Atomic Spectral Lines

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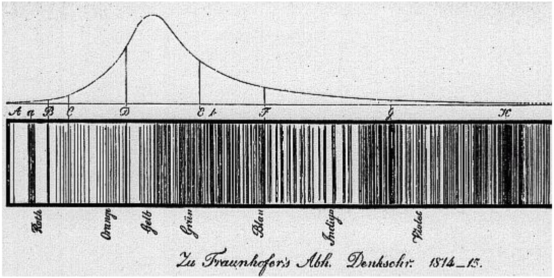
Hale COLLAGE, Boulder, Feb 18, 2016

Today's Lecture

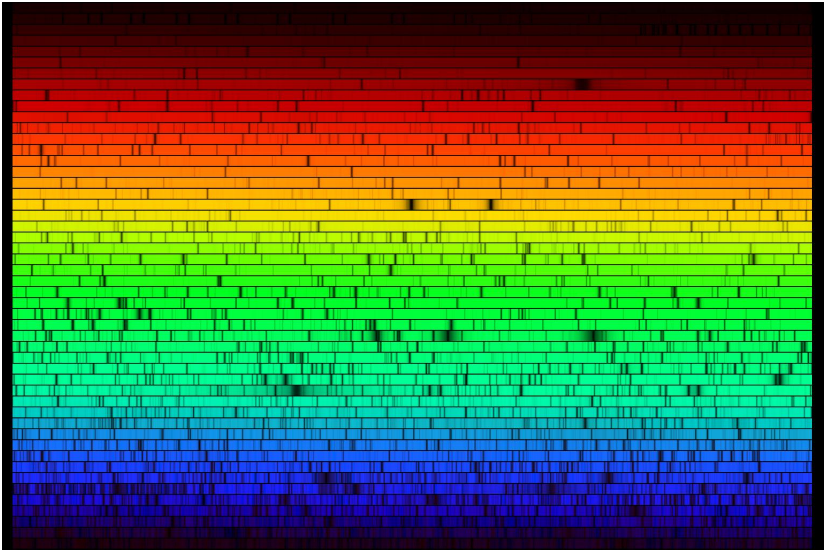
- How do we get absorption and emission lines in the spectrum?
- Atomic line- and continuum transitions
- Non-LTE radiative transfer in atomic models
- Real world examples:
  - Ca II H& K lines
  - He I 1083 nm line

Some History

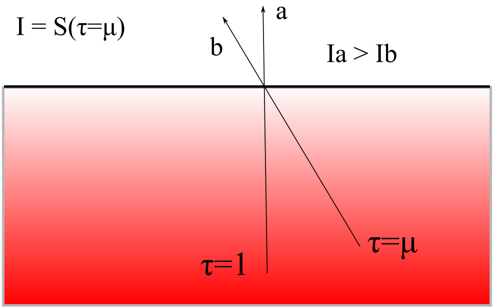
- **1802** Wollaston was the first to observe dark gaps in spectrum: spectral lines.
- **1814** Fraunhofer rediscovers lines. Assigns names that we still use, e.g., C (Hα), D (Na I), F (Hβ), G (CH molecules), and H (Ca II).



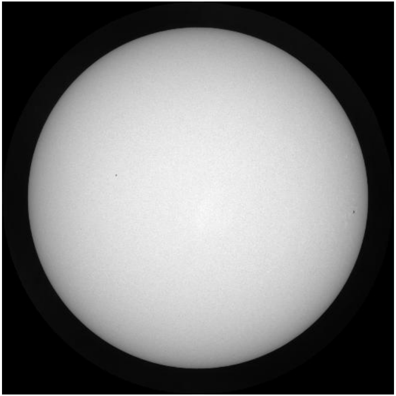
The spectrum at much better resolution

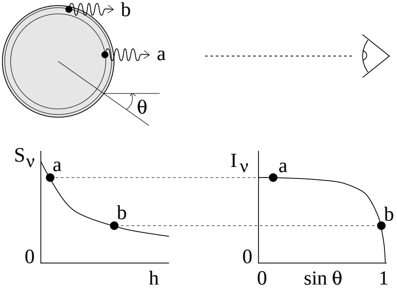


Remember: Eddington-Barbier approximation



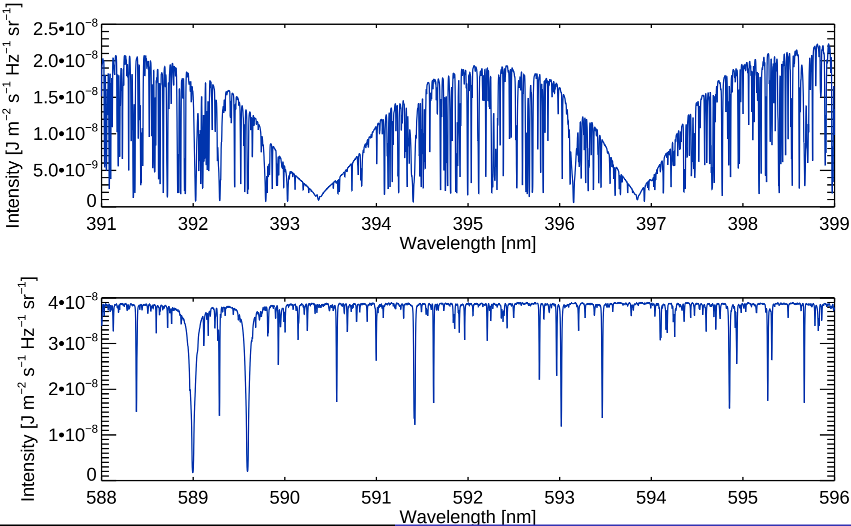
Limb Darkening Explained



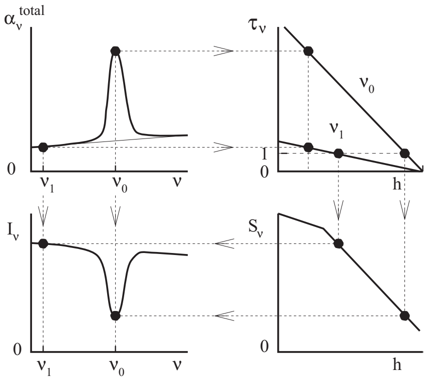


$$r/R = \sin\theta$$

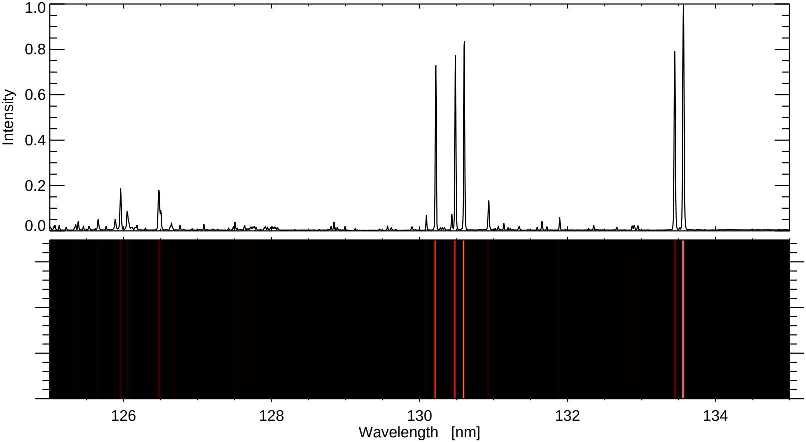
Can we now explain the Darkening in the Cores of Spectral Lines?



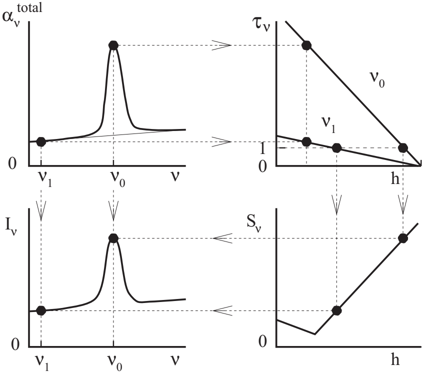
Explanation of Absorption Lines in the Spectrum



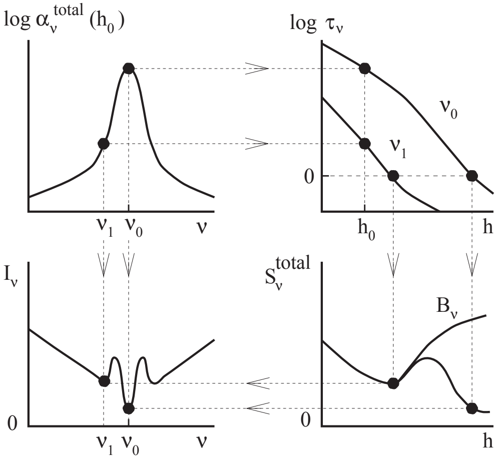
In the UltraViolet the Spectral Lines are in Emission



Explanation of Emission in Spectral Lines



Explanation of the Shape of the CaII Resonance Lines



Hα Spectral Line

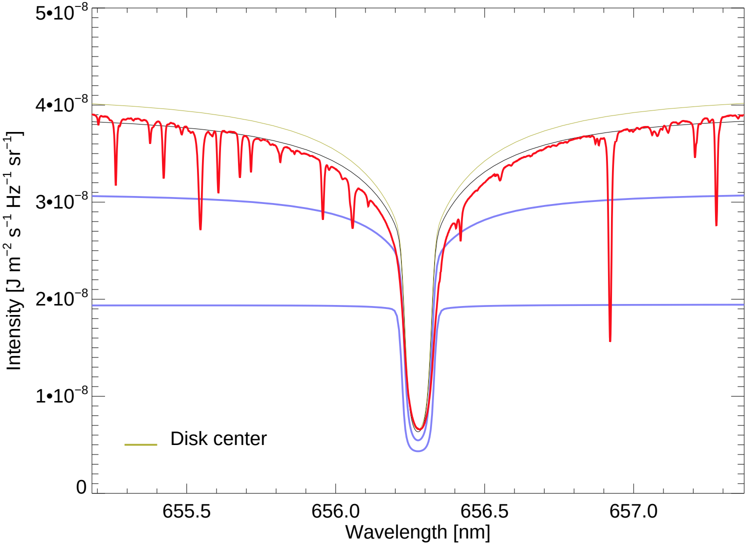
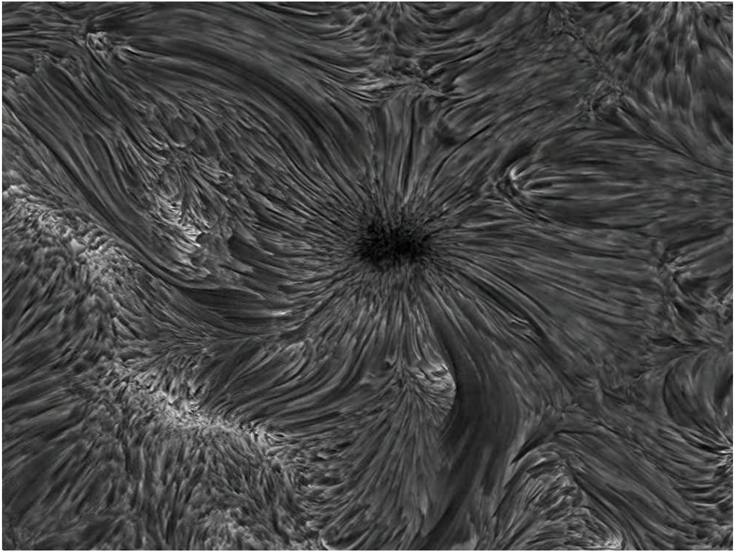


Image of the Sun in the light of Hα



Energy Levels and Transitions in Hydrogen Atom

$$\Delta E = h\nu = \frac{hc}{\lambda}$$

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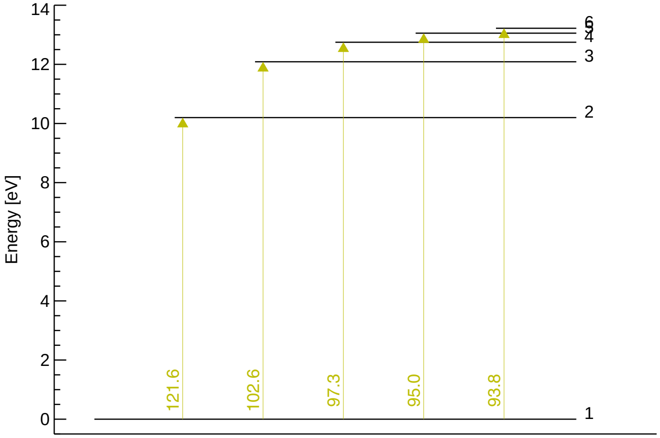

Energy Levels and Transitions in Hydrogen Atom

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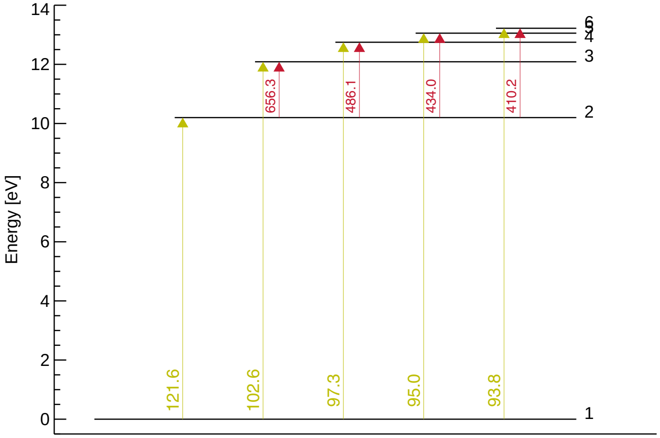

Energy Levels and Transitions in Hydrogen Atom

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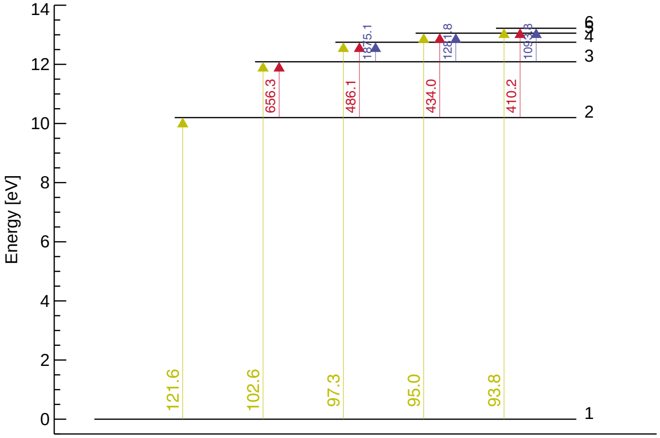
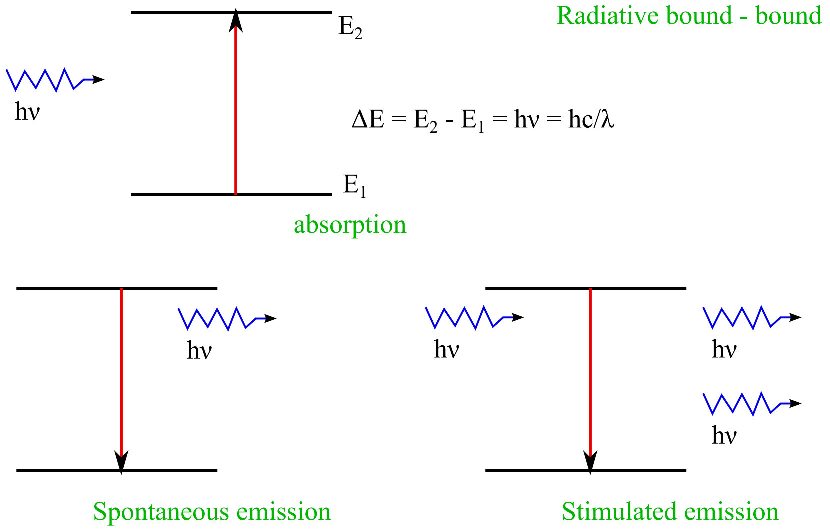
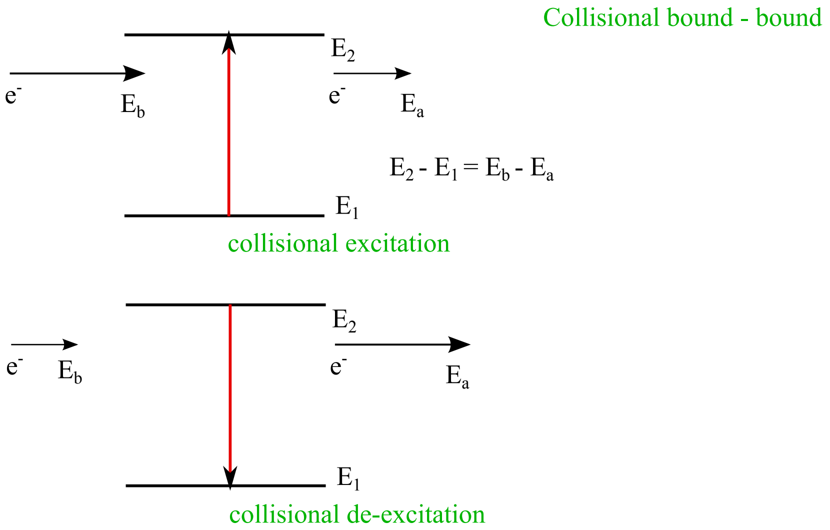


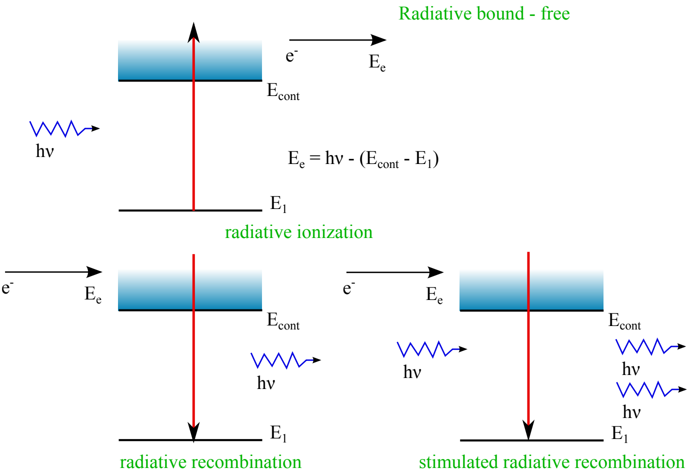
Radiative bound–bound Transitions



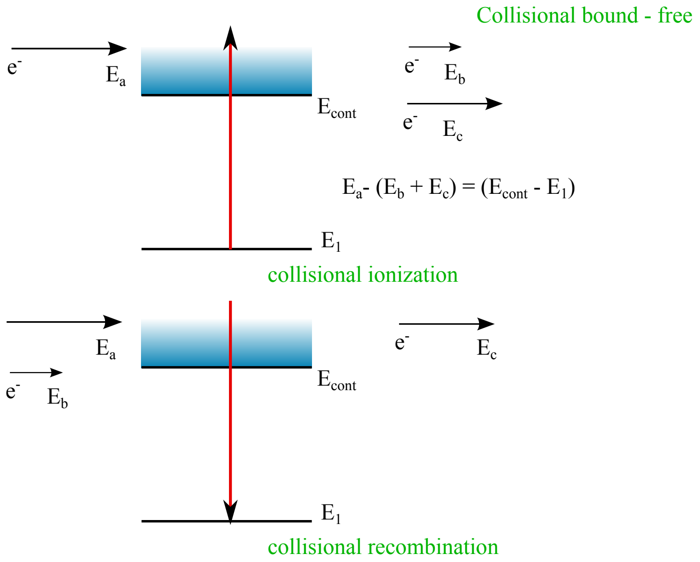
Collisional bound–bound Transitions



Radiative bound–free Transitions



Collisional bound–free Transitions



Absorption and Emission Coefficients for bound-bound Transitions

Spontaneous emission $j \rightarrow i$:

$$j_\nu^{\rm spont} = n_j (A_{ji} h\nu_{ij}/4\pi)\phi_\nu$$

Stimulated emission $j \rightarrow i$:

$$j_\nu^{\rm stim} = n_j (B_{ji} h\nu_{ij}/4\pi)\phi_\nu I_\nu, \qquad A_{ji} = (2h\nu^3/c^2)B_{ji}$$

Absorption $i \rightarrow j$:

$$\alpha_\nu = n_i (B_{ij} h\nu_{ij}/4\pi)\varphi_\nu, \qquad g_i B_{ij} = g_j B_{ji}$$

Source Function of bound–bound Transition

Transfer equation:

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu^{\mathrm{spont}} + j_\nu^{\mathrm{stim}} - \alpha_\nu I_\nu$$
$$= n_j(A_{ji} h\nu_{ij}/4\pi)\phi_\nu - h\nu_{ij}/4\pi\phi_\nu(n_i B_{ij} - n_j B_{ji}) I_\nu$$

Source function:

$$S_\nu = \frac{j_\nu}{\alpha_\nu} = \frac{n_j A_{ji}}{n_i B_{ij} - n_j B_{ji}}$$
$$= \frac{2h\nu_{ij}^3}{c^2} \frac{n_j}{g_j/g_i n_i - n_j}$$
$$= (1-\epsilon)\bar{J} + \epsilon B_\nu$$

$$\epsilon \equiv \frac{C_{ji}}{C_{ji} + A_{ji} + B_{ji}\bar{J}}; \qquad \bar{J} \equiv \int J_\nu \phi_\nu \mathrm{d}\nu; \qquad B_\nu \equiv \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

Radiative Rates

Radiative excitation

$$R_{ij} = B_i j \frac{h\nu}{4\pi} \int \mathrm{d}\Omega \int \frac{\mathrm{d}\nu}{h\nu} I_\nu \phi_\nu$$

$$= B_i j \overline{J}; \qquad \overline{J} \equiv \frac{1}{4\pi} \int \mathrm{d}\Omega \int \mathrm{d}\nu I_\nu \phi_\nu$$

Radiative de-excitation

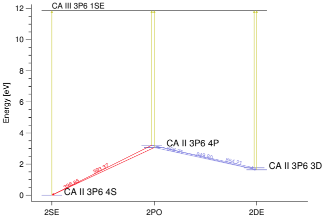
$$R_{ij} = Aji + B_{ji} \frac{h\nu}{4\pi} \int \mathrm{d}\Omega \int \frac{\mathrm{d}\nu}{h\nu} I_\nu \phi_\nu$$

$$= A_{ji} + B_{ji} \overline{J}$$

Basic Equation: Statistical Equilibrium

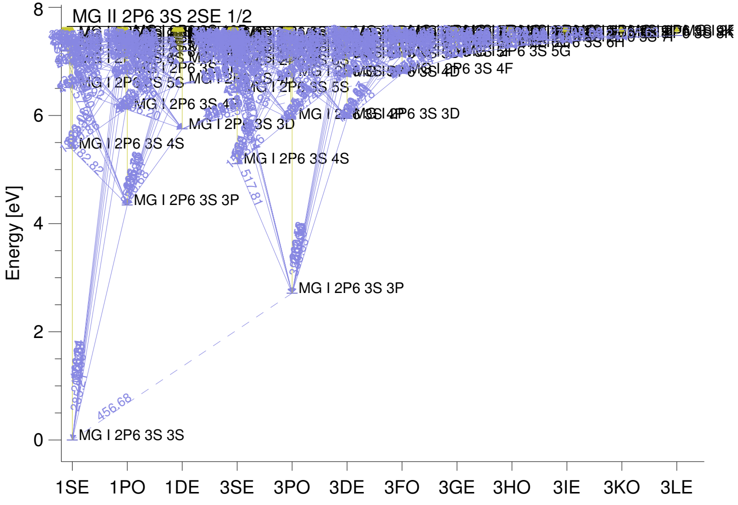
Consider and atom (or molecule) with levels $i = 0, \ldots, N-1$.
Statistical equilibrium for level i:

$$\sum_{j=0}^{N-1} n_j(Cji + Rji) = \sum_{j=0}^{N-1} n_i(Cij + Rij)$$

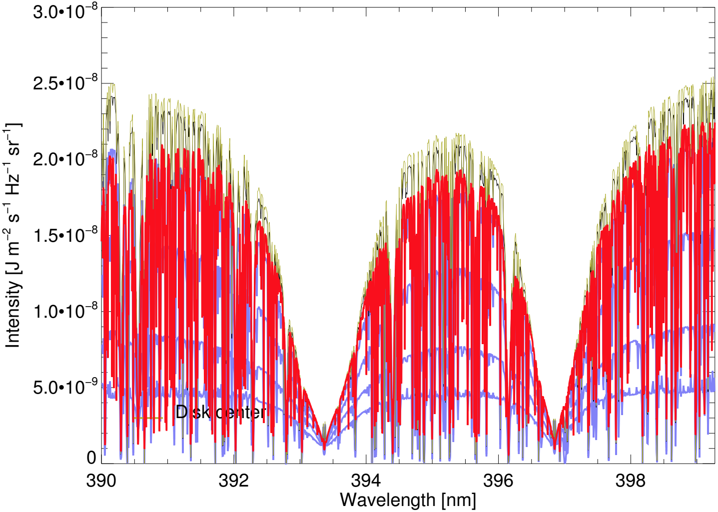


The set of equations for all levels forms a, generally non-linear, and non-local, set of equations for the population numbers n_i

Complicated Termdiagram for Magnesium



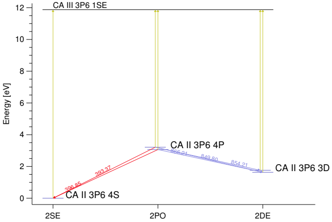
We want to Reproduce the Spectrum of the Ca II H&K

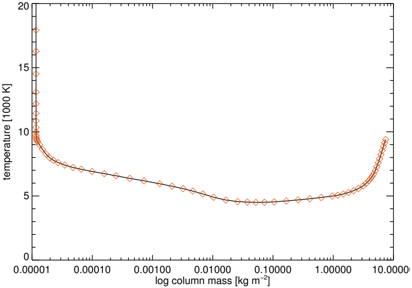


Ingredients for Reproducing the Ca II H&K spectrum

Atmospheric Model:

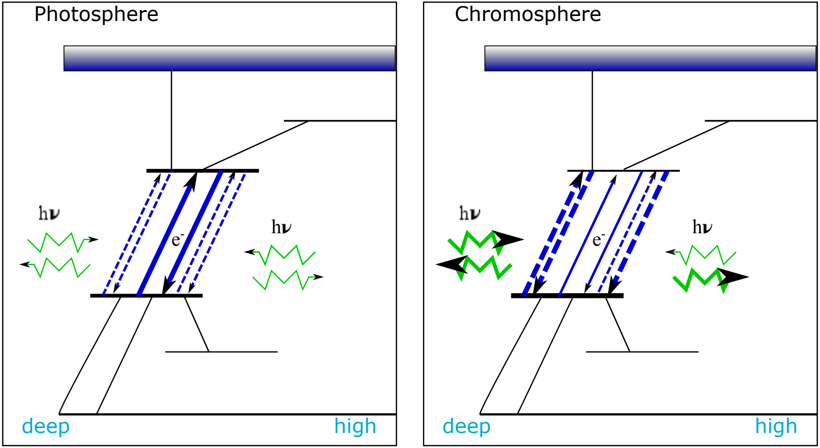
Atomic Model:



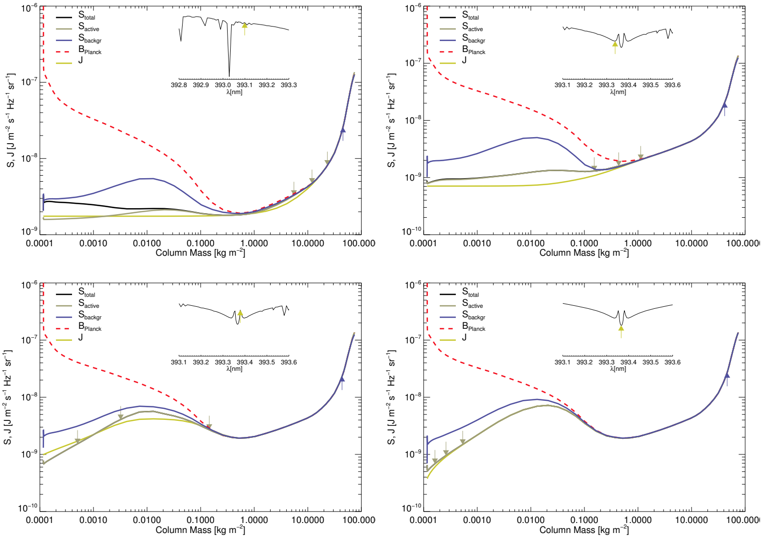


Solve Equations for radiative transfer and statistical equilibrium simultaneously.

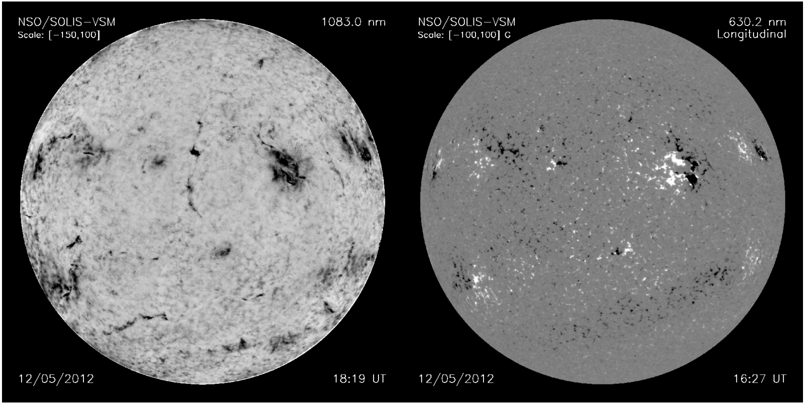
Collisional and Radiative Excitation in a realistic Case



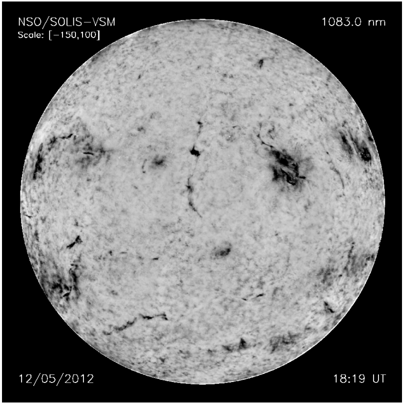
Source function Ca II K line (Non-LTE)

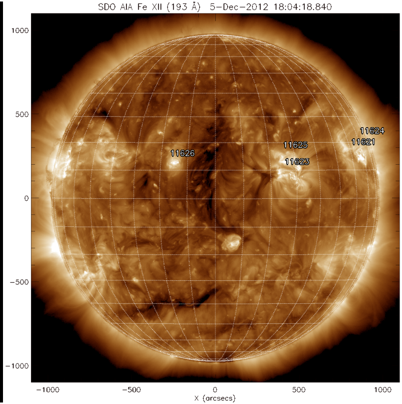


Full disk images of He I equivalent width and $B_\parallel$

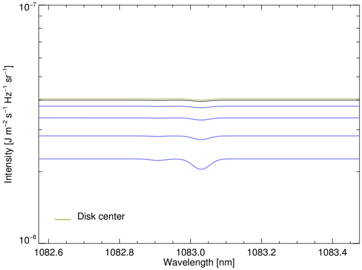


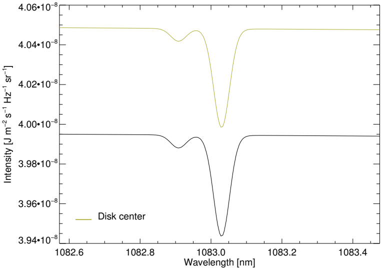
Full disk images of He I EQW and Fe XII 19.3 nm



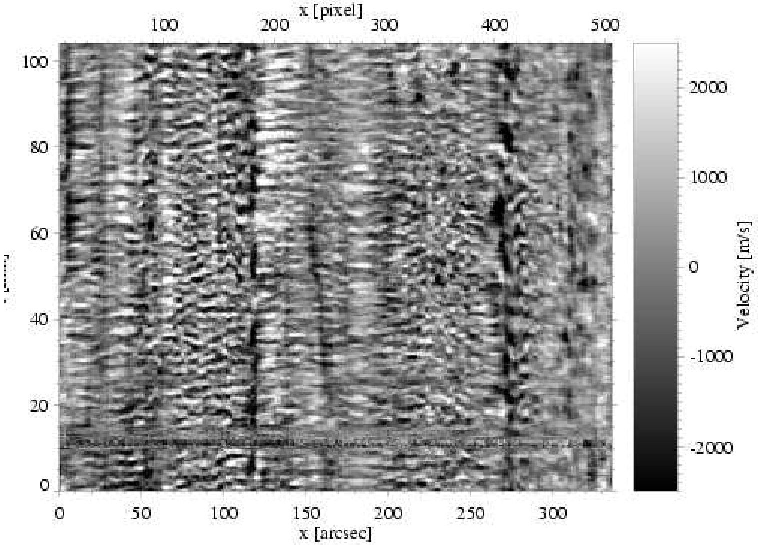


Line profiles of the He I 1083 nm triplet



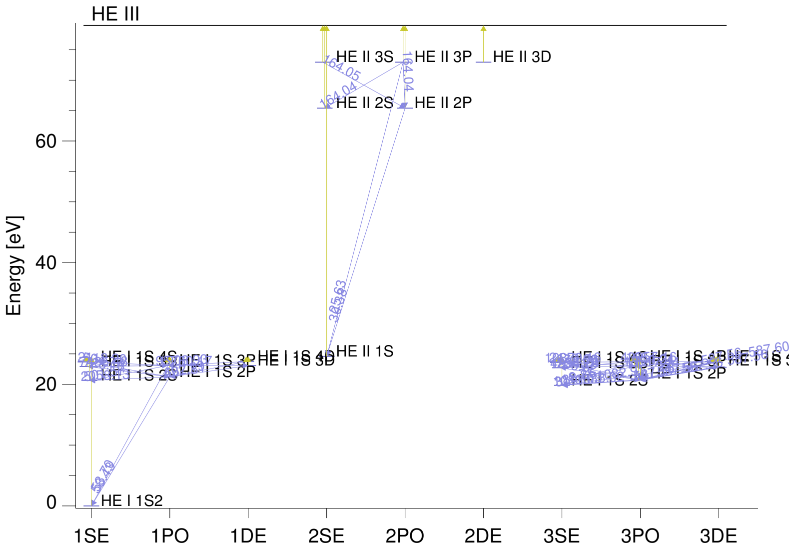


The He I 1083.0 nm line: chromospheric?

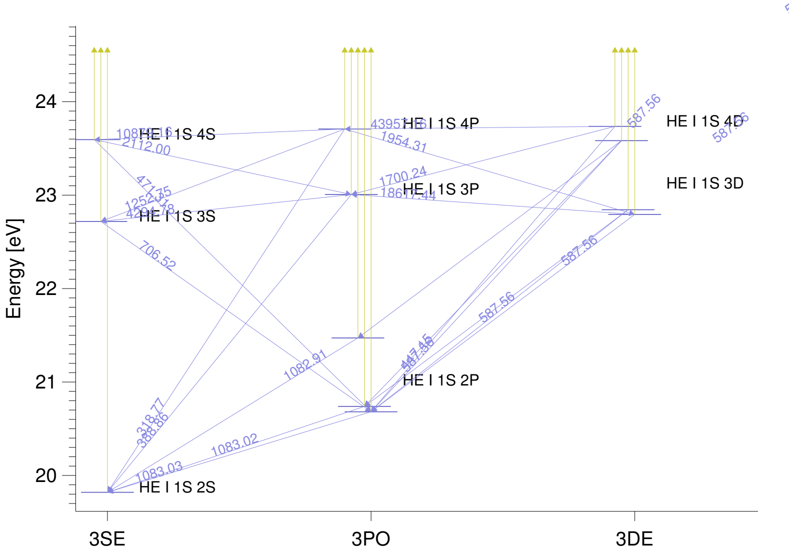


Courtesy Bernhard Fleck

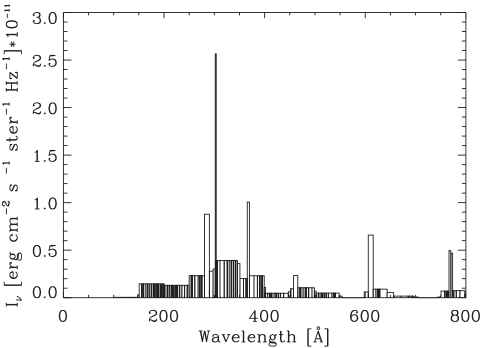
The He I 1083.0 nm termdiagram

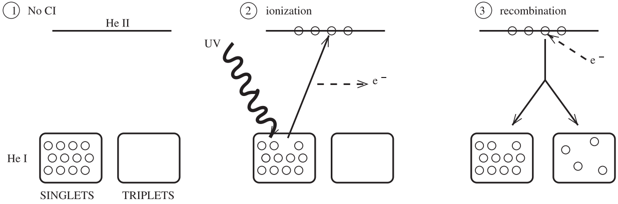


The He I 1083.0 nm termdiagram, triplet system

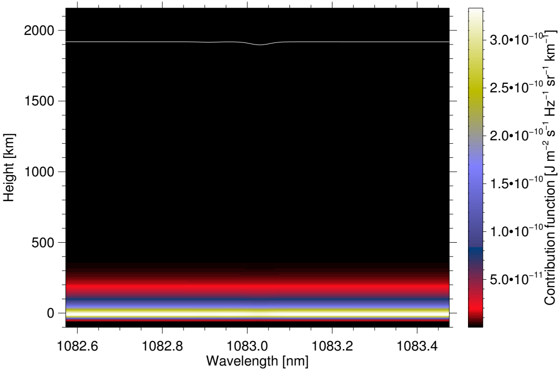


EUV irradiation from Corona populates triplet levels





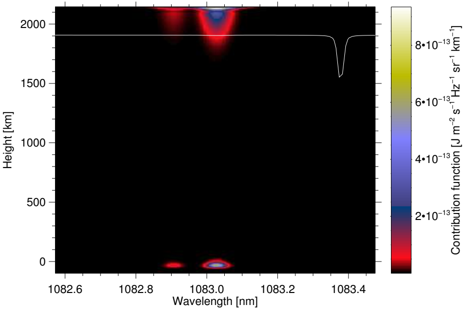
The He I 1083.0 nm contribution function



Contribution function:

$$C \equiv S(\tau) e^{-\tau} \frac{d\tau}{dh}$$

He I Line contribution function



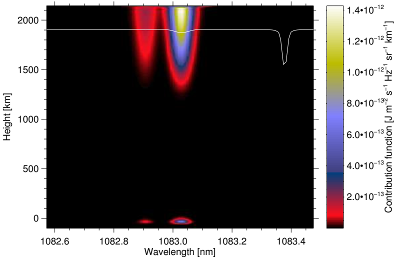
Line contribution function:

$$S_{\rm tot} = \frac{(\eta_l + \eta_c)}{(\chi_l + \chi_c)}$$

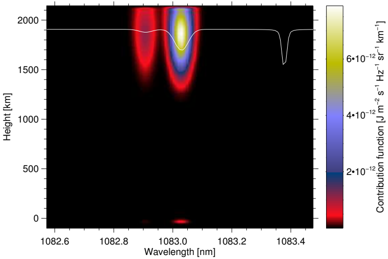
$$C = \left[\frac{\eta_l}{(\chi_l + \chi_c)} + \frac{\eta_c}{(\chi_l + \chi_c)}\right] e^{-\tau} \frac{d\tau}{dh}$$

He I Line contribution function with irradiation

1x



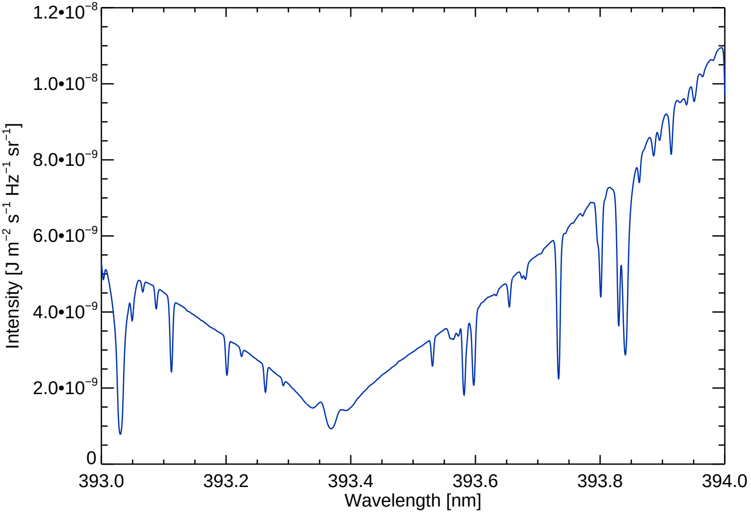
10x



Next lecture:

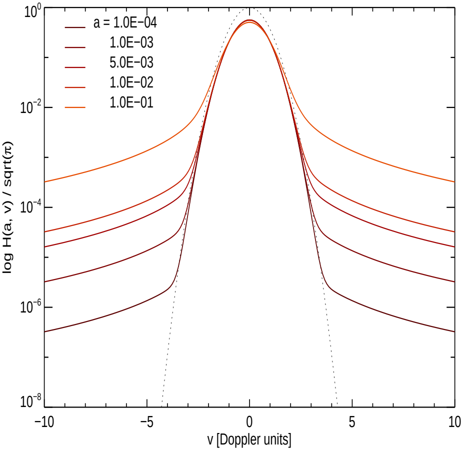
- Molecular line formation

Details of the CaII K line



Back

Voigt Functions



$$\phi(\nu - \nu_0) = \frac{H(a, v)}{\sqrt{\pi}\Delta\nu_D}$$

$$\Delta\nu_D \equiv \frac{\nu_0}{c}\sqrt{\frac{2kT}{m}}$$

$$a = \frac{\Gamma}{4\pi\Delta\nu_D}$$

Back