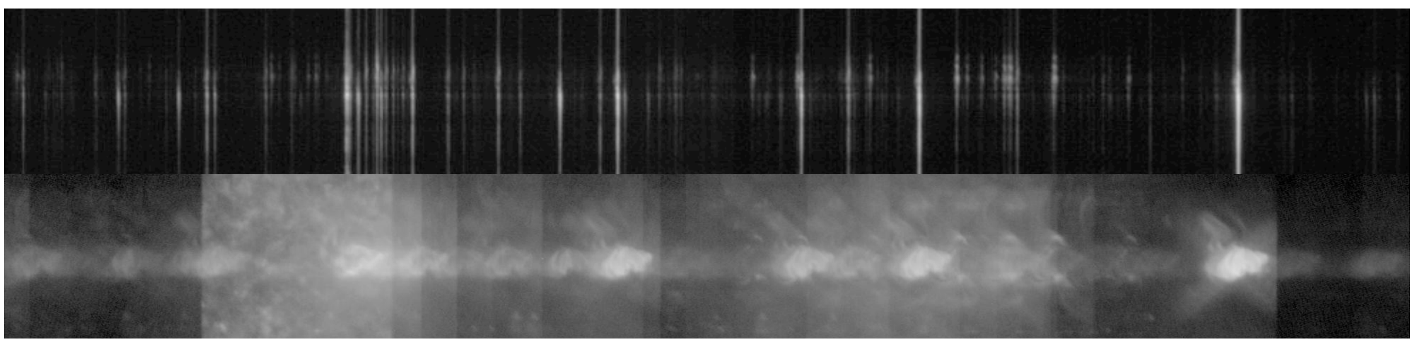
- Spectrum dominated by coronal ions (iron, particularly)
- Few useful transition region lines, but not strong



Young et al. (2007, PASJ, in press)

Different slits

- Four slits available, defined by their width
- 1” and 2” slits are for spectroscopy
- 40” and 266” slits for imaging

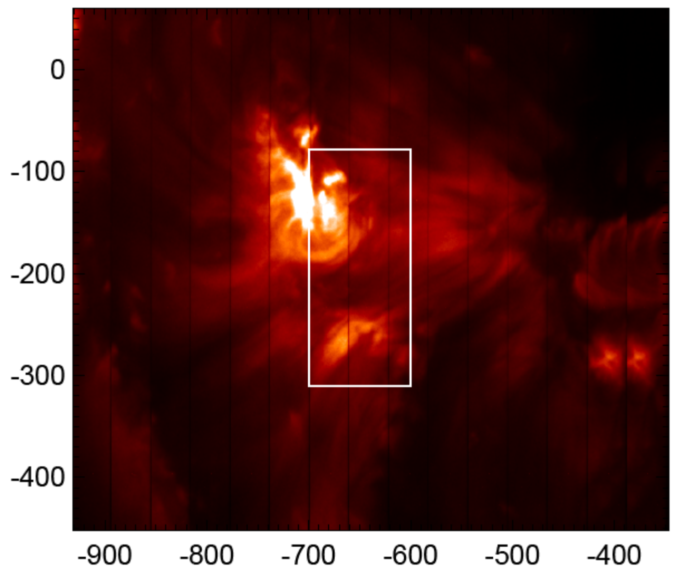


1”

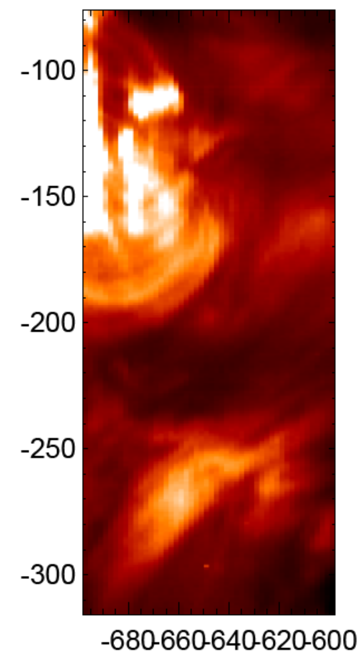
266”

Using wide slits: context images

Context slot raster, Fe XII 195
Duration: 3min 20s

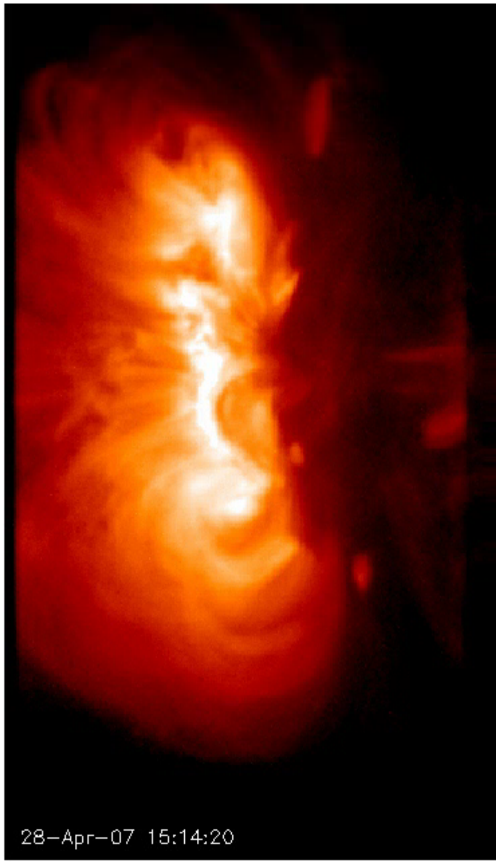


2" slit raster, Fe XII 195
Duration: 22min



266” slot movie

- The most ‘clean’ emission line for the 266” slit is Fe XV 284.16 (2 million K)



EIS wide slot movie
Fe XV 284.2 (logT=6.3)
Courtesy H. Warren (NRL)

Spectroscopy with EIS: processing the data

- Download data (all freely available)
  - http://sdc.uio.no/ [European archive]
  - http://msslxr.mssl.ucl.ac.uk:8080/SolarB/ [UK archive]
- Receive "level-zero" files, suitable for a "quick-look" but not serious analysis
- Use IDL routine **xfiles** which has several options for browsing data
- For narrow slit rasters, try 'browser' option

- To calibrate data, do:

```
IDL> eis_prep, filename, /default, /save
```

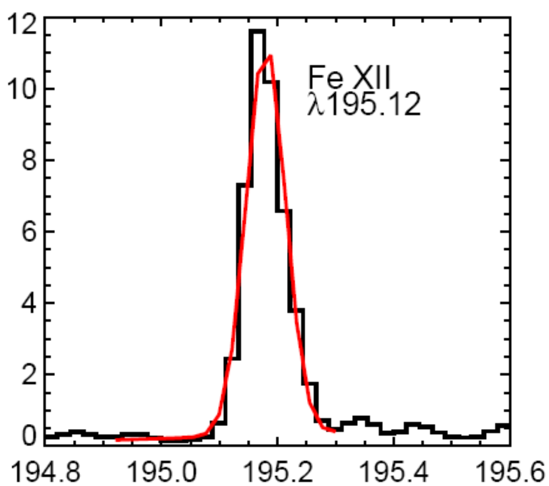
- creates a "level-one" file, suitable for science analysis

Fitting the EIS emission lines

- To automatically fit a Gaussian profile to an emission line, do:

```
IDL> wd=eis_getwindata(l1_name, 195.12)
IDL> eis_auto_fit, wd, fit, wvlpix=[194.9,195.3]
```

- output contains **intensity**, **centroid** and **width** arrays



Warning: take care with automatic Gaussian fits. Presence of nearby or blending lines can mess things up. Try **eis_fit_viewer**.

Spectroscopy

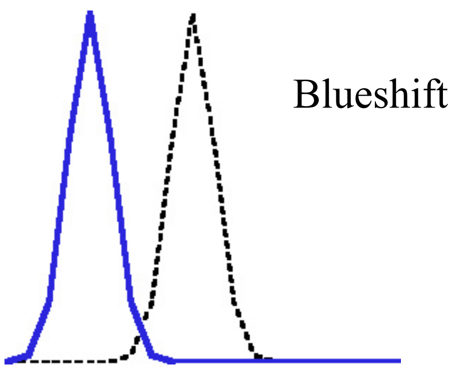
- Emission line diagnostics come in two types

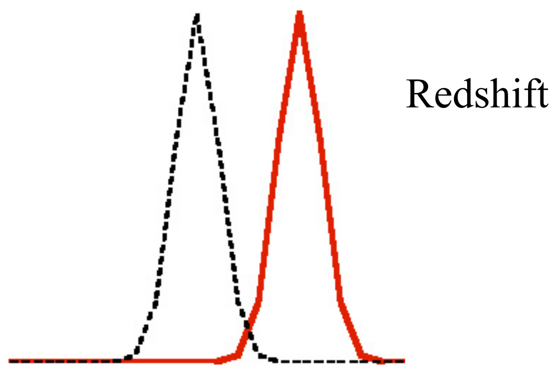
- *Study of shape and position of emission lines*
  - yields plasma velocity, broadening parameters

- *Study of emission line strengths*
  - yields temperatures, densities, abundances, emission measure
  - requires detailed atomic data

Doppler shifts

- Each emission line has a standard position (the *rest wavelength*)
- Shifts from this position imply motion of the plasma
  - *blueshifts*: towards the observer
  - *redshifts*: away from the observer





Line Width Diagnostics

- The width of emission lines can be written in velocity units as

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{c}$$

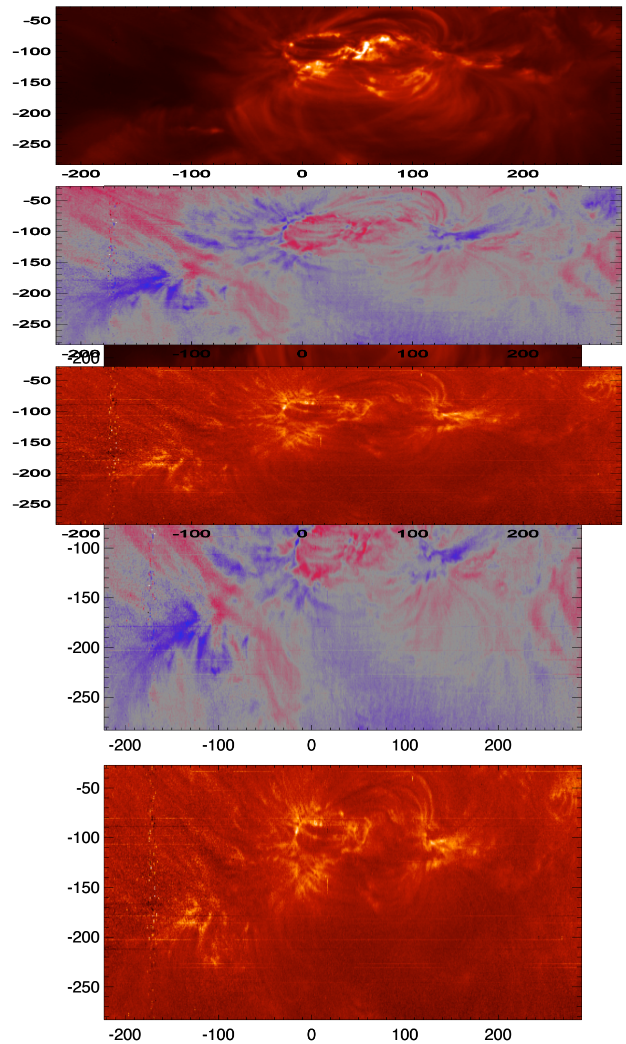
- The components of Δv are written as

$$\Delta v^2 = \Delta v_{\mathrm{I}}^{\;2} + \frac{2kT}{M} + \xi^2$$

- where
  - Δv_{I} is the instrumental width
  - $2kT/M$ is the thermal width
  - ξ is the non-thermal velocity

Intensity, velocity and line width maps

- Active region map
  - Fe XII 195.12 Å
  - 2006 Dec 2

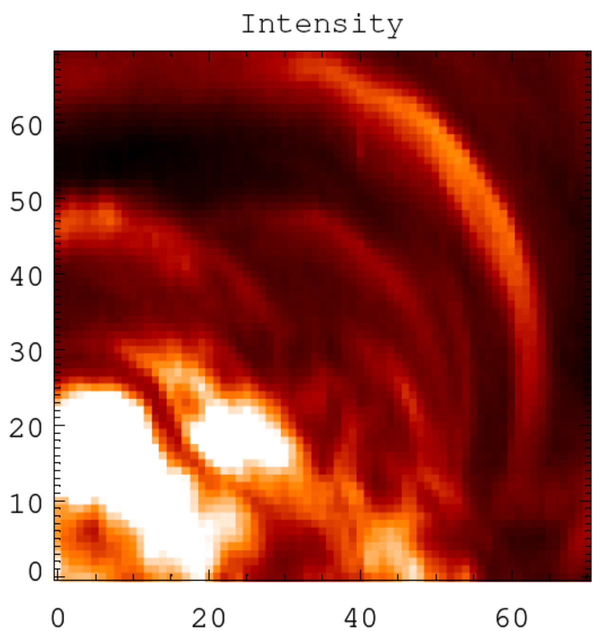


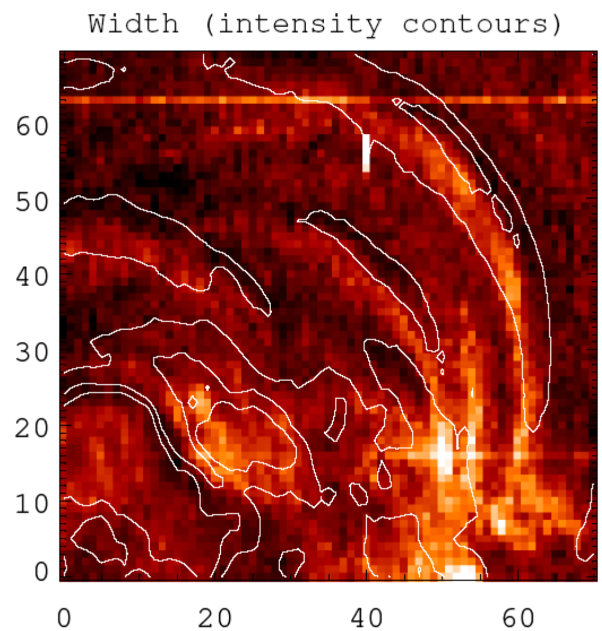
Intensity

Velocity

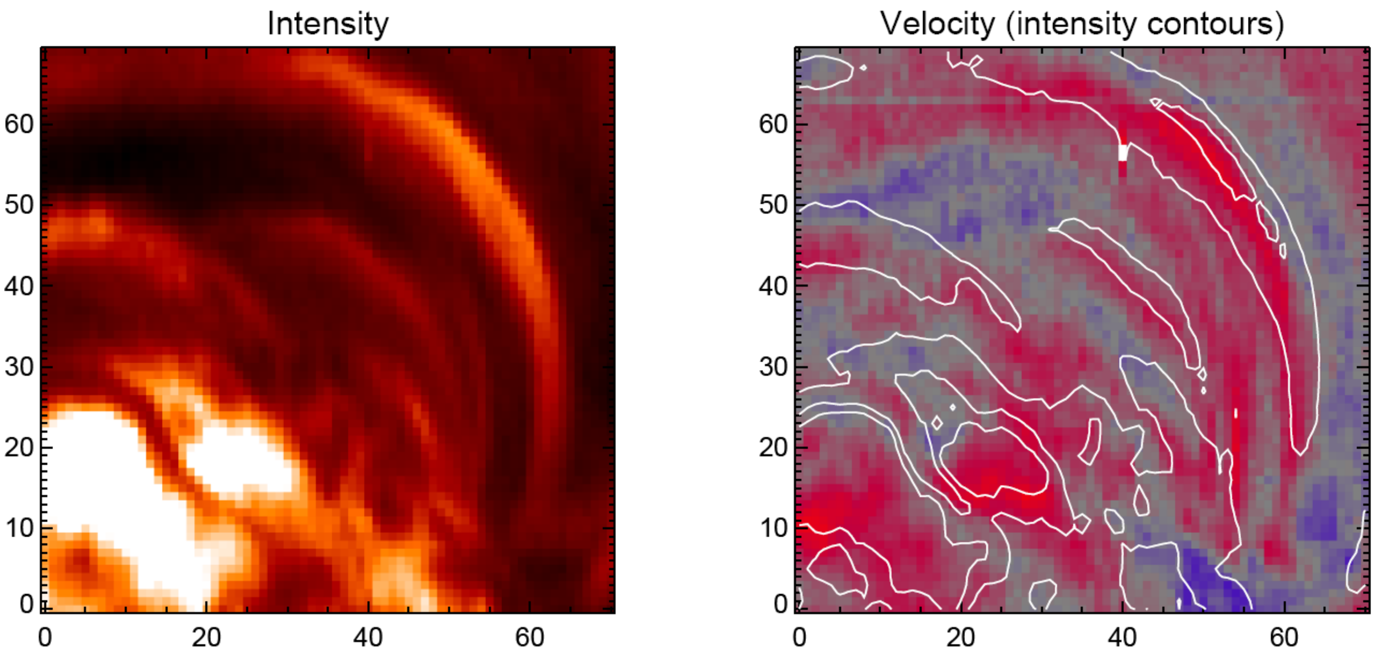
Width

Closeup of loop: line width





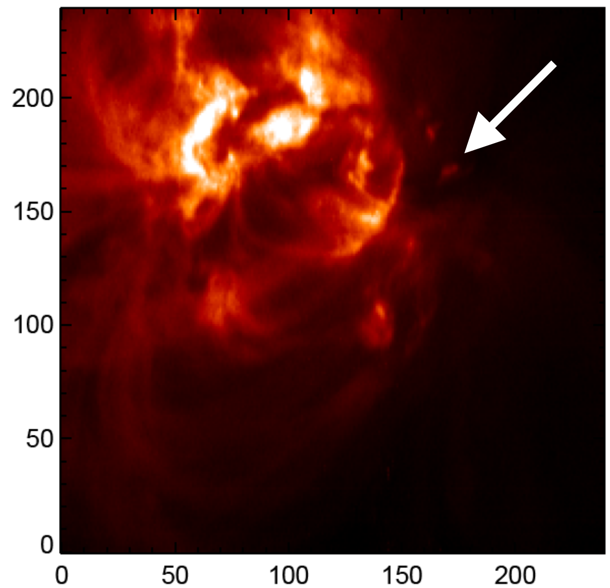
Closeup of loop: velocity

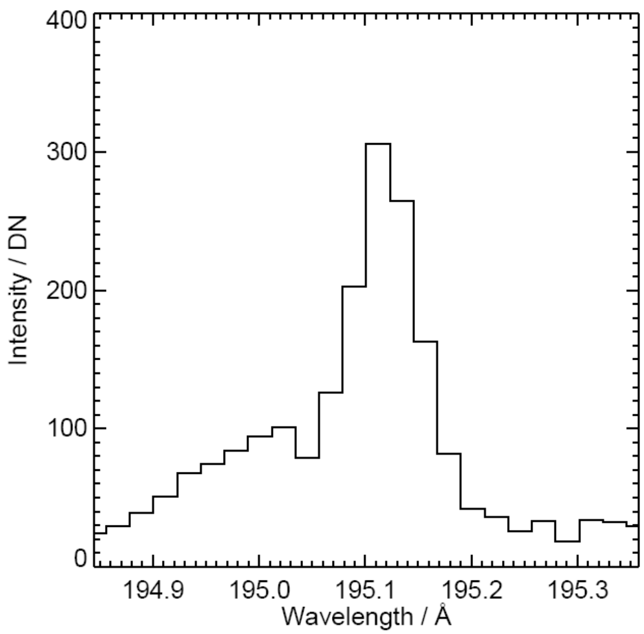


Caution: non-Gaussian profiles

- Line profiles are not always Gaussian

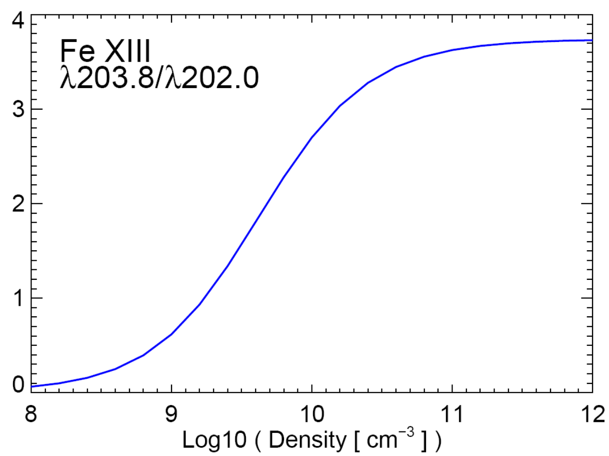
Fe XII 195 image

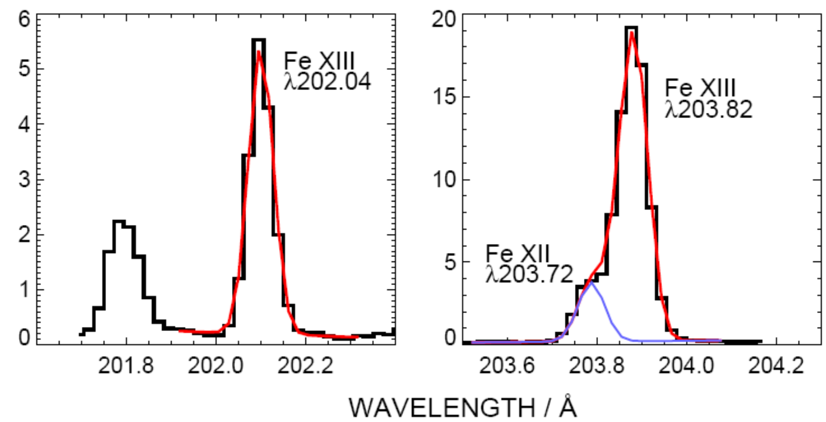




Line Ratio Diagnostics - Density

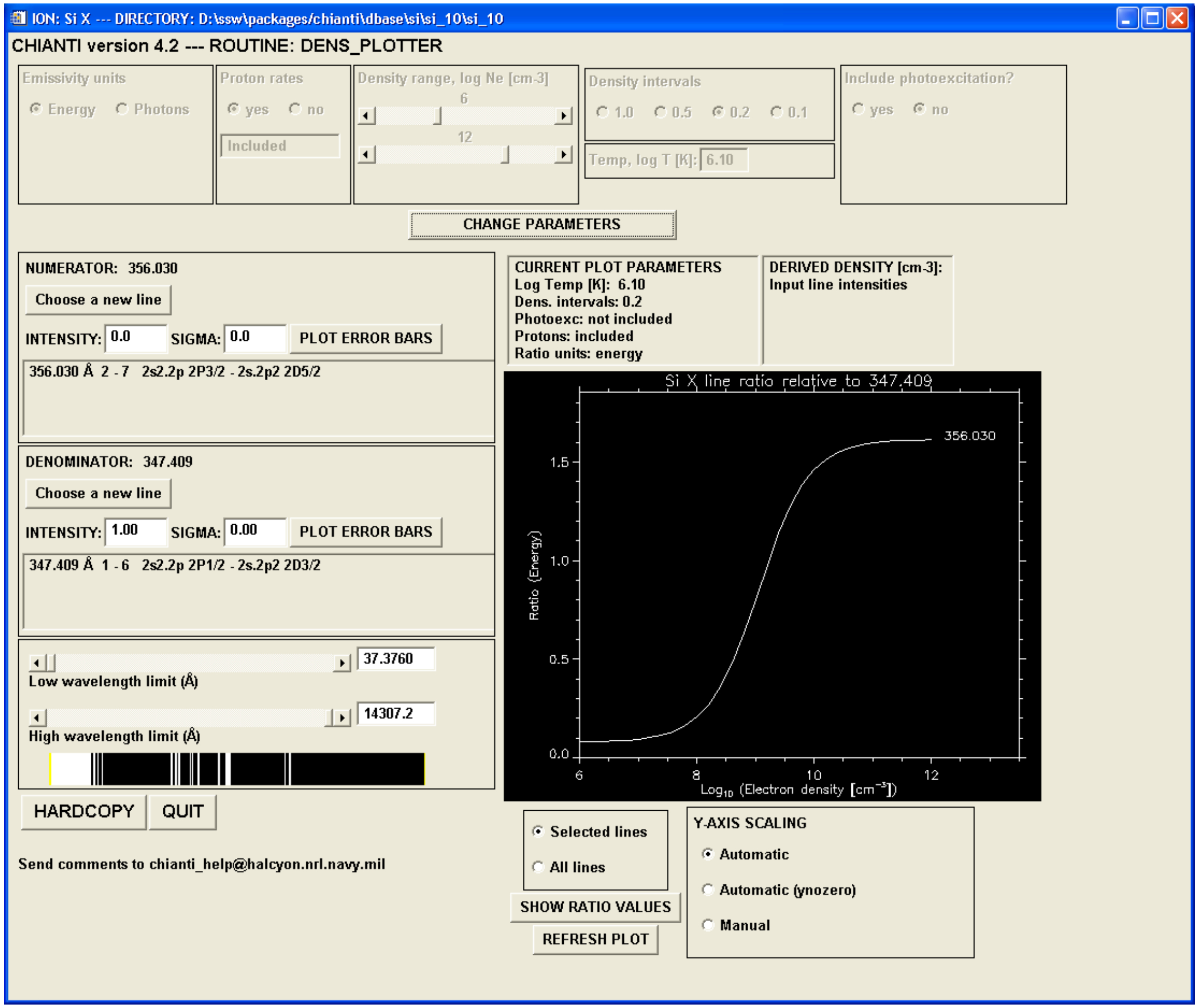
- Certain ratios of emission lines from the same ion are sensitive to the **electron density**
  - density is derived purely from atomic physics parameters
  - no assumptions for element abundances, plasma morphology, etc.





Question: why is electron density important? what about total density?

CHIANTI software

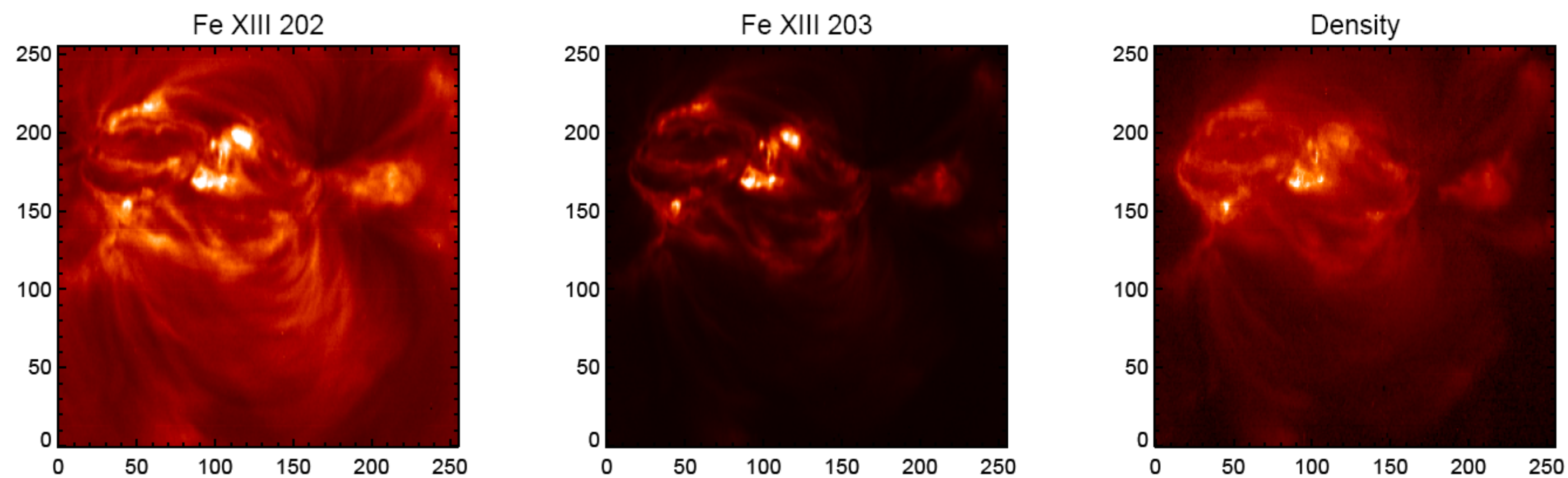


DENS_PLOTTER
CHIANTI IDL tool for studying density diagnostics

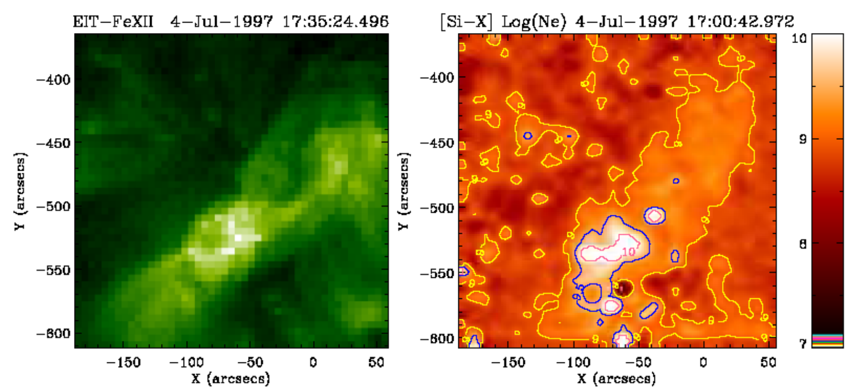
IDL> dens_plotter,'fe_13'

Active region density map

- The high quality of the EIS data makes density maps easy to generate

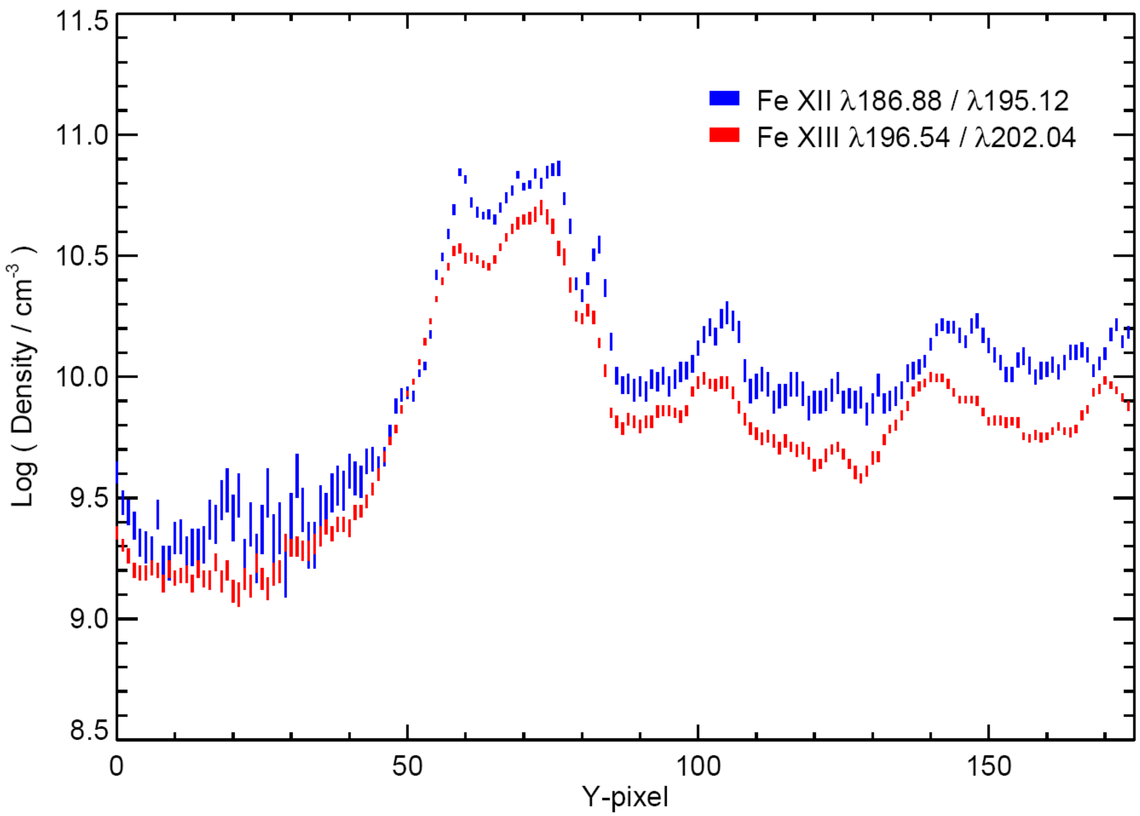


Density map from
SOHO/CDS
(Tripathi et al. 2006)



Recommended density diagnostics

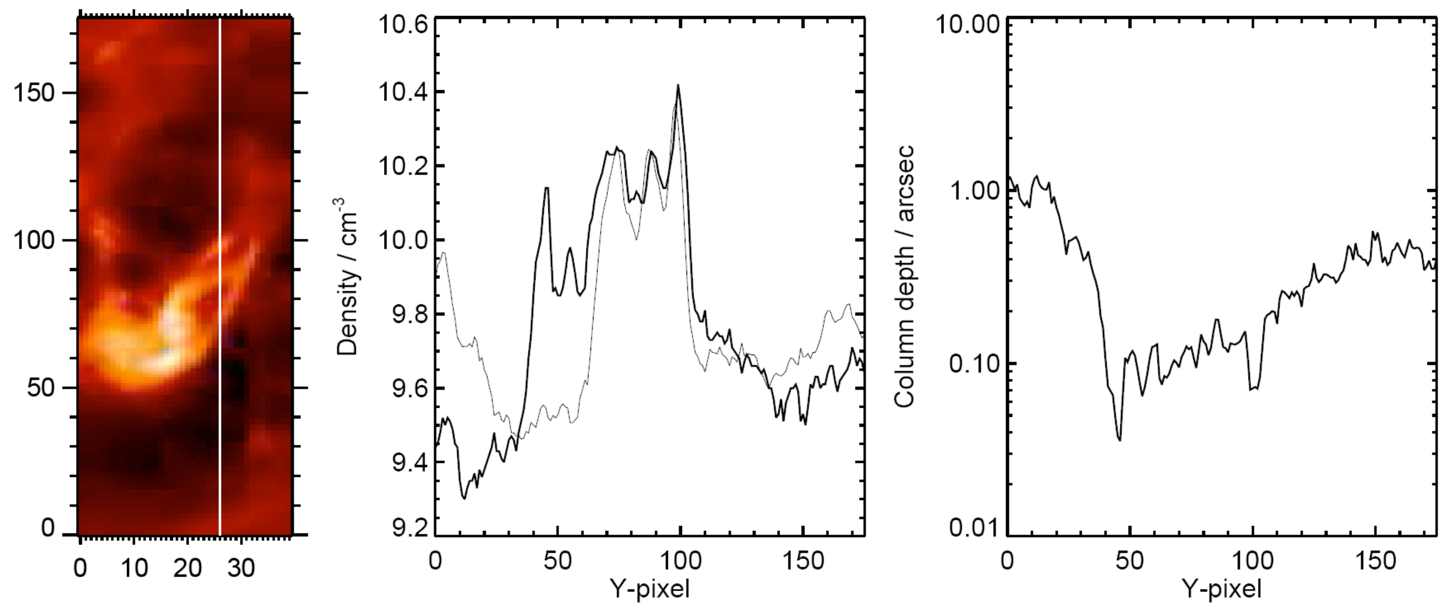
- Best diagnostics to use:
  - Fe XII 186.88 Å/195.12 Å
  - Fe XIII 196.54 Å/202.04 Å



From density to column depth to filling factor

- Once density has been measured, can estimate **column depth** (h) of plasma at each pixel

$$4\pi I = 0.83 E_{ij} Ab(Fe) F(T) n_j(N_e, T) A_{ji} N_e h$$



- with geometry assumptions can also get **filling factor**

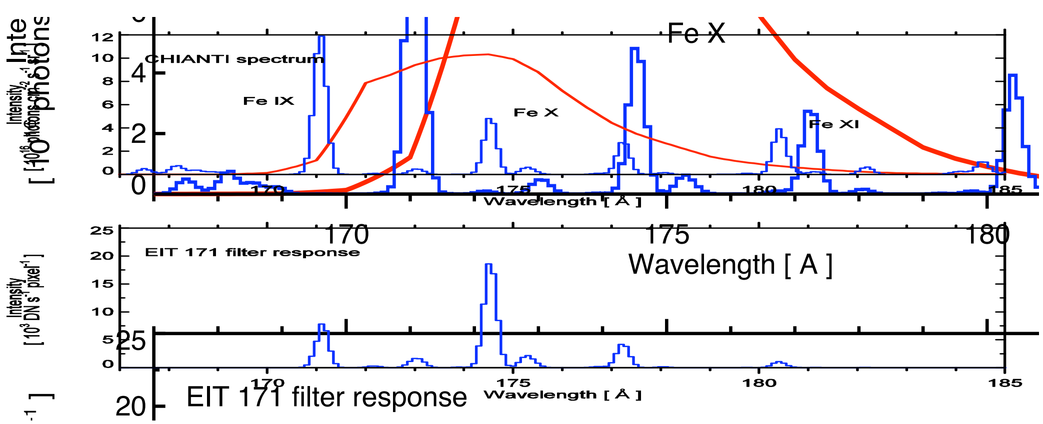
Overview

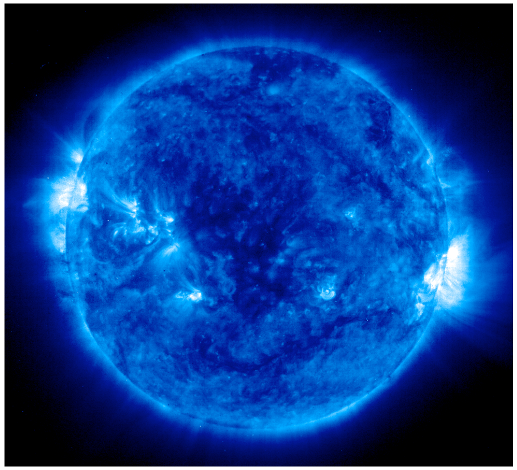
- Ultraviolet radiation
- Atomic physics in the Sun's atmosphere
- Application to Hinode/EIS
- **Limitations of imaging instruments**
- Using atomic data in theoretical models

Limitations of imaging instruments

- Using images from EIT/TRACE/EUVI is much easier than analysing spectra!

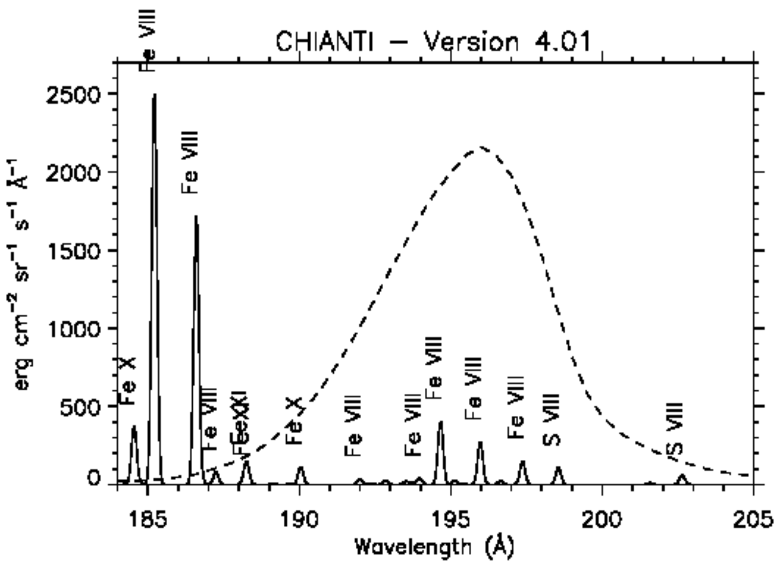
- EIT/TRACE/EUVI have filters to select particular emission lines (e.g., Fe IX 171, Fe XII 195)
- *but*, the solar EUV spectrum is crowded
- other emission lines can ‘contaminate’ the wavebands

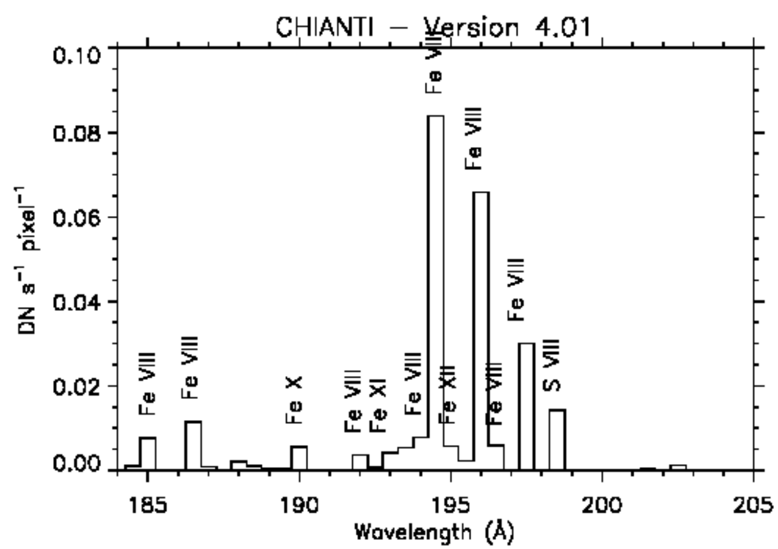




EIT & TRACE 195 band

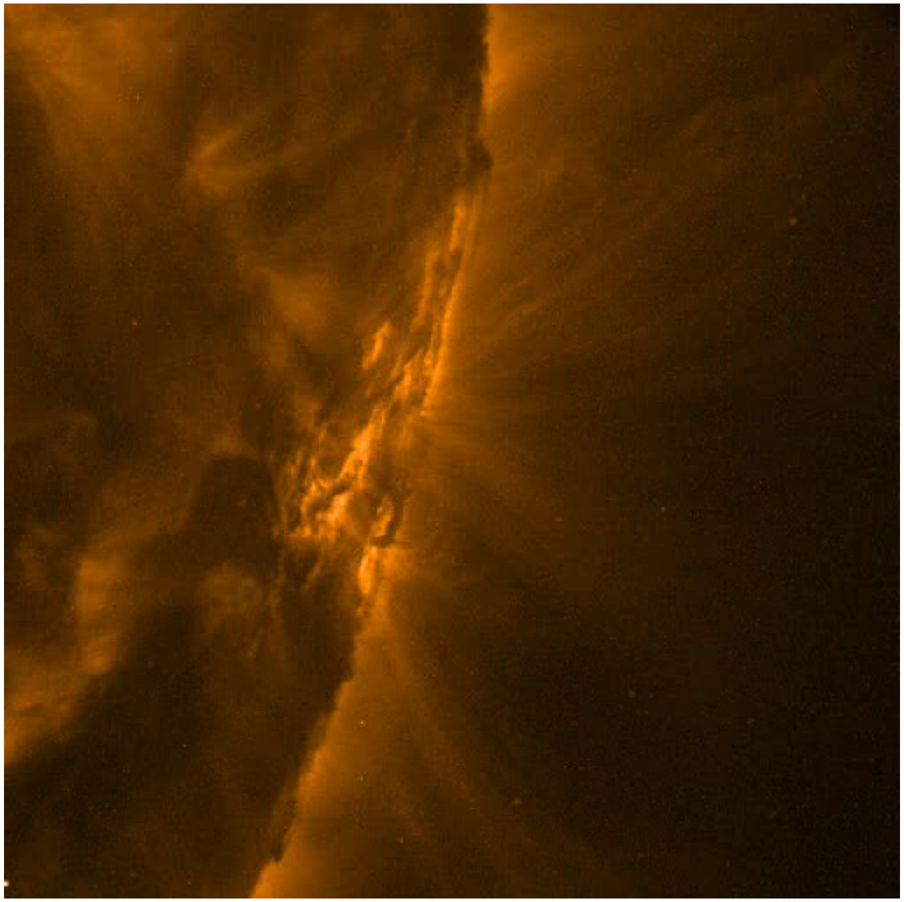
- In most cases the EIT and TRACE 195 band is dominated by Fe XII emission implying temperatures of ≈ 1.5 million K
- At temperatures < 1 million K, there is no Fe XII emission and Fe VIII dominates the 195 band (Del Zanna & Mason 2003)
- Fe VIII is formed around 600,000 K





TRACE: Fe XII & Fe XXIV

- At flare temperatures (~10 million K) a strong Fe XXIV line appears in TRACE 195 band



Overview

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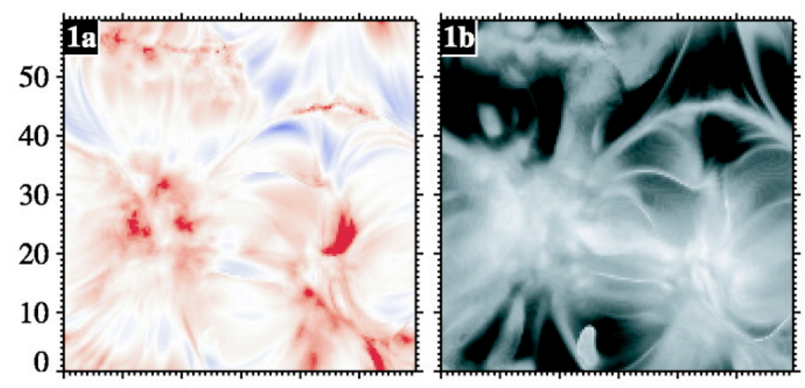
Using atomic data in theoretical models

- Theoretical models that make predictions for the solar spectrum are becoming popular
  – method referred to as **forward modelling**
- If the model predicts temperature, density and emitting volume then emitted spectrum can be predicted using CHIANTI

- Examples:
  – Bradshaw & Mason (2003, A&A)
  – Peter, Gudiksen & Nordlund (2006, A&A)

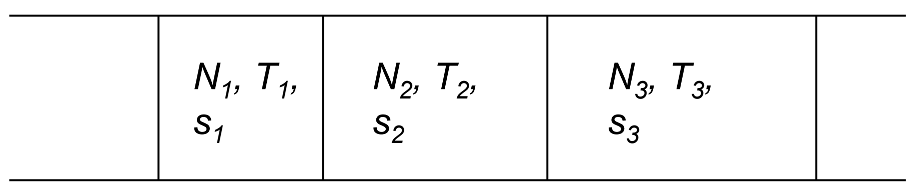


Method for using CHIANTI

- Write out a table giving theoretical emissivities for the emission lines of interest
  - tabulated as function of temperature and density
  - use CHIANTI routine EMISS_CALC.PRO

- Modelling code reads in table, assigning appropriate emissivities to the model elements

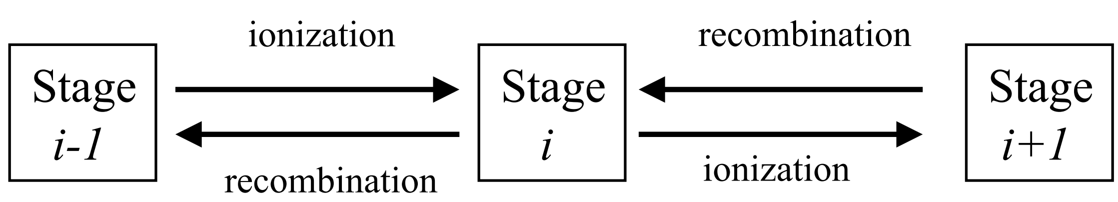
loop divided into elements of variable size



Non-equilibrium ionization balance

- Dynamic plasmas will often by out of equilibrium
- 1st order approximation:
  - ionization/recombination out of equilibrium (time dependent)
  - level balance remains in equilibrium

- Emissivity tables can still be used
- Ion balance needs to be generated dynamically
  - see Bradshaw & Mason (2003, A&A, 401, 699)



End of Talk

- Atomic data is vital for understanding the Sun
- The CHIANTI database provides assessed atomic data for use in analysing spectra and also for modelling

- The spectra from the UK-led Hinode/EIS are superb and present many opportunities for new science