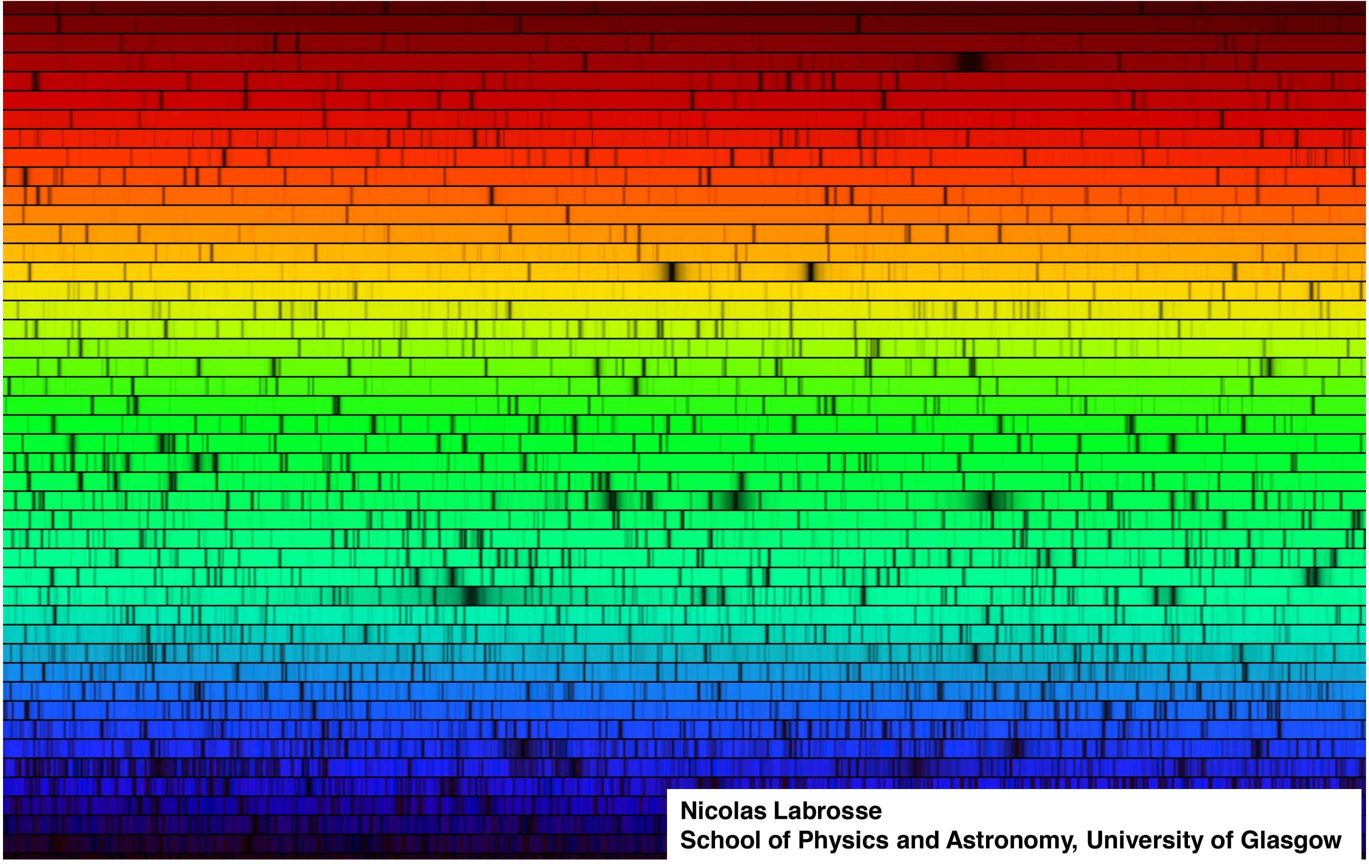
Solar radiation and plasma diagnostics



Nicolas Labrosse
School of Physics and Astronomy, University of Glasgow

University of Glasgow

Outline

I – Solar radiation

II – Plasma diagnostics

(III – Arbitrary selection of research papers) <- If time allows!

I. Solar radiation

I.1 Overview

I.2 Radiation basics

I.3 Radiative transfer

I.4 How is it formed?

I.5 How do we detect it?

I.1 Overview

- **Basic facts**
  - Too many photons for your naked eyes!
  - Optical telescopes show the visible surface (photosphere)
    - Has particular features such as sunspots (appear dark)
  - Spectroscopy (late 1800s) allowed the chromosphere to be studied
  - Although the corona can be observed during eclipses, most of our knowledge comes from
    - Radio observations: patchy microwave emission
    - Soft X-rays: diffuse emission over solar disk except in coronal holes
    - Hard X-rays: bright in localised areas (active regions)

I.2 Radiation basics

- **Radiation field in the solar atmosphere**

– Amount of radiant energy flowing through unit area per unit time per unit frequency and per unit solid angle: intensity I_ν

– If radiation field is in thermal equilibrium with surroundings (a closed cavity at temperature T): blackbody radiation

Planck function

$$\boxed{I_\nu = \frac{2\pi h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1} \equiv B_\nu(T)} \quad \mathrm{erg\ s^{-1}\ cm^{-2}\ sr^{-1}\ Hz^{-1}}$$

– Deep in the solar atmosphere, local thermodynamic equilibrium holds, and mean free path of photons is short (a few km): photons within a small volume can be considered to be contained in a cavity where the temperature is ~ constant.

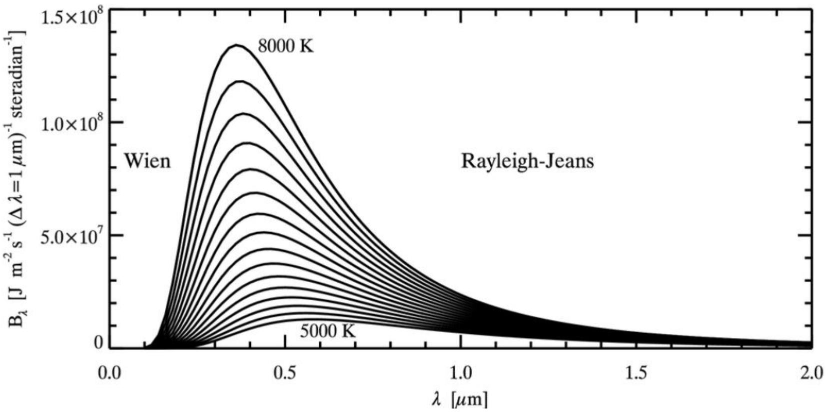
I.2 Radiation basics

- **Radiation field in the solar atmosphere**

Approximations

Wien: $B_\nu(T) \approx \frac{2h\nu^3}{c^2}\,\mathrm{e}^{-h\nu/kT}$

Rayleigh-Jeans: $B_\nu(T) \approx \frac{2\nu^2 kT}{c^2}$



From Rutten's notes

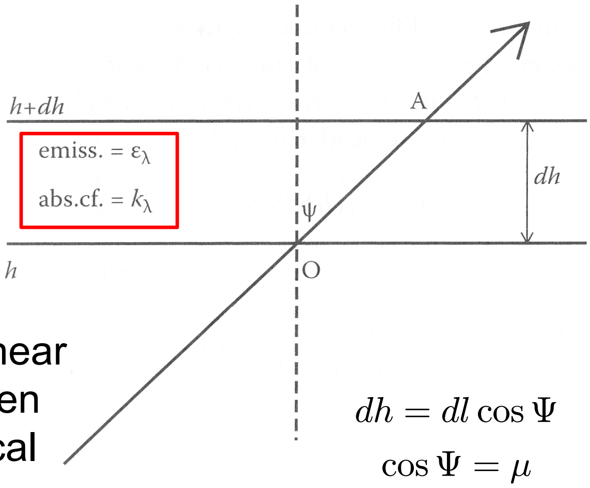
I.3 Radiative transfer

- **The interaction of the radiation field with the plasma is described by the Radiative Transfer Equation**

– Medium emits radiant energy at rate ϵ_λ erg cm^{-3} s^{-1} sr^{-1} Å^{-1}

– and absorbs radiant energy k_λ is the linear absorption coefficient in cm^{-1}

– If a beam of radiation with intensity $I_\lambda(0)$ enters a uniform slab of linear thickness x, the emergent radiation is then $I_\lambda(x)$=$I_\lambda(0)$ e$^{-\tau}$, where τ=k_λ x is the optical depth of a uniform slab at wavelength λ. E.g. k$_\lambda$=10^{-6} cm^{-1} around 5000 Å



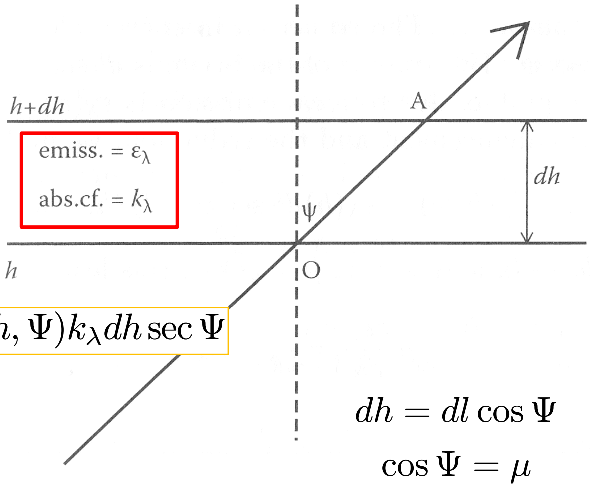
$$dh = dl\cos\Psi$$
$$\cos\Psi = \mu$$

I.3 Radiative transfer

- **The interaction of the radiation field with the plasma is described by the Radiative Transfer Equation**

– More generally we have $\tau = \int k_\lambda dx$

– Radiation propagating through the slab along OA varies between h and h+dh due to absorption and emission:



$$I_\lambda(h+dh,\Psi) - I_\lambda(h,\Psi) = \epsilon_\lambda(h)dh\sec\Psi - I_\lambda(h,\Psi)k_\lambda dh\sec\Psi$$

– In the limit where $dh\rightarrow 0$, we get

$$\mu\frac{dI_\lambda}{dh} = \epsilon_\lambda - k_\lambda I_\lambda$$

$$dh = dl\cos\Psi$$
$$\cos\Psi = \mu$$

I.3 Radiative transfer

- **The interaction of the radiation field with the plasma is described by the Radiative Transfer Equation**

$$\mu \frac{dI_\lambda}{dh} = \epsilon_\lambda - k_\lambda I_\lambda$$

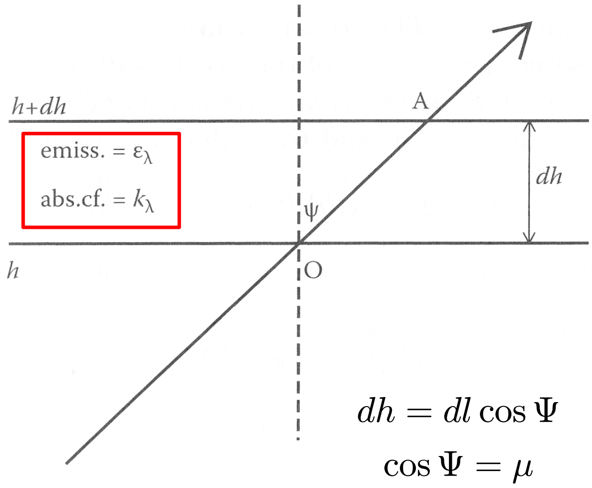
– Finally, in the solar atmosphere, the optical depth at height h' is

$$\tau_\lambda(h') = \int_\infty^{h'} k_\lambda dh$$

– The radiative transfer equation is then

$$\boxed{\mu \frac{dI_\lambda}{d\tau_\lambda} = I_\lambda - S_\lambda} \quad \textbf{RTE}$$

with the source function $S_\lambda = \epsilon_\lambda / k_\lambda$



$$dh = dl \cos \Psi$$

$$\cos \Psi = \mu$$

I.3 Radiative transfer

- **Solutions to the Radiative Transfer Equation** $\boxed{\mu \frac{dI_\lambda}{d\tau_\lambda} = I_\lambda - S_\lambda}$

– The intensity of radiation flowing through the upper atmosphere (relative to the point where the optical depth is τ) is given by

$$I(\tau, \mu+) = -e^{\tau/\mu} \int_\infty^\tau \frac{S(t)}{\mu} e^{-t/\mu} dt$$

– If $\tau \rightarrow$ 0 then

$$I(0, \mu+) = \int_0^\infty \frac{S(t)}{\mu} e^{-t/\mu} dt$$

- If S is constant at all depths: $I(0, \mu+) = S$
- If S is constant in only a small slab of optical thickness τ': $I(0, \mu+) = S(1 - e^{-\tau'/\mu})$ emergent intensity not as large as S; reduced by optical depth term. If τ' is very small, then $I(0, \mu+) = S\tau'/\mu$

In the case of constant source function, the emergent intensity from a slab cannot be greater than S, but may be much smaller than S if the optical depth is small.

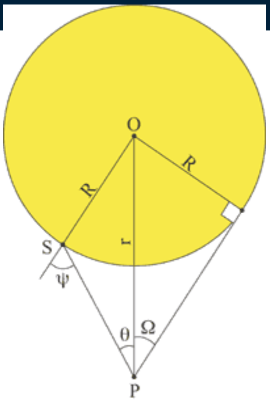
I.3 Radiative transfer

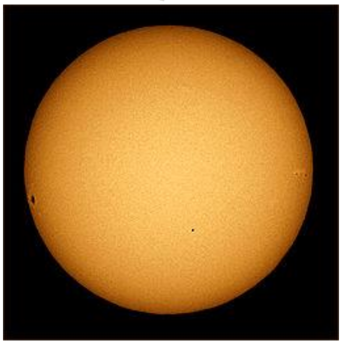
- **Solutions to the Radiative Transfer Equation**

- If S is not constant at all depths: taking $S(\tau) = a + b\tau$ one finds $I(0, \mu+) = a + b\mu$

This solution matches the limb darkening of the Sun!

- This particular form of the source function is actually a natural consequence of the assumption of a Gray atmosphere, where the opacity is independent of wavelength.
- This results in the Eddington-Barbier relationship:
  the intensity observed at any value of μ equals the source function at the level where the local optical depth has the value $\tau = \mu$.
  It means that you see deeper in the atmosphere as you look towards the centre (μ=1) than towards the limb ($\mu \rightarrow 0$).
- Limb darkening and EB also imply that T increases with τ

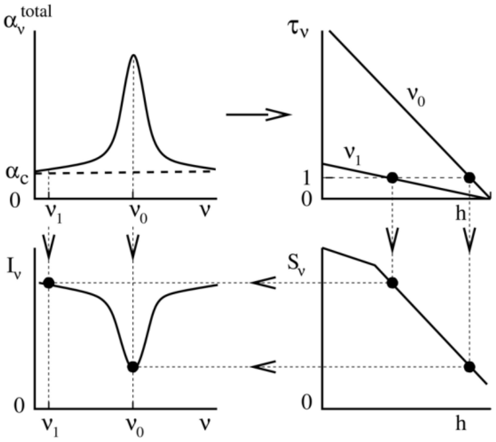




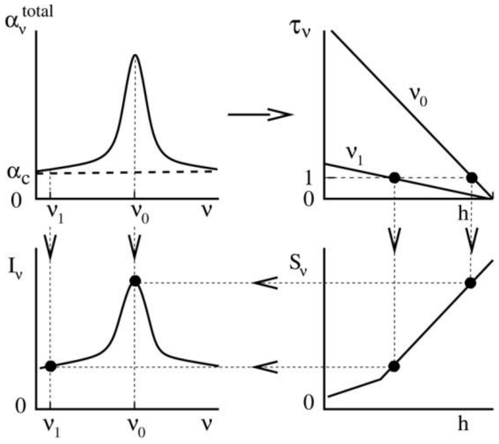
I.4 How is it formed?

- **From Rob Rutten's notes**

Simple absorption line



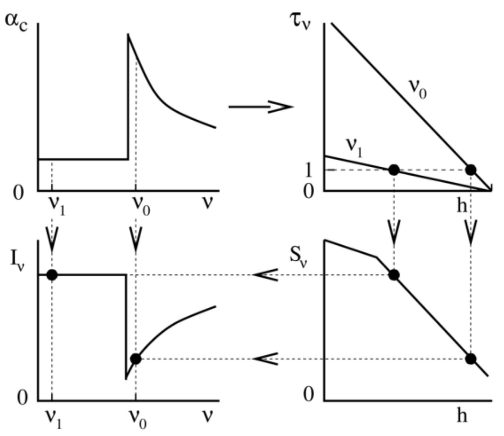
Simple emission line



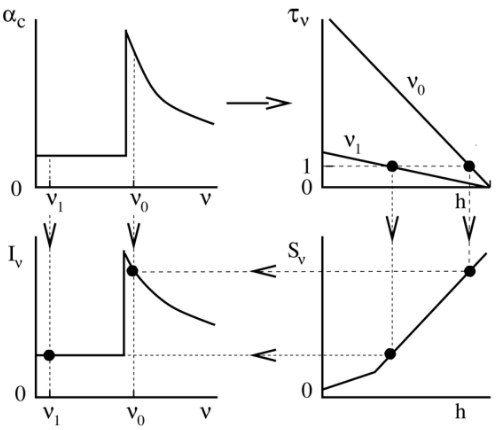
I.4 How is it formed?

- **From Rob Rutten's notes**

Simple absorption edge



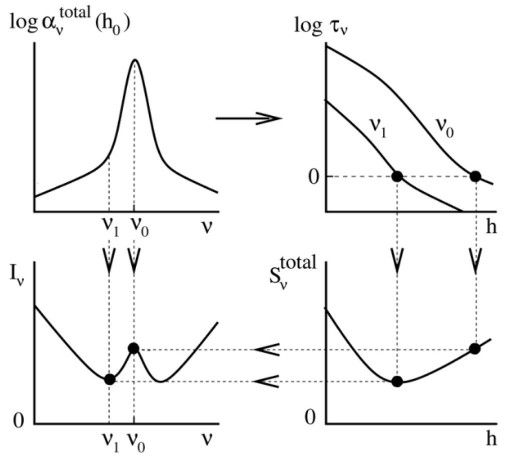
Simple emission edge



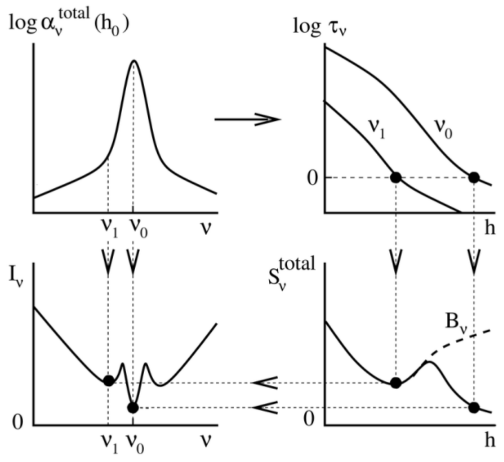
I.4 How is it formed?

- **From Rob Rutten's notes**

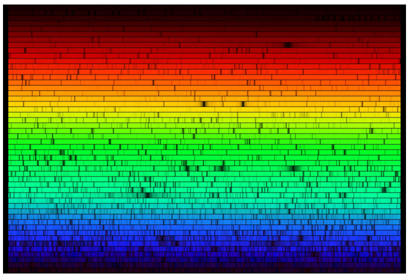
Self-reversed absorption line



Doubly-reversed absorption line



I.5 How do we detect it?



- **The photosphere (in short)**
  - Take advantage of photons that have optical depth unity at the surface of the Sun
  - This happens in the visible around 5000 Å
  - Many absorption lines (dark) superimposed on continuum signal presence of atoms / ions in solar atmosphere absorbing radiation coming from below.
  - The line strengths depend on the column densities of these atoms / ions which contain electrons in the lower state of the transition

---

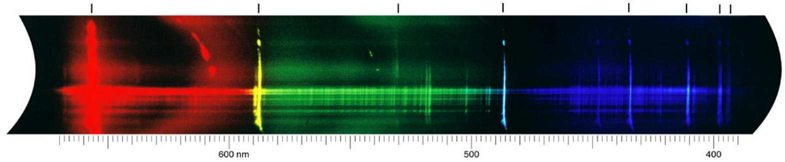
I.5 How do we detect it?

- **The photosphere (in short)**
  - The continuum...

University of Glasgow

I.5 How do we detect it?

- **The chromosphere: most poorly understood layer**



– Don’t wait for an eclipse!

– Tune your instrument to detect photons for which τ~1 about 1000-2000 km above the photosphere

– This means looking at

  – the core of lines such as Hα or Ca II K, or

  – submillimetre and millimetre continua

– No limb darkening: rather, limb brightening!

T decreases with τ

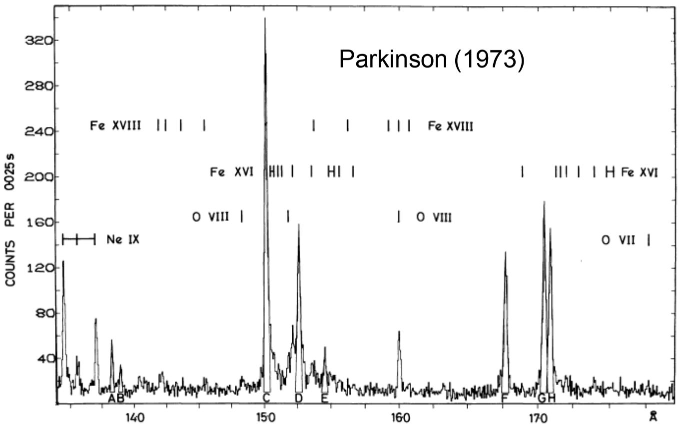
University of Glasgow

I.5 How do we detect it?

- **The corona (in short)**

– Optical forbidden lines tell us it’s hot ~ 1-2 MK and tenuous (less than 10^9 cm^{-3})

See Edlen (1945) on Fe X 6375 Å and Fe XIV 5303 Å



-Soft X-ray spectrum shows strong emission lines and no obvious sign of continuum

University of Glasgow

II. Plasma diagnostics

II.1 Overview

II.2 Direct spectral inversion

II.3 Imaging vs spectroscopy

University of Glasgow

II.1 Overview

- **What do we (I) mean by *plasma diagnostics*? An empirical derivation of:**
  - Temperatures
  - Densities
  - Mass flow velocities
  - Pressure
  - Chemical abundances

in a specific (observed) region of the solar atmosphere at a certain time.

- **What for?**
  - E.g., energy and momentum balance and transport

II.1 Overview

- **Direct inversion of spectral data**
  - For optically thin plasma (all emitted photons leave freely without interaction)
  - Yields spatially averaged values
- **Forward approach**
  - Necessary for optically thick plasma
  - Semi-empirical models
    - Start with given spatial distribution of T, p, n
    - Solve excitation and ionisation balance for all species
    - Determines opacities and emissivities
    - Solve RTE to get the emergent spectrum
    - Compare with observed spectrum ... and adjust model to start over again

---

II.2 Direct spectral inversion

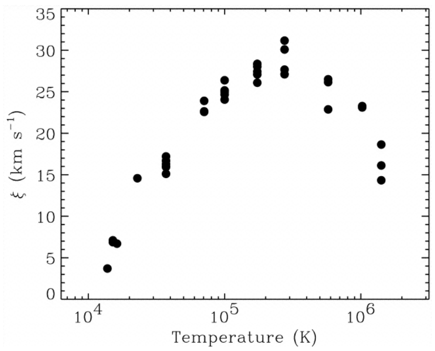
- **Optically thin plasma emitting Gaussian-shaped line**
  - Line width yields ion temperature T and non-thermal (or microturbulent) velocity ξ

$$\Delta\lambda_D = \frac{\lambda_0}{c}\left(\frac{2kT}{m} + \xi^2\right)^{1/2}$$

– Observations of different lines give an idea of variation of T and ξ, and so of distribution of energy in different layers

– See e.g. Chae et al (1998) analysis of SOHO/SUMER observations.

“The isotropic and small-scale nature of the nonthermal motions appear to be suited for MHD turbulence.”



University of Glasgow

II.2 Direct spectral inversion

- **Optically thin plasma emitting Gaussian-shaped line**
  - Electron density estimated by
    - Stark broadening (generally yields upper limits)
    - Collisional depolarization
    - Thompson scattering measurements
    - Emission measure methods
  - Neutral and ion densities; abundances
    - Line strengths, or absorption of radiation
    - Often requires good photometric calibration and accurate atomic data
  - Gas pressure
    - Derived from density and temperature measurements
    - Using pressure-sensitive lines (or line intensity ratios)

University of Glasgow

II.2 Direct spectral inversion

- **Application to XUV / EUV / UV lines**
  - A lot of data: SOHO/SUMER, SOHO/CDS, SOHO, UVCS, Hinode/EIS, and then IRIS (?)
  - Techniques described now applicable to plasma with $n_\mathrm{e} < 10^{13}$ cm^{-3} in ionization equilibrium
  - See work of Feldman et al (1977), Mariska (1992), Mason and Monsignori Fossi (1994), ...

II.2 Direct spectral inversion

- **Line emission from optically thin plasma**

– Emissivity of b-b transition

$$P(\lambda_{ji}) = \frac{hc}{4\pi\lambda_{ji}} n_j A_{ji} \ [\mathrm{erg\,cm^{-3}\,s^{-1}\,sr^{-1}}]$$

– Under the coronal approximation, only the ground level (g) and excited level (j) are responsible for the emitted radiation. The statistical equilibrium reduces to:

$$n_e n_g C_{gj} = n_j A_{jg}$$

– Now balance excitation from ground level with spontaneous radiative decay

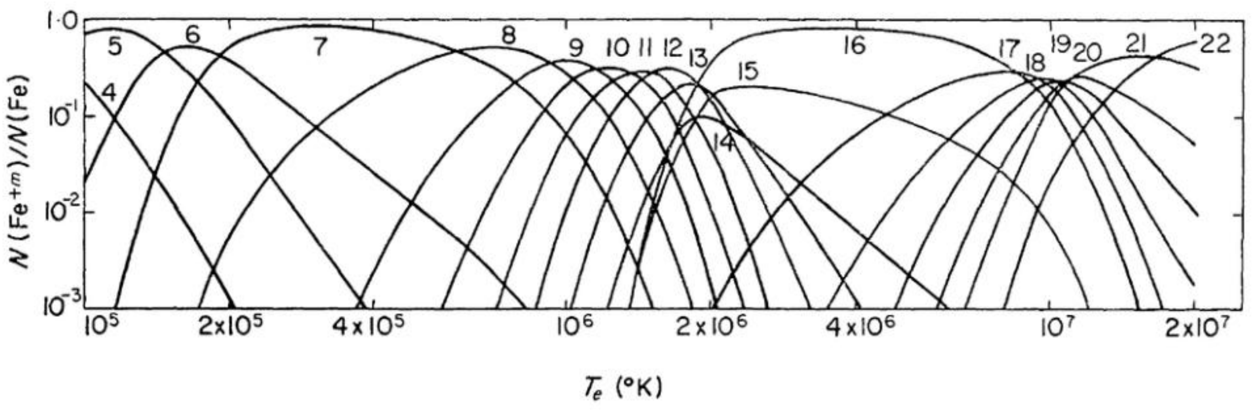
$$I(\lambda_{jg}) = \frac{hc}{4\pi\lambda_{jg} A} \int_V n_e n_g C_{gj} \mathrm{d}V \ [\mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}}]$$

– Now the population of the g level can be written as:

$$n_g = \underbrace{\frac{n_g}{N_\mathrm{ion}}}_{\sim 1} \frac{N_\mathrm{ion}}{N_\mathrm{el}} \frac{N_\mathrm{el}}{N_\mathrm{H}} \underbrace{\frac{N_\mathrm{H}}{n_e}}_{\sim 0.8} n_e$$

Abundance of element with respect to H

II.2 Direct spectral inversion



Carole Jordan's work

University of Glasgow

II.2 Direct spectral inversion

- **Line emission from optically thin plasma**
  - Collisional excitation coef: (assuming Maxwellian velocity distribution)

$$C_{gj} = \frac{8.63 \times 10^{-6} \Upsilon_{gj}(T)}{\omega_g} T^{-1/2} \exp\left(-\frac{hc}{\lambda_{jg} kT} \right)$$

Statistical weight

Collision strength

  - Finally...

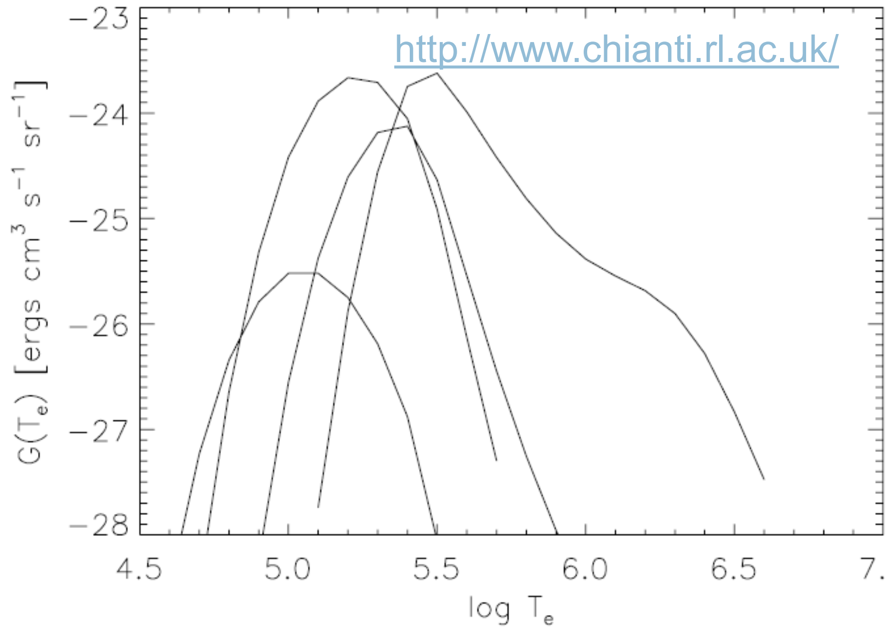
$$\boxed{I(\lambda_{jg}) = \frac{1}{4\pi A} \int_V AbG(T) n_e^2 \mathrm{d}V}$$

where we have introduced the contribution function $G(T)$

$$G(T) = \frac{8.63 \times 10^{-6} \Upsilon_{gj}(T)}{\omega_g} \frac{N_{\rm ion}}{N_{\rm el}} \frac{N_{\rm H}}{n_e} T^{-1/2} \exp\left(-\frac{hc}{\lambda_{jg} kT} \right) \frac{hc}{\lambda_{jg}}$$

University of Glasgow

II.2 Direct spectral inversion



Contribution functions for lines belonging to O III – O VI ions, CHIANTI v.5.1

II.2 Direct spectral inversion

- **Electron temperature**

– Emission measure: yields amount of plasma emissivity along LOS

- Use the fact that contribution function is peaked to write

$I(\lambda_{jg}) = \frac{1}{4\pi} Ab \langle \mathrm{EM} \rangle \langle G(T) \rangle$, with $\langle \mathrm{EM} \rangle = \int_h n_{\mathrm{e}}^2 \mathrm{d}h \ [\mathrm{cm}^{-5}]$

- EM can be directly inferred from the observation of spectral lines
- It may be defined also as $\mathrm{EM} = n_e^2 V_c \quad [\mathrm{cm}^{-3}]$, with $\mathrm{V_c}$ the coronal volume emitting the line
- EM also yields the electron density

II.2 Direct spectral inversion

- **Electron temperature**

– Differential Emission Measure:
yields distribution in temperature of plasma along LOS

$\mathrm{DEM}(T) = n_{\mathrm{e}}^2 \frac{\mathrm{d}h}{\mathrm{d}T} \ [\mathrm{cm}^{-5}\,\mathrm{K}^{-1}]$ and thus $I(\lambda_{jg}) = \frac{1}{4\pi} Ab \int_T G(T) \mathrm{DEM}(T) \mathrm{d}T$

- The DEM contains information on the processes at the origin of the temperature distribution, BUT
- The inversion is tricky, using observed line intensities, through calculating $G(T)$, assuming elemental abundances, and is sensitive to uncertain atomic data (see Hannah & Kontar, A&A 539, 146, 2012)

II.2 Direct spectral inversion

- **Electron density from line ratios**

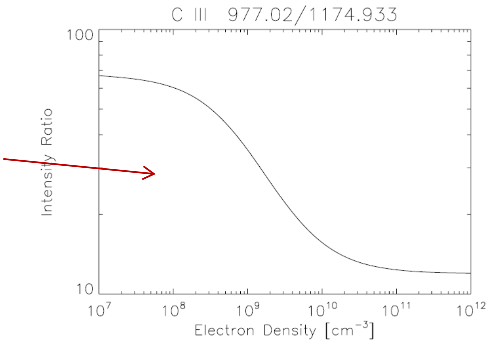
– Allowed transitions have $I \propto n_e^2$

– Forbidden and intersystem transitions, with a metastable (long lifetime) upper state m, can be collisionally de-excited towards level k

– For such a pair of lines from the same ion:

$$\frac{I(\lambda_{jg})}{I(\lambda_{mk})} = \frac{n_g}{n_m}\frac{C_{gj}}{C_{mk}}\frac{\lambda_{mk}}{\lambda_{jg}}, \text{ so } \quad \frac{I(\lambda_{jg})}{I(\lambda_{mk})} \propto \frac{n_e}{F(T, n_e)}$$

This is because of the density dependence of the population of level m



– Intensity ratio yields n_e averaged along LOS at line formation temperature

II.2 Direct spectral inversion

- **What is the volume filling factor?**

– Measures the fraction of the volume filled by material

$$f_V \sim \mathrm{EM}/n_e^2$$

II.3 Imaging vs spectroscopy

- **Line profiles give us key information on plasma parameters**
  - Line width: thermal and non-thermal processes
  - Line position: Doppler shifts, mass flows
  - Line intensity: densities, temperature
  - Line profile shape: optical thickness
- **Issues**
  - It takes time to acquire spectra on rather limited field of views
  - Data analysis relies on complex atomic data with high uncertainties
  - Line identification and blends can cause headaches!

II.3 Imaging vs spectroscopy

- **Spectra are still useful even without detailed profiles**
  - Integrated intensities should not be affected by instrumental profile

- **Imaging**
  - No detailed line profile, no Doppler shifts
  - High cadence, high temporal resolution
  - Narrow-band imaging getting close to spectroscopic imaging
    - Still issues about what lines contribute (and to what extent) to observed emission

Further reading

- **Where can I look to learn more about solar radiation and plasma diagnostics?**
  - ADS (see some suggestions next page)
  - Nuggets (UKSP, EIS, RHESSI, ...)
  - Rob Rutten's lectures: http://www.astro.uu.nl/~rutten/Lectures.html
  - Physics of the Sun: A first course, by D. Mullan, CRC Press
  - Solar Astrophysics, by Foukal, Wiley-vch

Further reading

- **Bibliography**

  - New Observations of Fe XVII in the Solar X-ray Spectrum
  - SUMER Measurements of Nonthermal Motions: Constraints on Coronal Heating Mechanisms
  - XUV spectra of the 1973 June 15 solar flare observed from Skylab. II - Intersystem and forbidden transitions in transition zone and coronal ions
  - The solar transition region
  - Spectroscopic diagnostics in the VUV for solar and stellar plasmas
  - CHIANTI - an atomic database for emission lines - Paper XII: Version 7 of the database
  - Differential emission measures from the regularized inversion of Hinode and SDO data
  - Probing the solar wind acceleration region using spectroscopic techniques
  - Hα Doppler Brightening and Lyman-α Doppler Dimming in Moving Hα Prominences
  - EUV lines observed with EIS/Hinode in a solar prominence
  - Diagnostics of active and eruptive prominences through hydrogen and helium lines modelling
  - Effect of motions in prominences on the helium resonance lines in the extreme ultraviolet
  - On the Lyman α and β lines in solar coronal streamers
  - ...