Yunnan/Beijing 2019

Stellar Atmospheres

A very brief introduction

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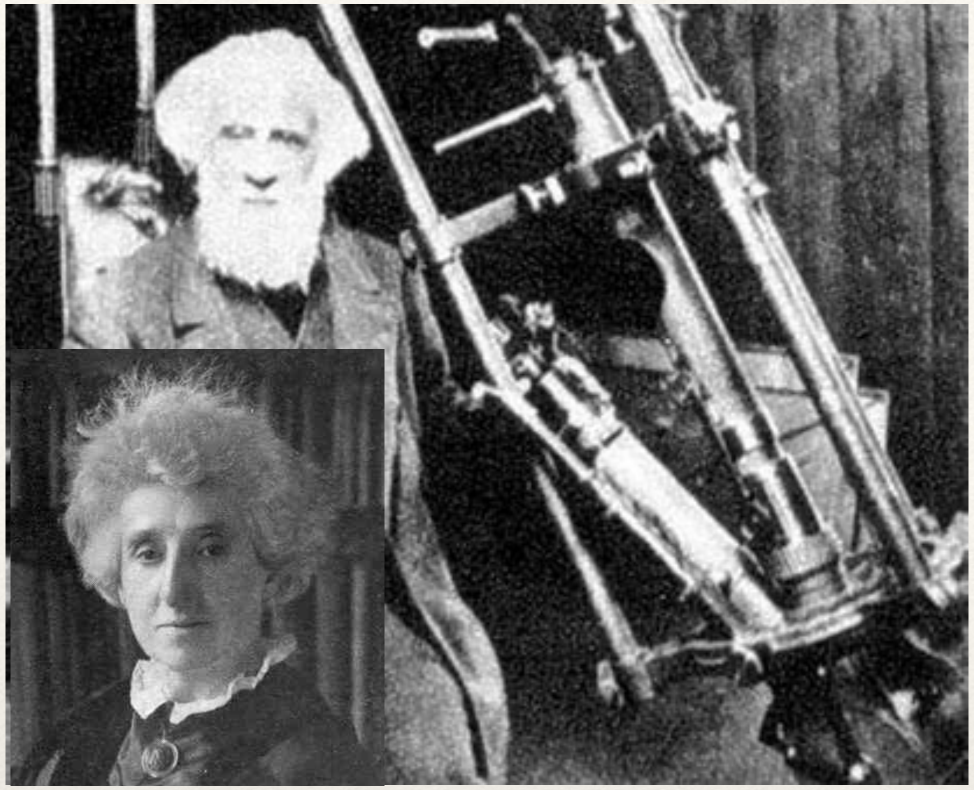
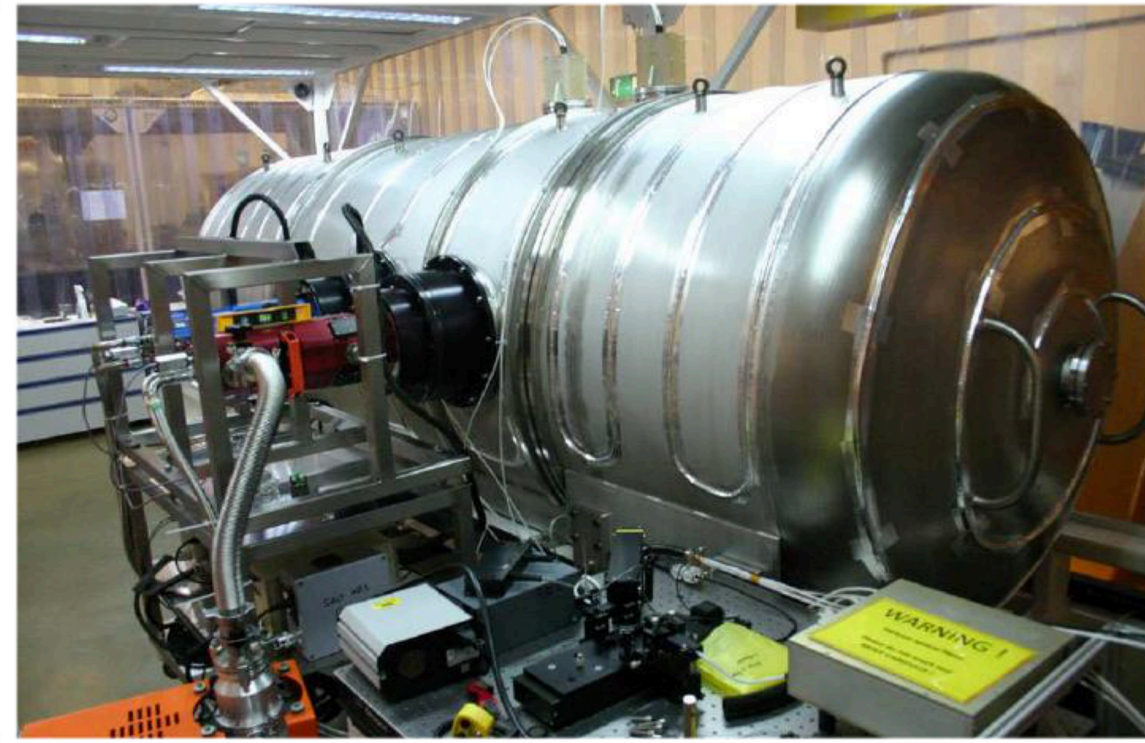
Programme

1. The Model Atmosphere
2. The Line Profile
3. Spectral Analysis

0. Introduction

1. Astronomical spectrographs
2. Spectroscopy as a tool for stellar exploration

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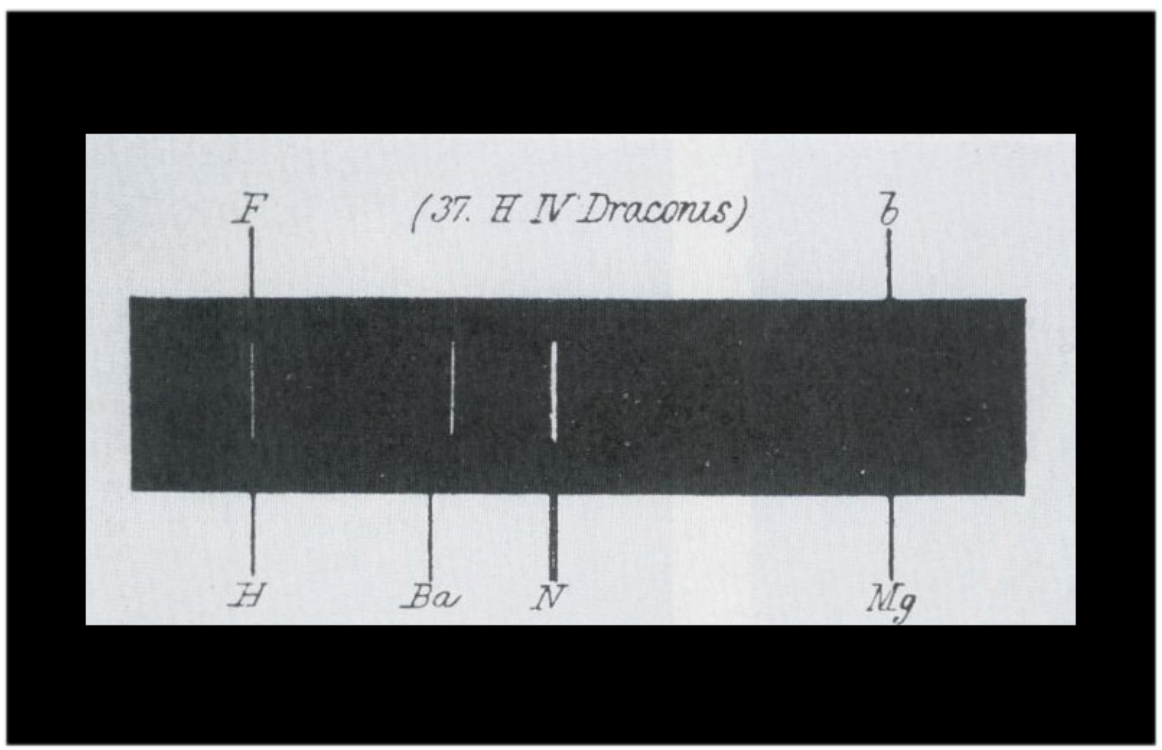
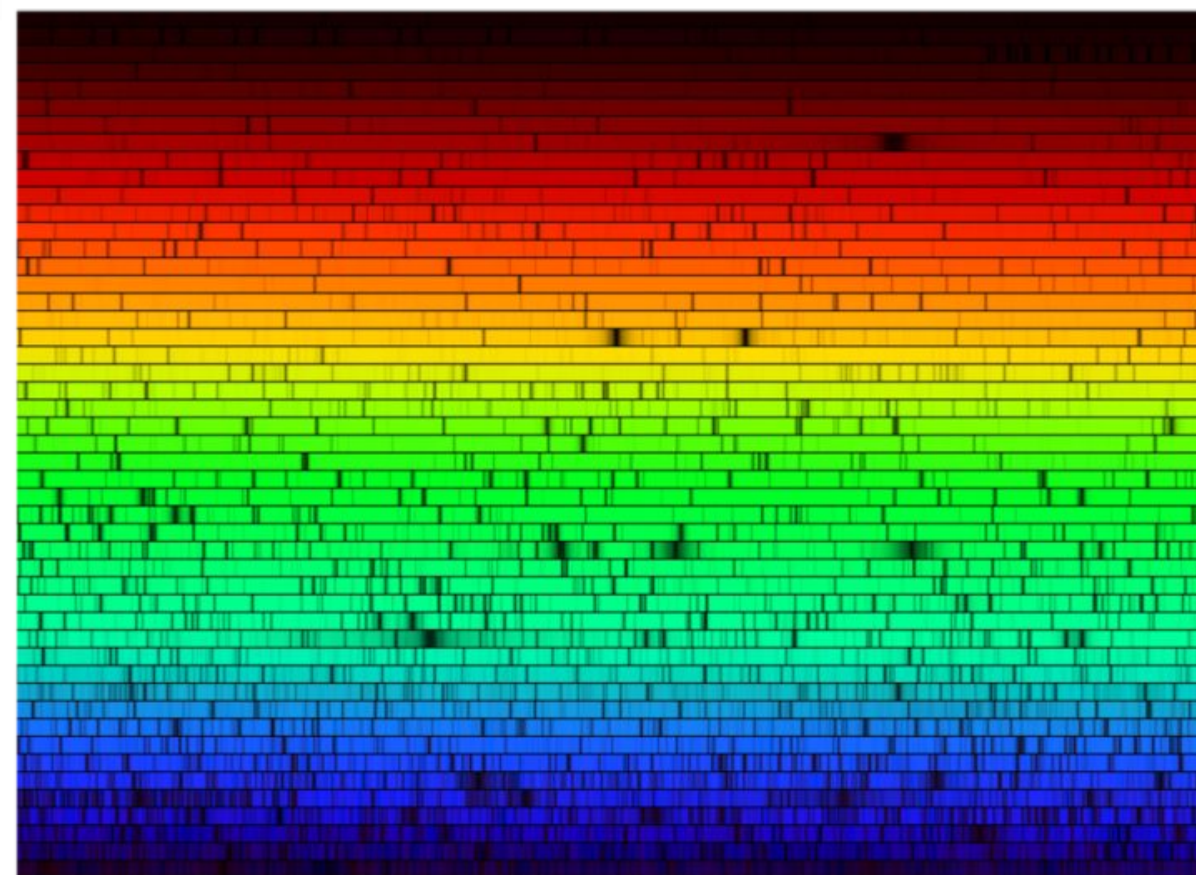
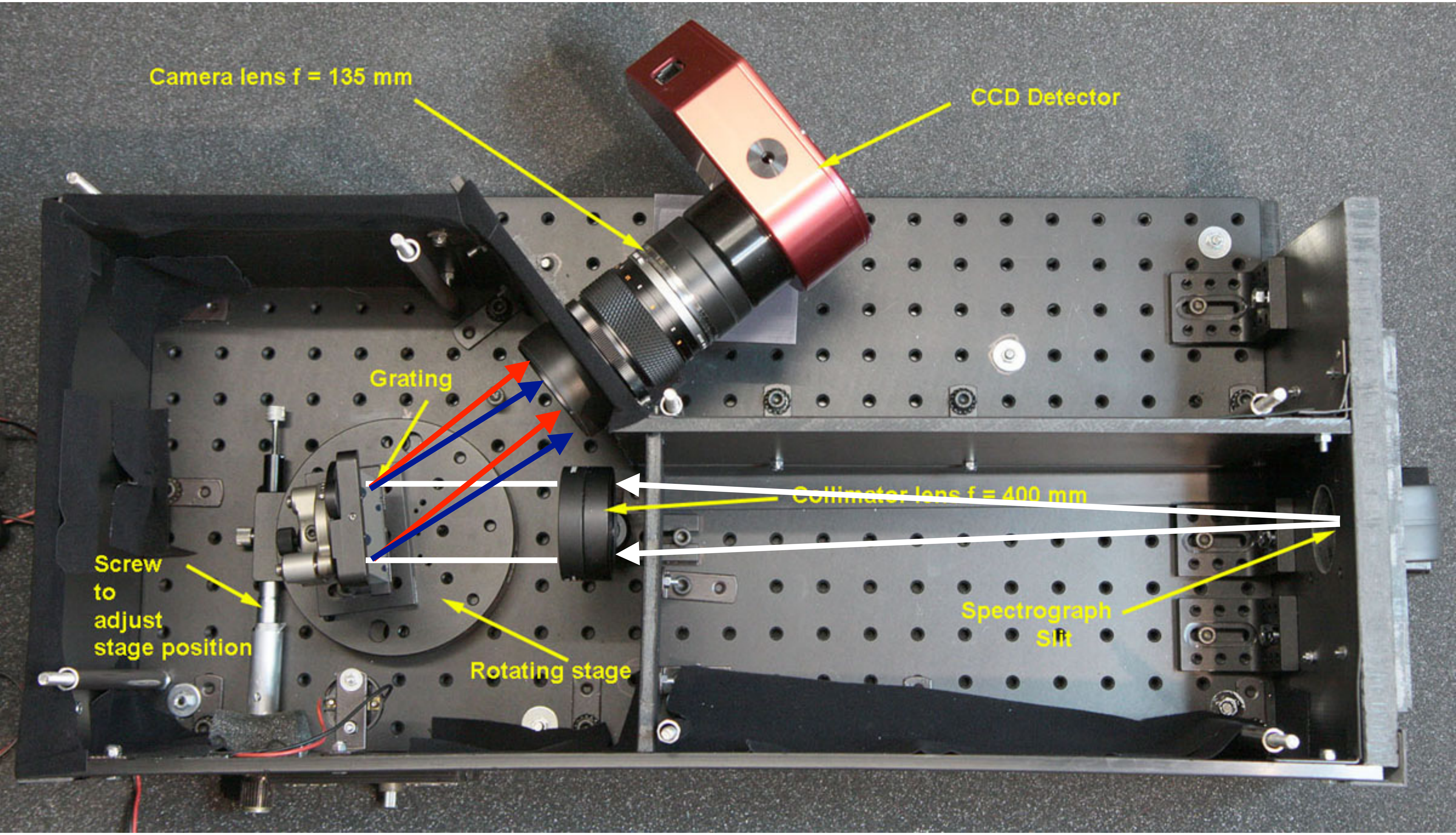
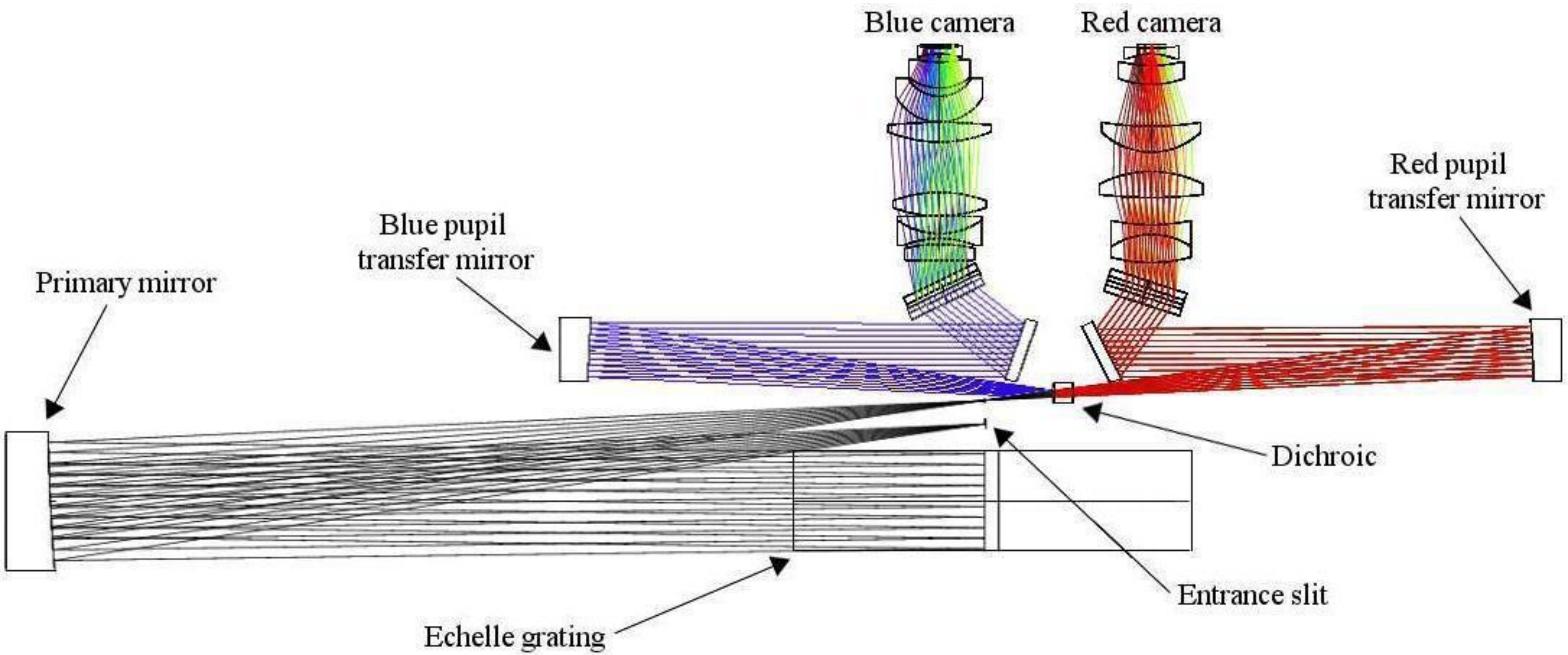
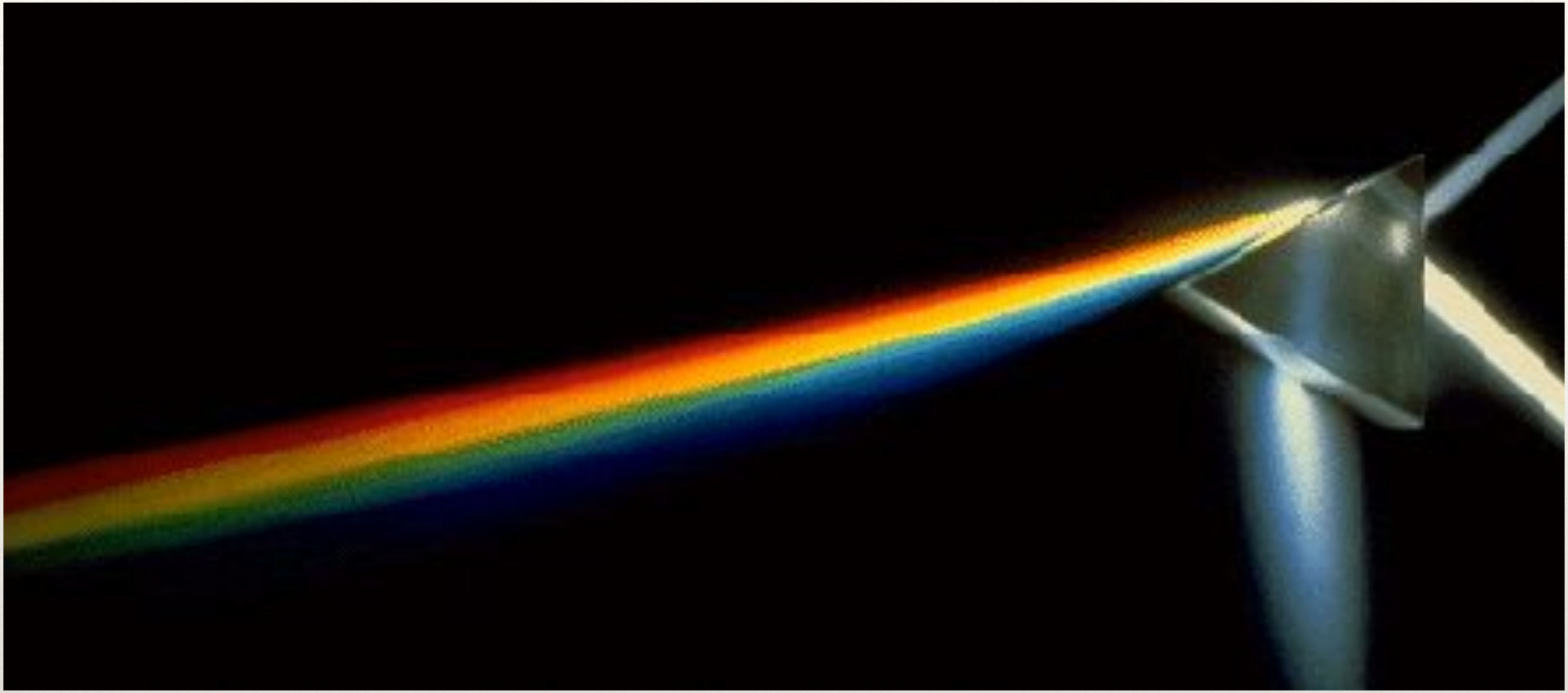

F
(37. H IV Draconis)
b
H
Ba
N
Mg




Camera lens f = 135 mm
CCD Detector
Grating
Collimator lens f = 400 mm
Screw
to
adjust
stage position
Rotating stage
Spectrograph
Slit


Blue camera
Red camera
Red pupil transfer mirror
Blue pupil transfer mirror
Primary mirror
Dichroic
Entrance slit
Echelle grating

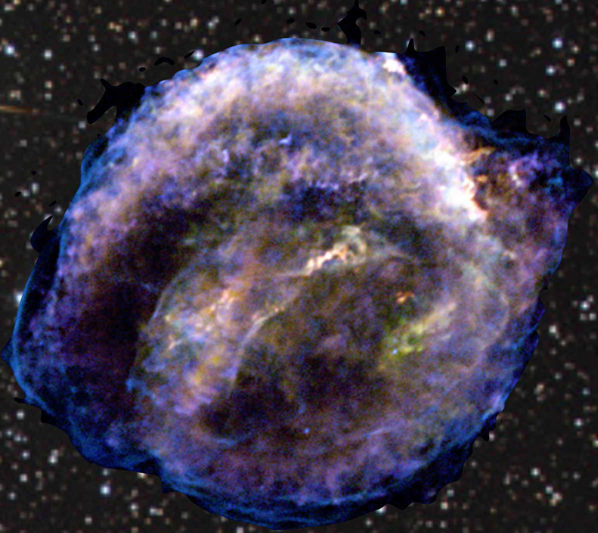


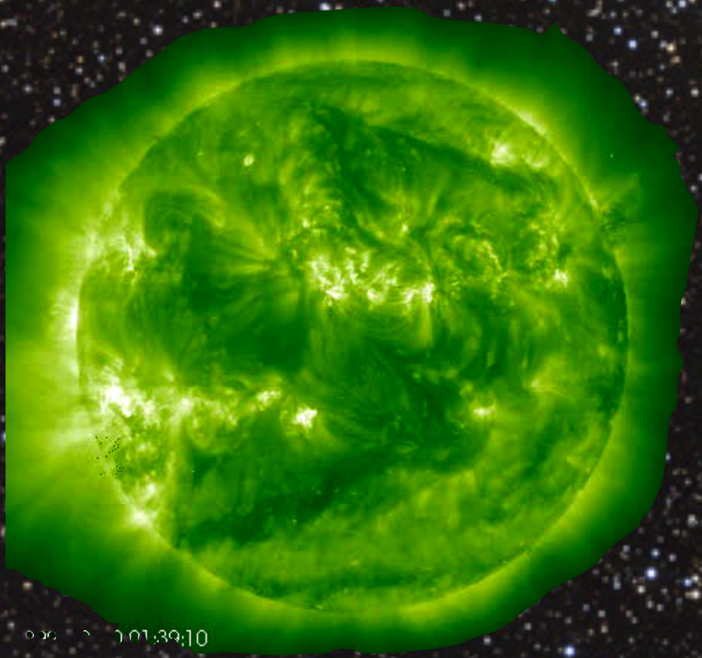
Spectrum reveals physics and chemistry of a stellar surface

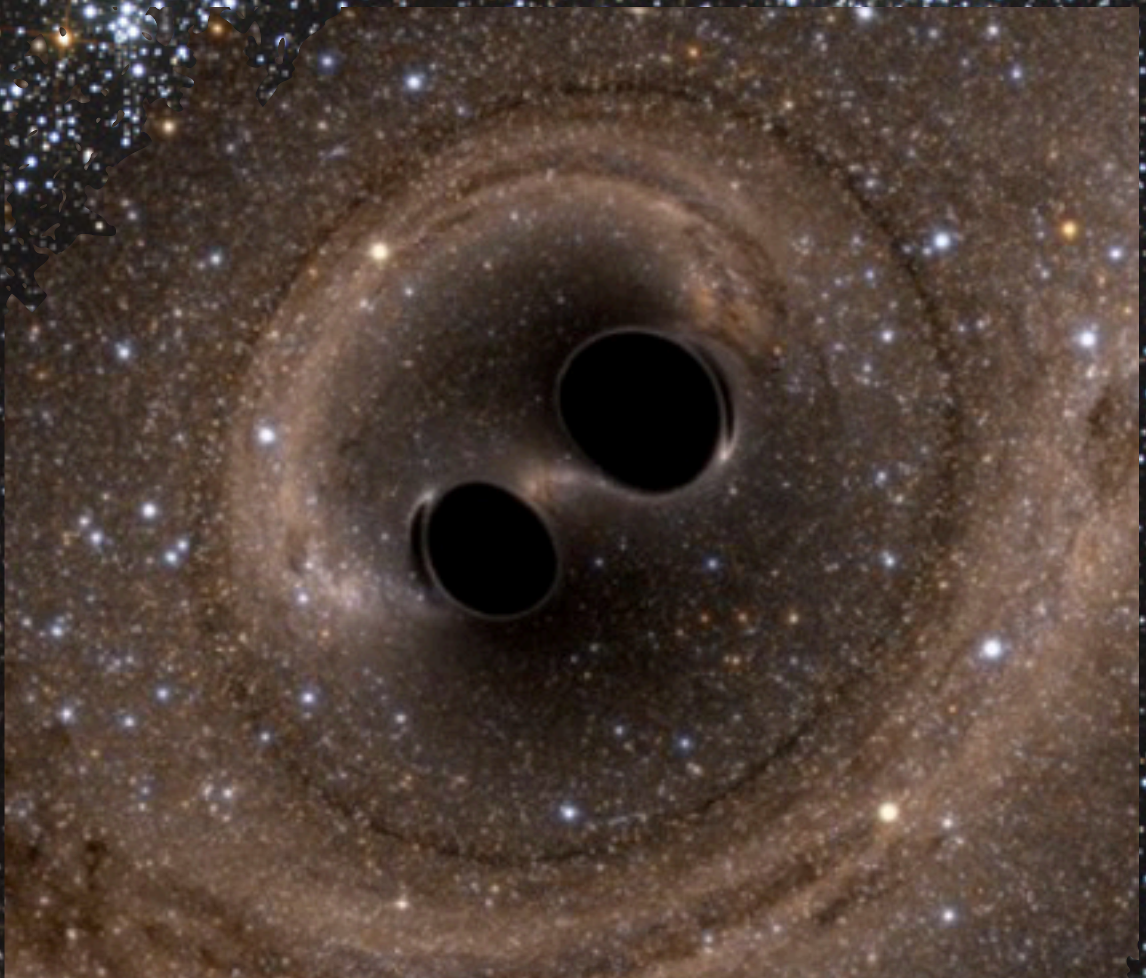
Spectroscopy

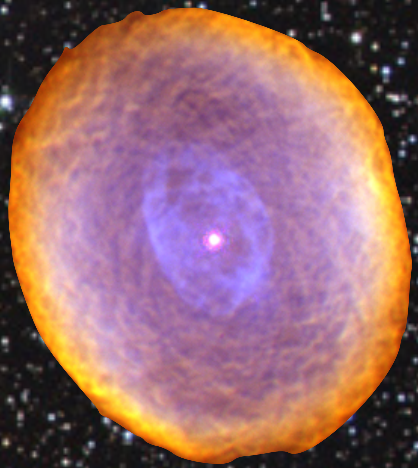
- Effective temperature
- Density -> surface gravity -> radius
- Luminosity
- Chemical composition
- Dynamics

Stellar Evolution







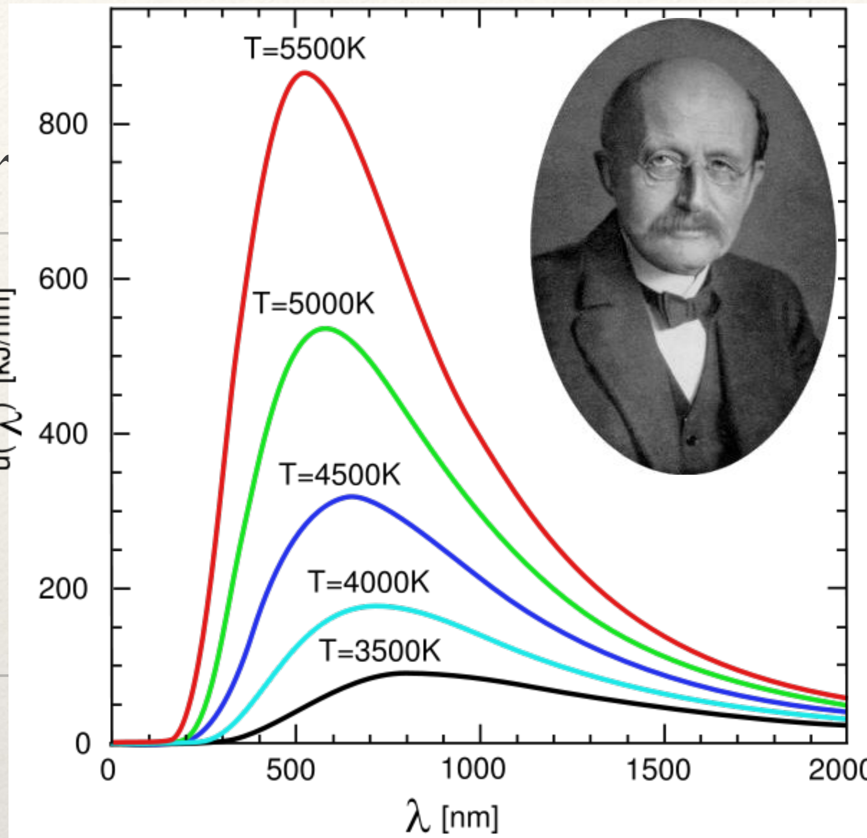


1. The Model Atmosphere

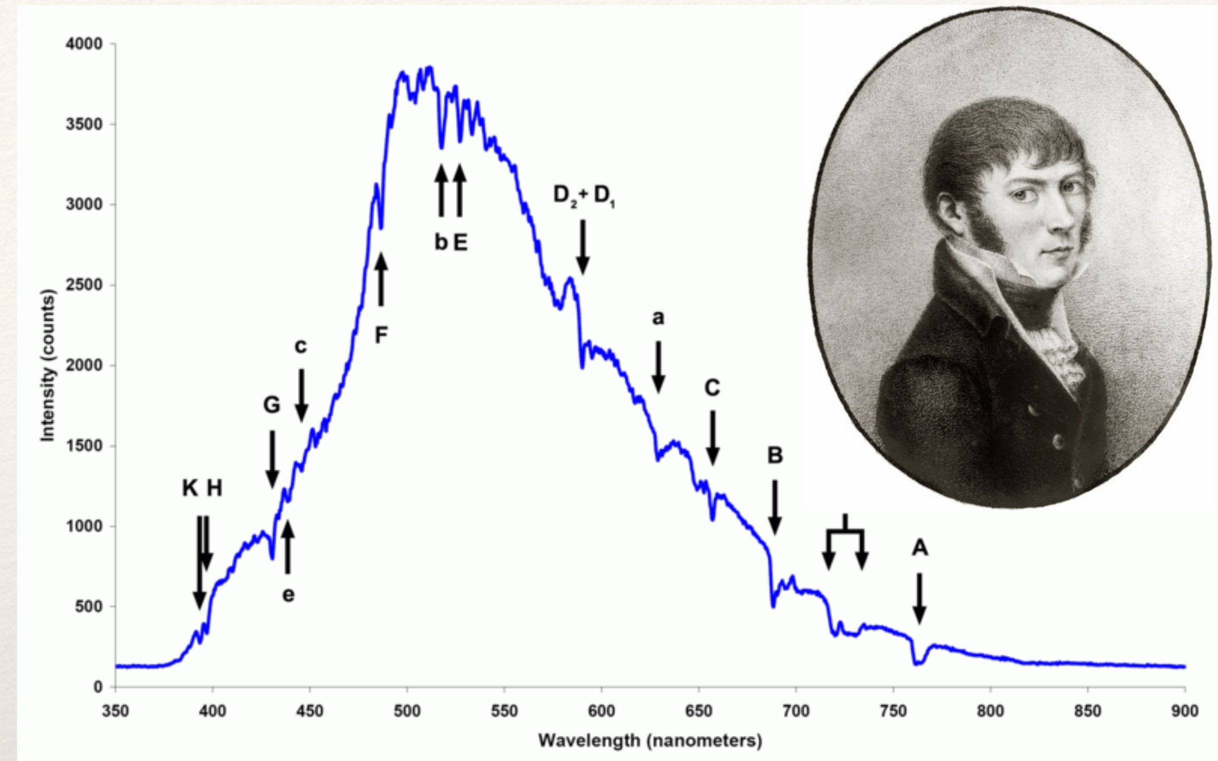
1. The radiative transfer equation
2. Radiative and hydrostatic equilibrium
3. Local and non-local thermodynamic equilibrium
4. Statistical equilibrium
5. Radiative opacity and atomic physics
6. Building a model atmosphere
7. Non-classical models (winds, diffusion, molecules)

Stellar Atmospheres

1894: Max Planck



1814: Joseph von Fraunhofer



Stellar interior: radiation in full LTE is “grey”: obeys Planck’s law

Stellar surface: radiation obeys Kirchoff’s laws

Absorption lines governed by number of ions and density of electrons

A “model atmosphere” allows the emergent radiation to be compared with the observed spectrum.

Early models were “one zone” models. Limited …

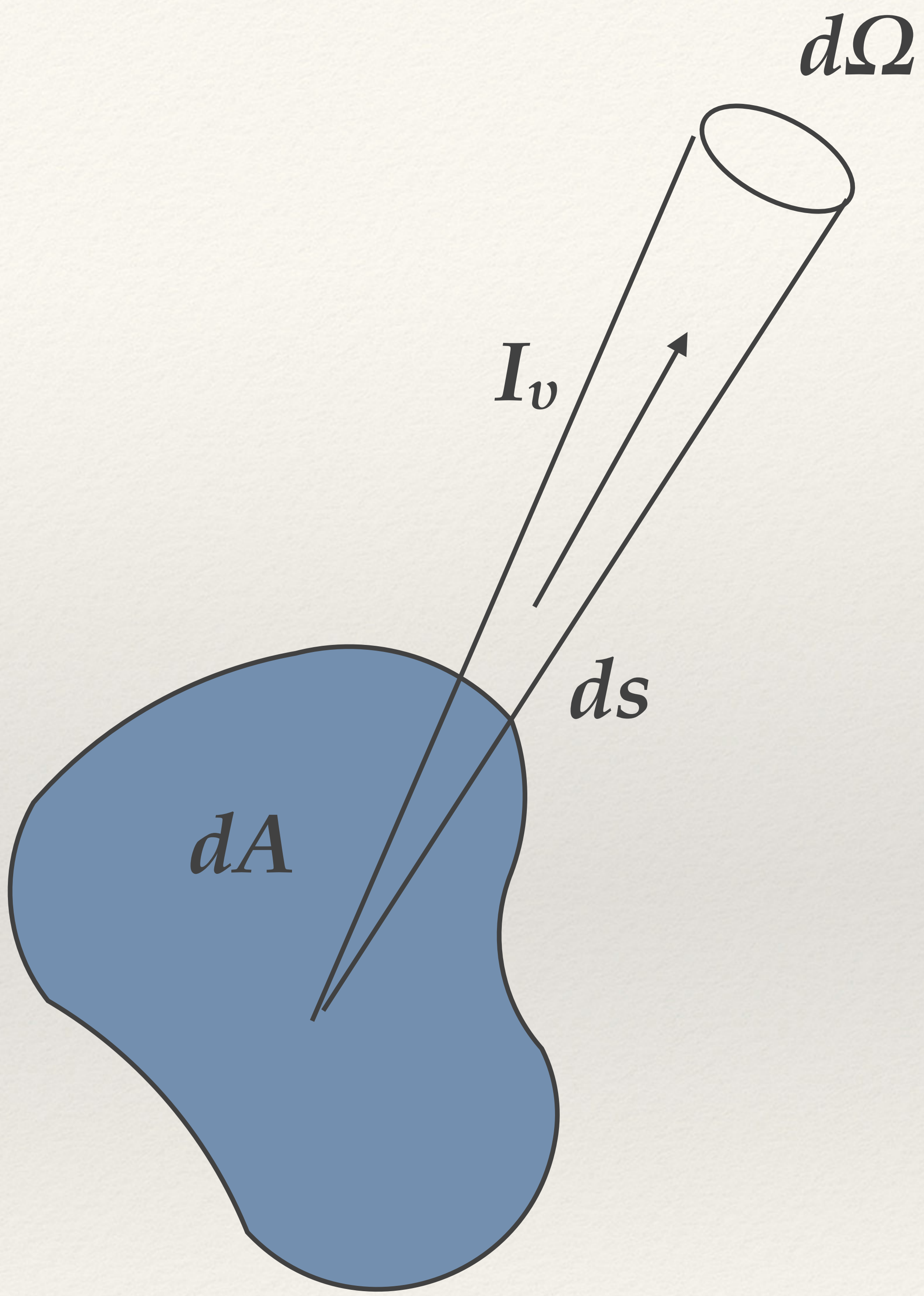
0. Assumptions

1. The model atmosphere
    1. **LTE** or non-LTE
    2. **Plane-parallel** or spherical
    3. **Stationary**, expanding, or time-dependent
    4. Chemically **homogeneous** or stratified
    5. Line-opacity (none, **atoms**, molecules)
    6. Magnetic or **not**

1. Radiative Transfer

Specific Intensity, I_ν

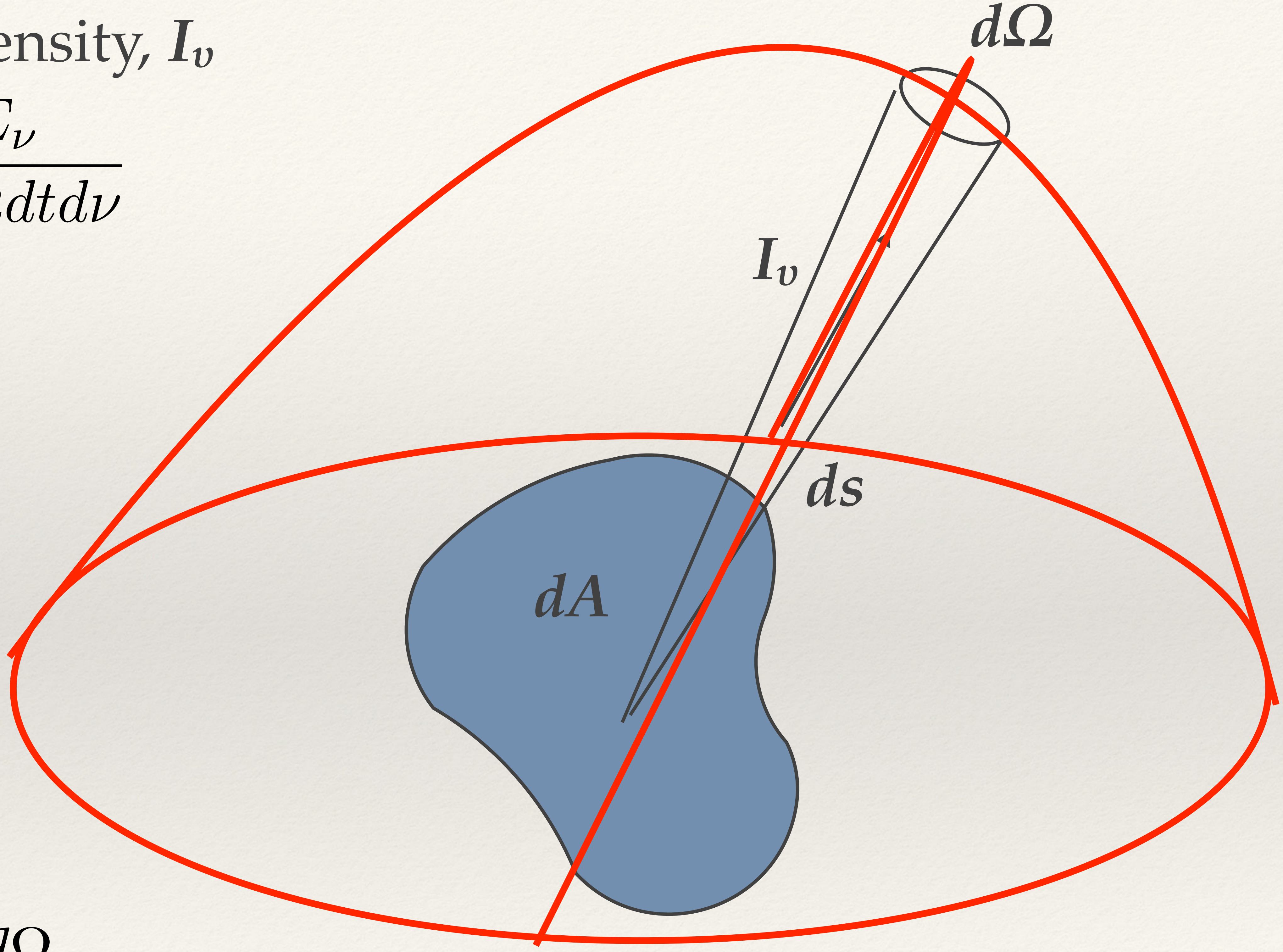
$$I_\nu = \frac{dE_\nu}{dA\,d\Omega\,dt\,d\nu}$$



1. Radiative Transfer

Specific Intensity, I_υ

$$I_\nu = \frac{dE_\nu}{dA d\Omega dt d\nu}$$



Flux, F_υ

$$F_\nu = \oint I_\nu d\Omega$$

1. Radiative Transfer

Specific Intensity, I_υ

The radiative energy per frequency interval, per normally incident area, per unit solid angle, per unit time.

$$I_\nu = \frac{dE_\nu}{dA d\Omega dt d\nu}$$

$$d\Omega = \sin\theta d\theta d\phi$$

Flux, F_υ

The radiative energy per unit area. The specific intensity from solid angles in all directions.

$$F_\nu = \oint I_\nu d\Omega$$

1. Radiative Transfer

Extinction Coefficient, κ_ν

The combined effects of absorption and scattering of radiation. The energy removed from a beam of radiation by an elementary volume of cross-section ***dA*** and length ***ds***:

$$dE_\nu = \kappa_\nu I_\nu dA ds d\Omega d\nu dt$$

Optical Depth, τ_ν

A dimensionless quantity used to describe the opaqueness of a stellar atmosphere. The optical depth decreases with height ***s***.

$$\tau_\nu = \int_{s_1}^{s_2} \kappa_\nu(s) ds$$

1. Radiative Transfer

Emission Coefficient, j_v

The energy added to a beam of radiation by an elementary volume of matter intercepting the beam is:

$$dV = dAds$$

$$dE_\nu = j_\nu dAdsd\Omega d\nu dt$$

Source Function, S_v

The ratio of the emission coefficient to the extinction coefficient. A useful quantity in computing the changes to radiation passing through a gas.

$$S_\nu = j_\nu / \kappa_\nu$$

1. Radiative Transfer

Radiative Transfer Equation (RTE)

The net change in intensity of a radiation beam as a result of its interaction with matter is obtained by combining the effects of emission and extinction:

net change in radiative energy = emission - extinction

$$dI_\nu dA d\Omega d\nu dt = j_\nu dA ds d\Omega d\nu dt - \kappa_\nu I_\nu dA ds d\Omega d\nu dt$$

this implies:

$$\frac{dI_\nu}{ds} = j_\nu - \kappa_\nu I_\nu$$

using the definition for optical depth:

$$\frac{dI_\nu}{d\tau_\nu} = \frac{j_\nu}{\kappa_\nu} - I_\nu$$

and finally:

$$\frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu$$

2. Radiative and Hydrostatic Equilibrium

Radiative Equilibrium

Conservation of energy is assumed to apply to the atmosphere of the star, hence no sources or sinks and the divergence condition yields:

$$\frac{d}{ds}\mathcal{F}(s) = 0$$

If all energy is carried by radiation:

$$\mathcal{F} = \int_0^\infty \mathcal{F}_\nu d\nu$$

Hydrostatic Equilibrium

Pressure gradient in equilibrium with local gravity so nett radial acceleration is zero.

$$\frac{dP}{d\tau} = \frac{g}{\kappa}$$

3. Local Thermodynamic Equilibrium

Local thermodynamic equilibrium (LTE) implies that:
electron and ion velocity distributions are Maxwellian,
the equation of state for matter (atoms and ions) balances the local radiation field;
temperatures measured from ions should match that from the flux distribution (as defined by the Planck function).
The principal criterion is that collisional processes dominate over radiative.

In strict LTE:

$$S_\nu = I_\nu = B_\nu$$

In LTE, the level populations for atoms and ions may be obtained from the Boltzmann excitation and Saha ionisation equations.

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-\frac{(E_u - E_l)}{kT}} \qquad \frac{N^{n+} N_{\mathrm{e}}}{N^{(n-1)+}} = \frac{2u^{n+}}{u^{(n-1)+}} \frac{(2\pi m_{\mathrm{e}} kT)^{3/2}}{h^3} e^{-\chi_{\mathrm{ion}}/kT}$$

3. Non-local Thermodynamic Equilibrium

When densities are low, or temperatures are high, radiative processes become significant relative to collisions. This has two consequences.

1. Radiation field departs from the Planck function: $S_\nu \neq B_\nu$
2. Electron-level populations depart from Saha-Bolzmann equilibrium.

4. Statistical Equilibrium

When densities are low, or temperatures are high, radiative processes become significant relative to collisions. This has two consequences.

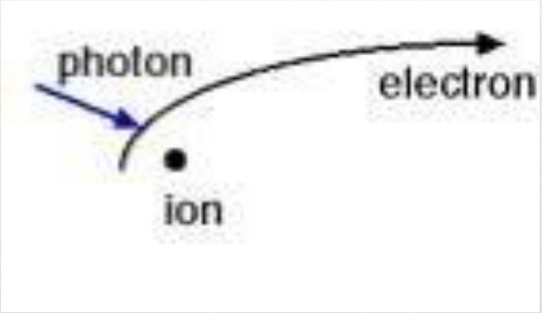
1. Radiation field departs from the Planck function: $S_\nu \neq B_\nu$
2. Electron-level populations depart from Saha-Boltzmann equilibrium.
3. Need to be calculated with Einsten-Milne rate equations to obtain details balance for all level populations

5a. Radiative Opacity and Atomic Physics

Continuous Opacity:

Scattering processes: between atoms, free electrons and photons

free-free



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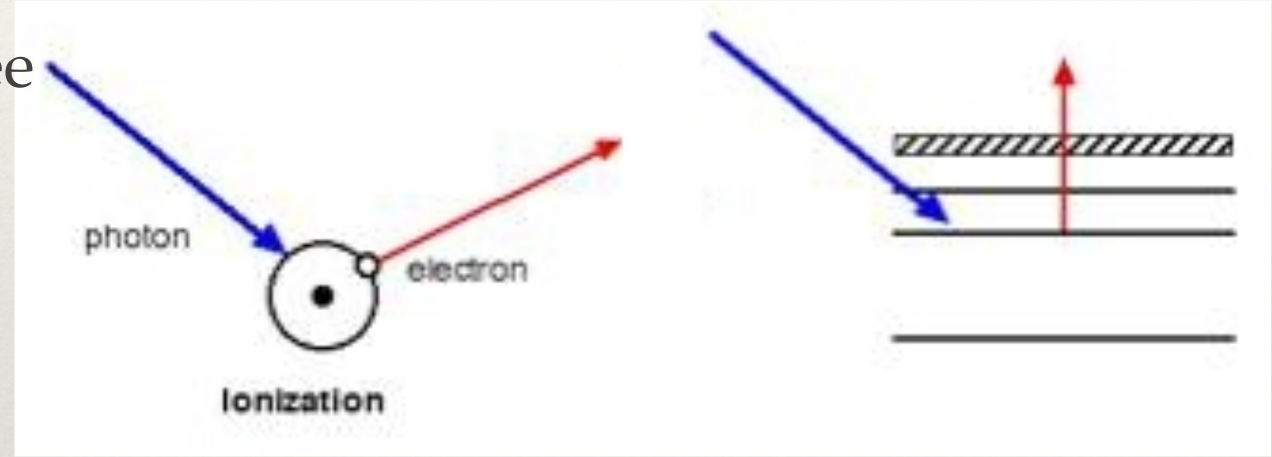
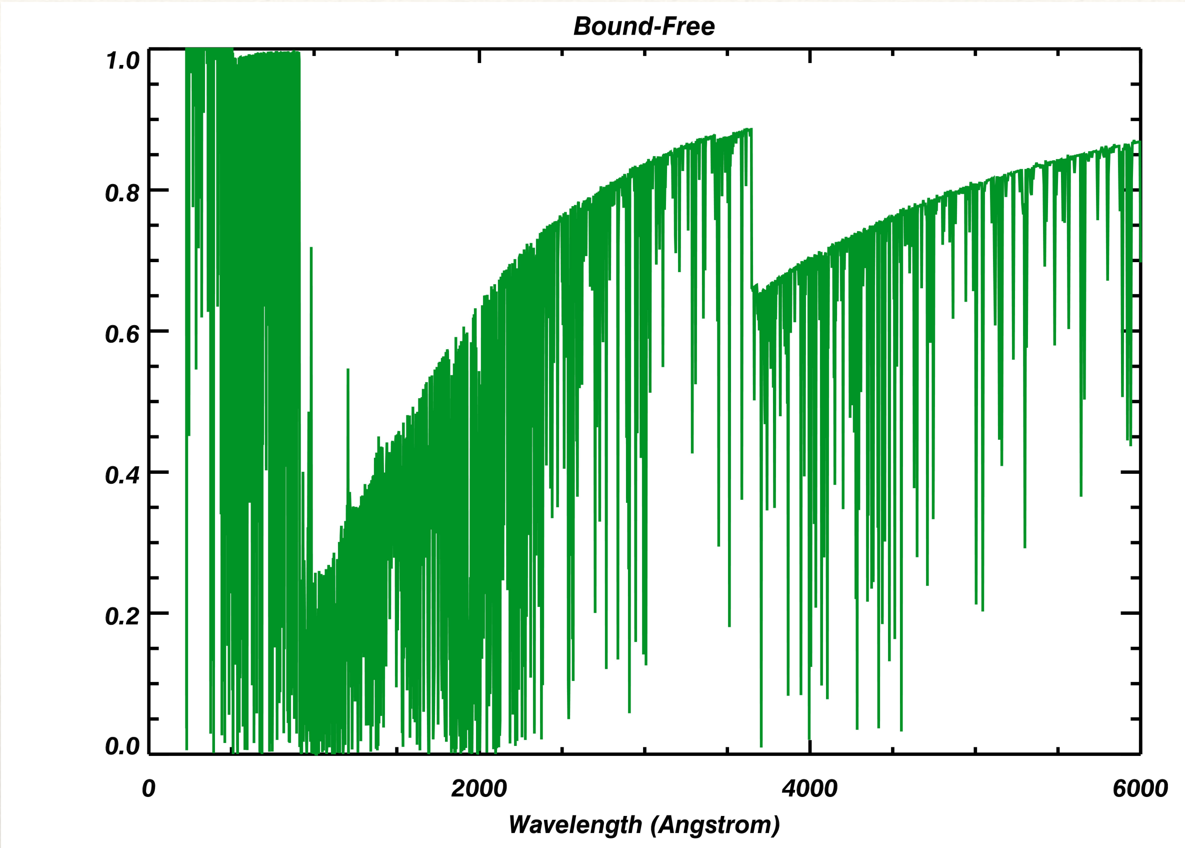
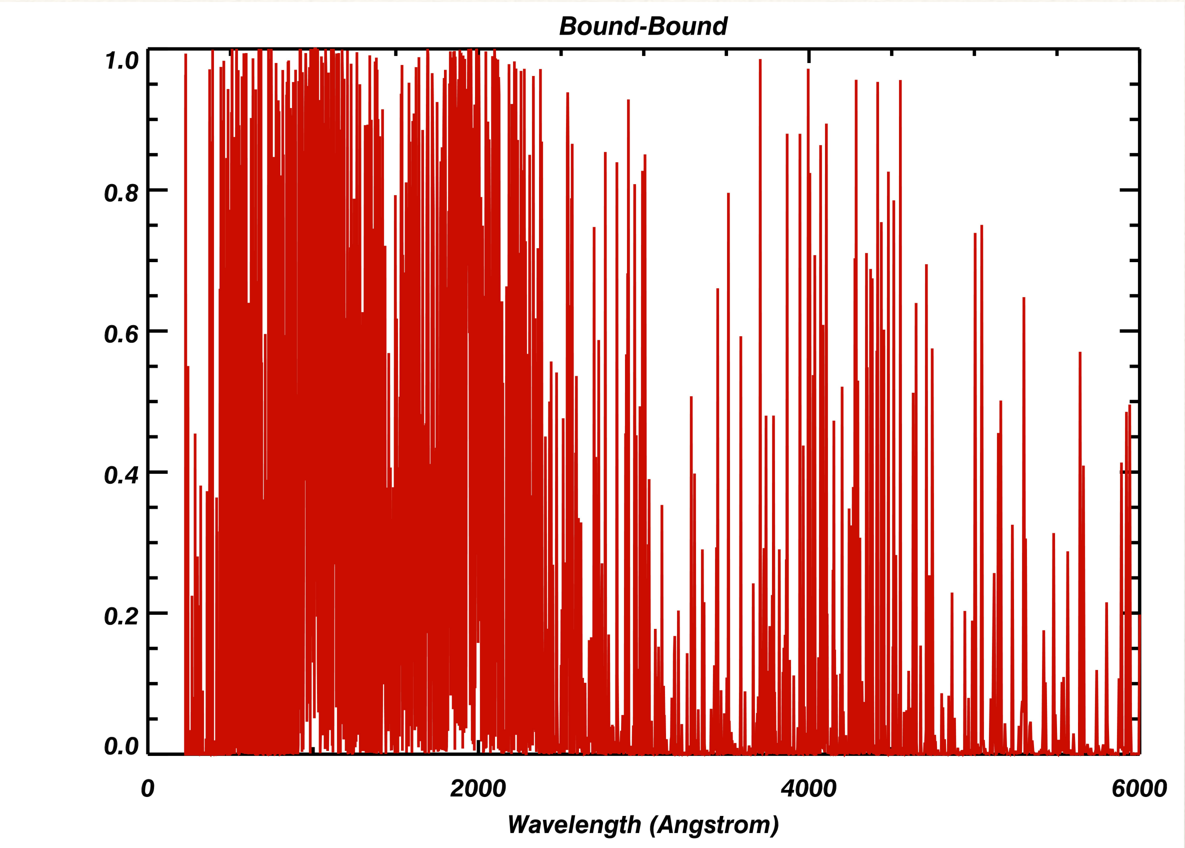


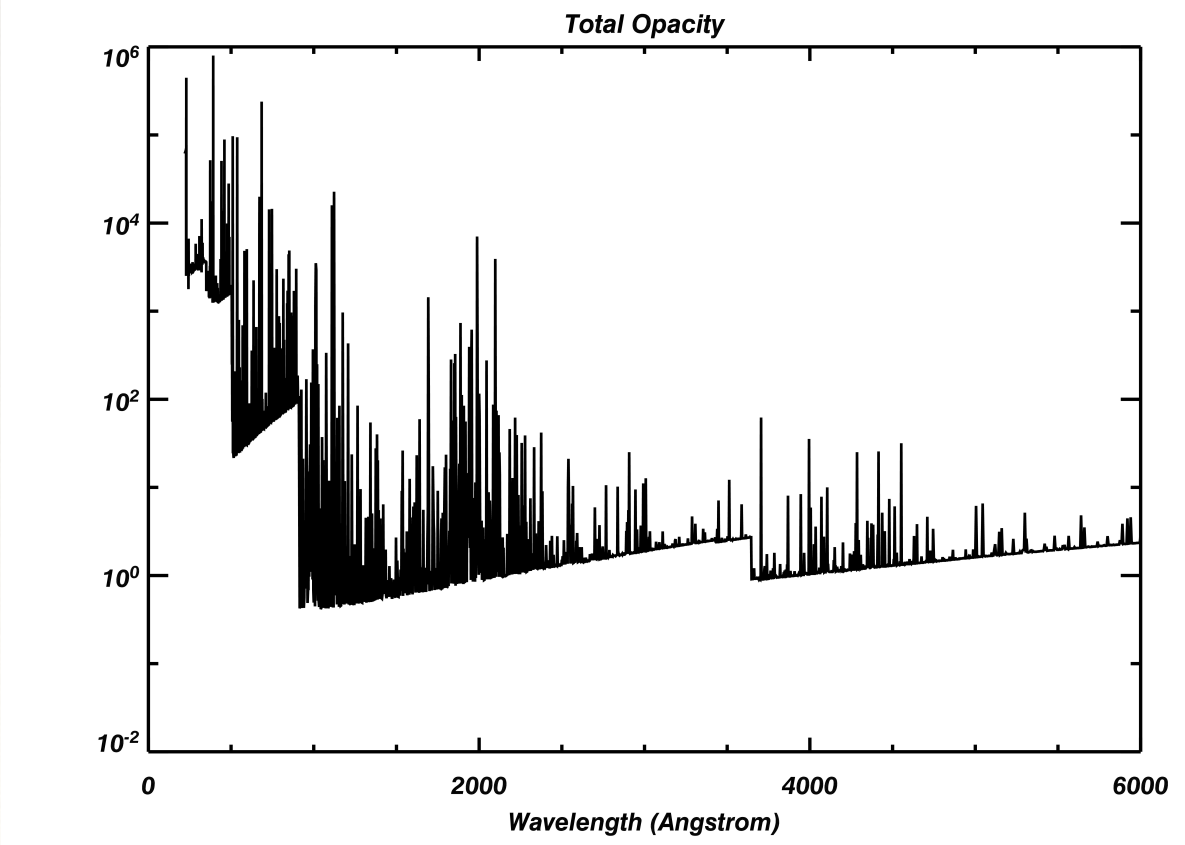
Line Opacity:

bound-bound

Contribution of processes to the opacity







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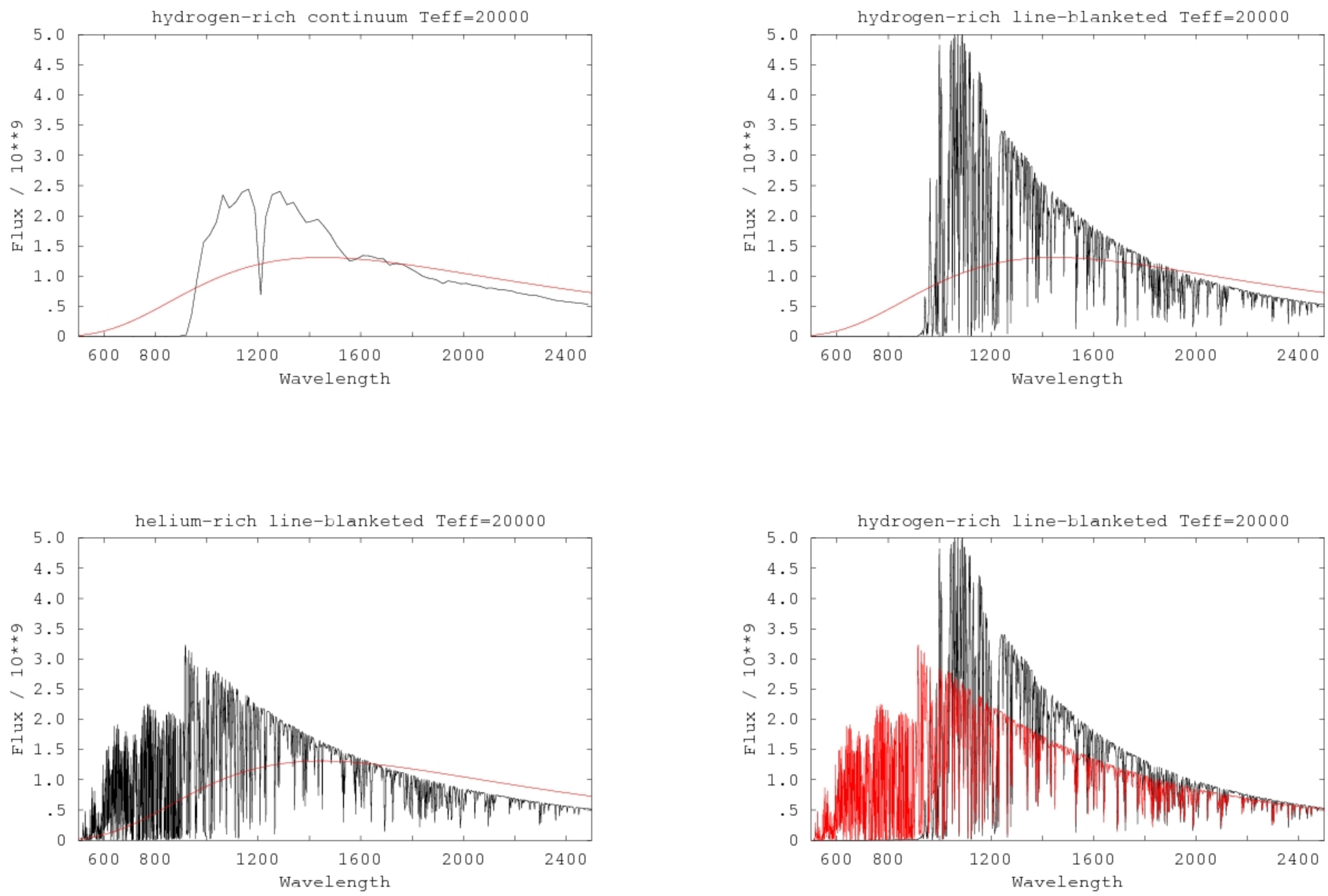
Effect of opacity on model atmosphere



6. Building a model atmosphere

v0

1. Adopt an initial temperature distribution: $T(\tau_{v0})$
2. Integrate the equation of hydrostatic equilibrium to obtain the pressure profile $P(\tau_{v0})$
3. Calculate other physical variables such as $\rho(\tau_{v0})$, $\kappa_{v0}(\tau_{v0})$ since they depend only on $P(\tau_{v0})$ and $T(\tau_{v0})$ under LTE
4. Construct an optical depth scale τ_v for each v
5. The source function $S_v(\tau_{v0})$ can now be found as a function of τ_{v0} and the RTE can be integrated
6. Adjust $T(\tau_{v0})$ to satisfy radiative equilibrium:

$$\frac{d}{ds}\mathcal{F}(s) = 0 \qquad\qquad F = \sigma T_{\mathrm{eff}}^4$$

7. [Adjust composition to satisfy chemical equilibrium]

7. model inputs and outputs

Assumptions: … several choices … + atomic data

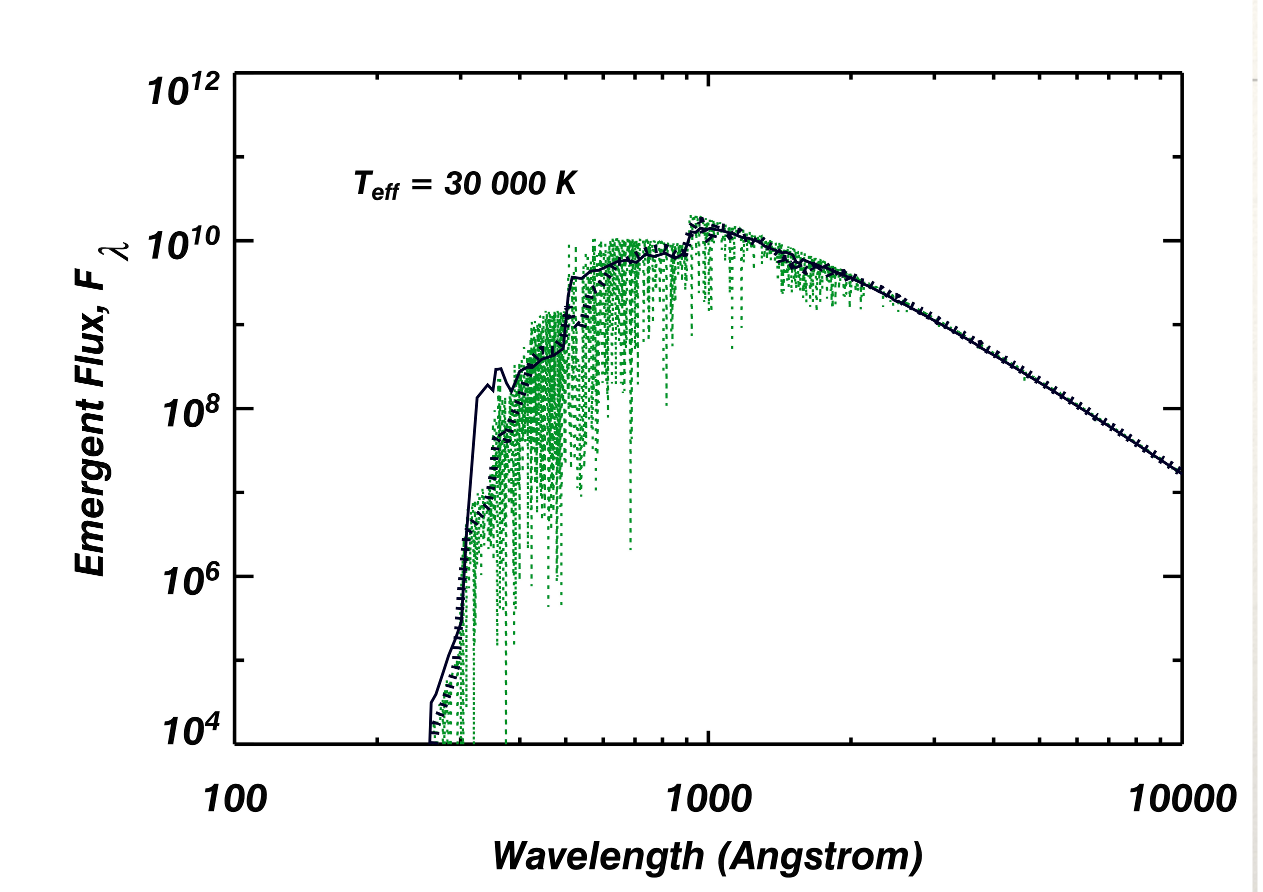
Input: T_{eff}, g, n_i, v_{turb}

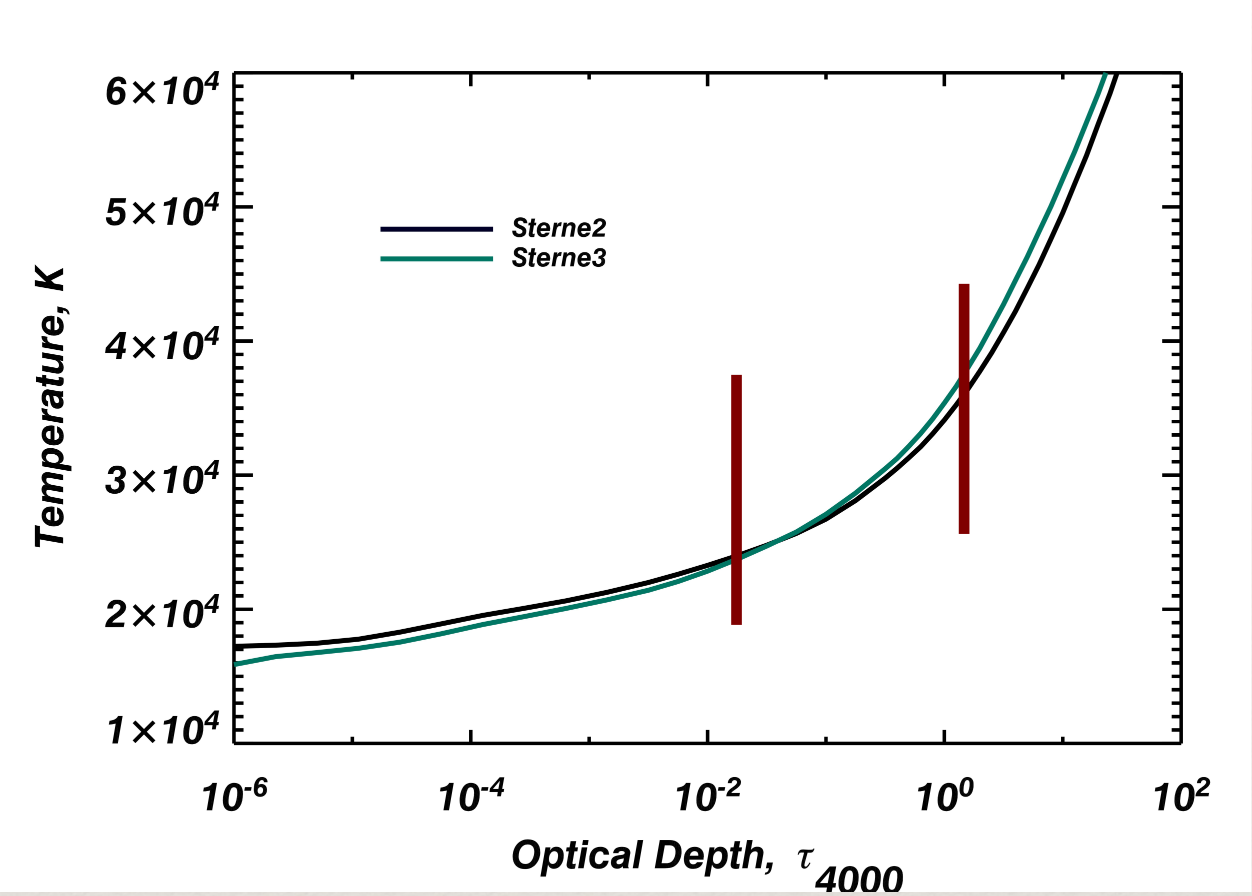
Output: **structure** T, P, n_e, κ as fn of $\tau_{\nu 0}$ or z (optical or geometric depth)

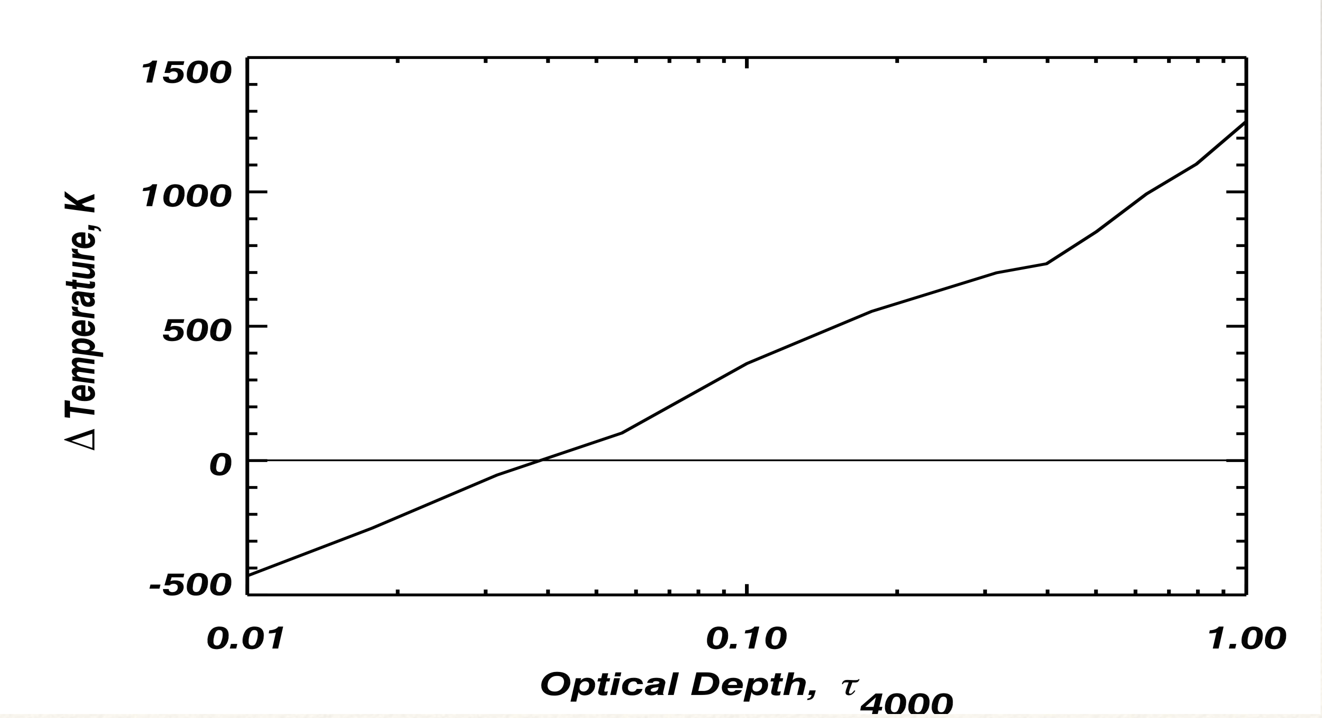
From **formal solution**: F_ν and $F_{\nu c}$ (line and continuum) :

1. low resolution spectrum over large frequency range
2. photometric magnitude for any filter
3. line profiles, equivalent widths for any line
4. high-resolution spectrum for any frequency range

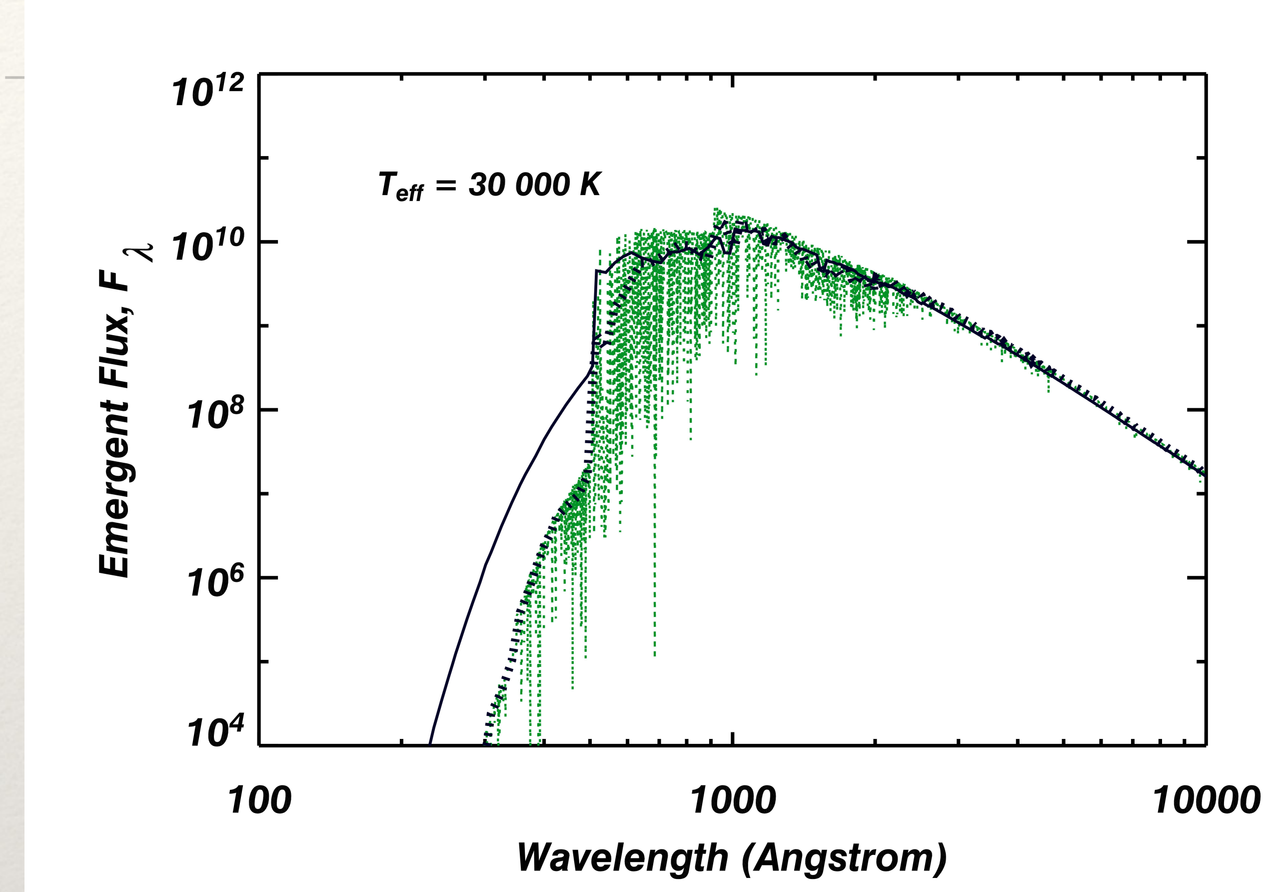
Results: Hydrogen-rich atmosphere

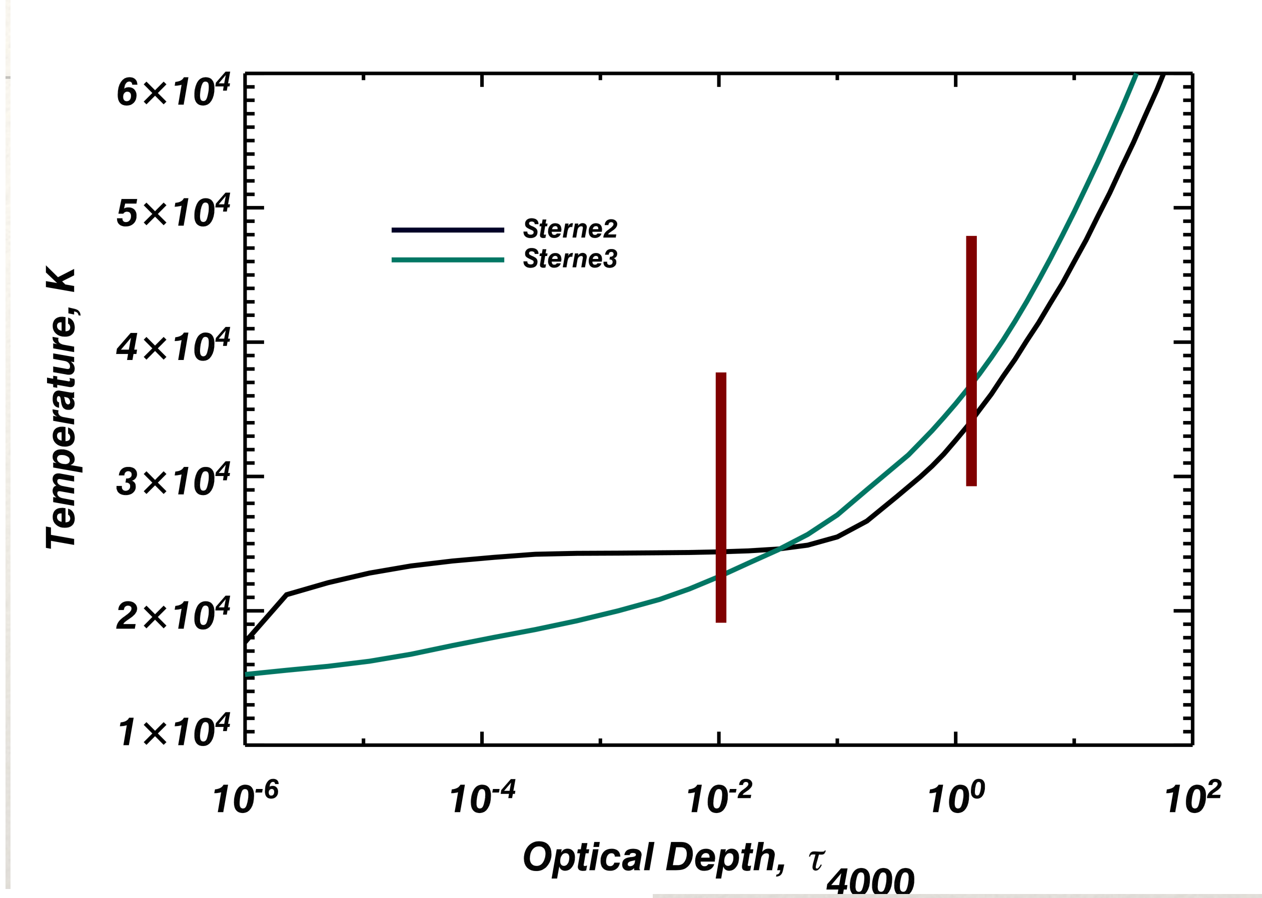


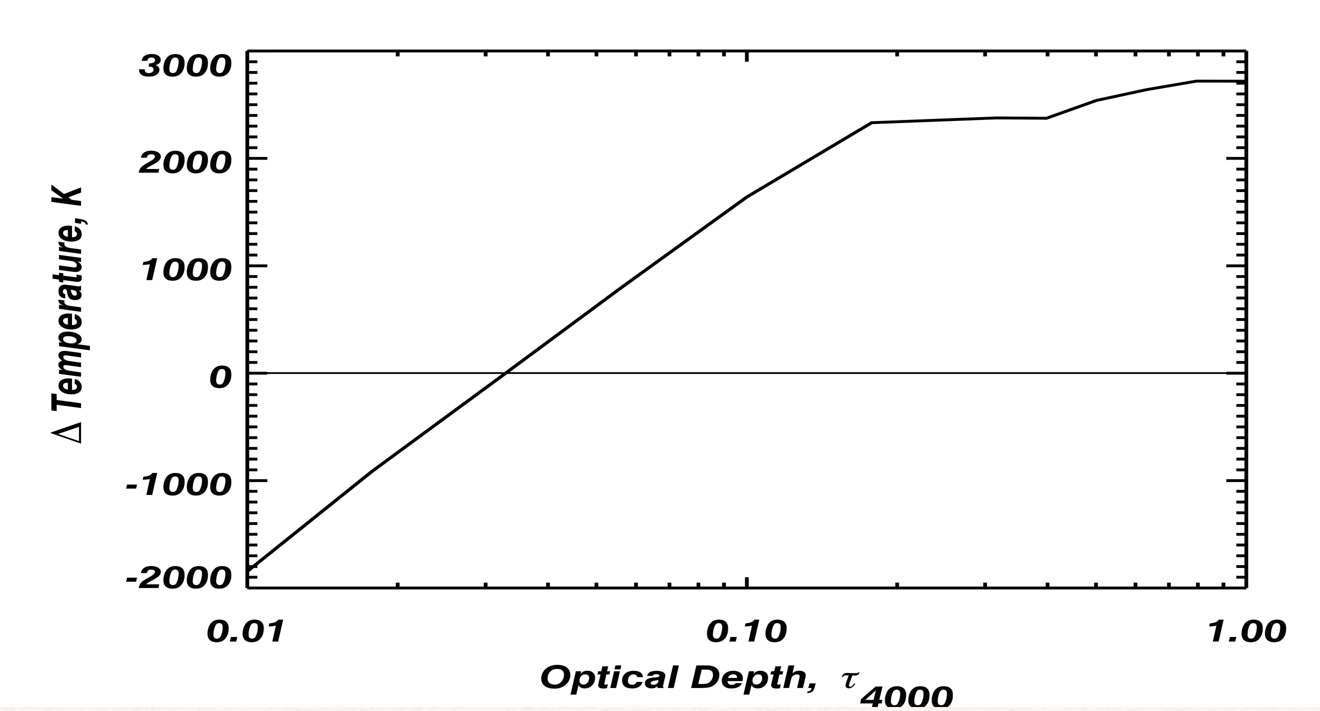




Results: Helium-rich atmosphere





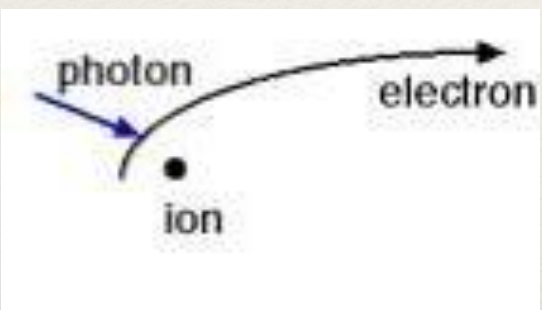


A1. Stellar Opacities

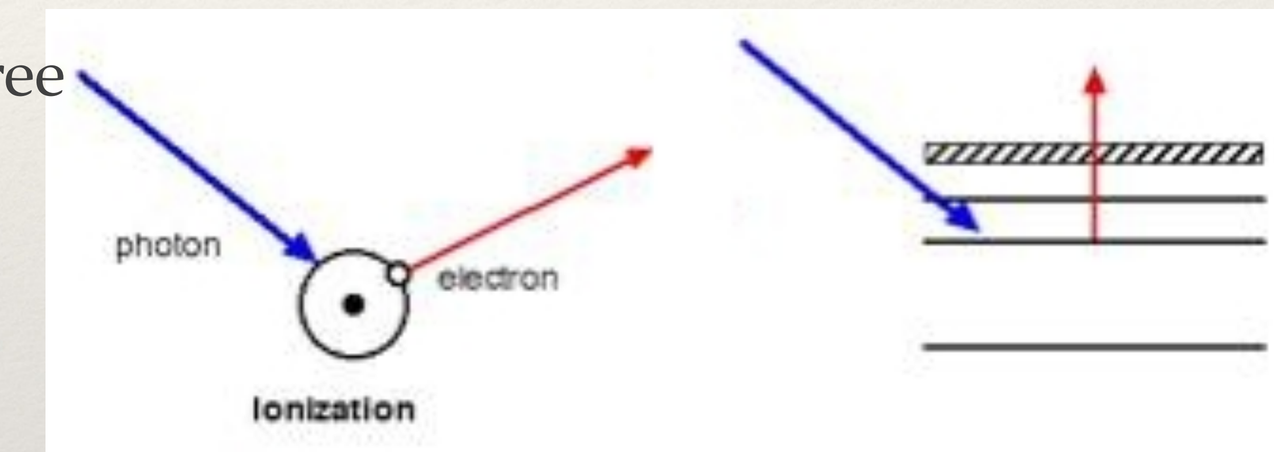
Continuous Opacity:

Scattering processes: between atoms, free electrons and photons

free-free



bound-free



Line Opacity:

bound-bound

Bound-free absorption cross-section

The cross-section for absorption of a photon and ionisation from energy level n is approximately Gaunt (1930):

$$\sigma_\lambda^{bf} = \frac{32\pi^2 e^6}{3^{3/2} h^3 c^3} R \frac{\lambda^3}{n^5} g_n \cong \frac{\alpha_o g_n \lambda^3}{n^5}$$

where $\alpha_o = 1.044 \times 10^{-26}$ when λ is in angstroms

STERNE2(2003) used photoionisation cross-sections calculated by Kurucz (1970):

H, He, O, Mg, Al, Si and Ca

& Peach(1970):

C & N

The Opacity Project & The IRON Project

The Opacity Project (OP), formed in 1984, is an international collaboration involving research groups from the U.K., France, Germany, Venezuela and the United States.

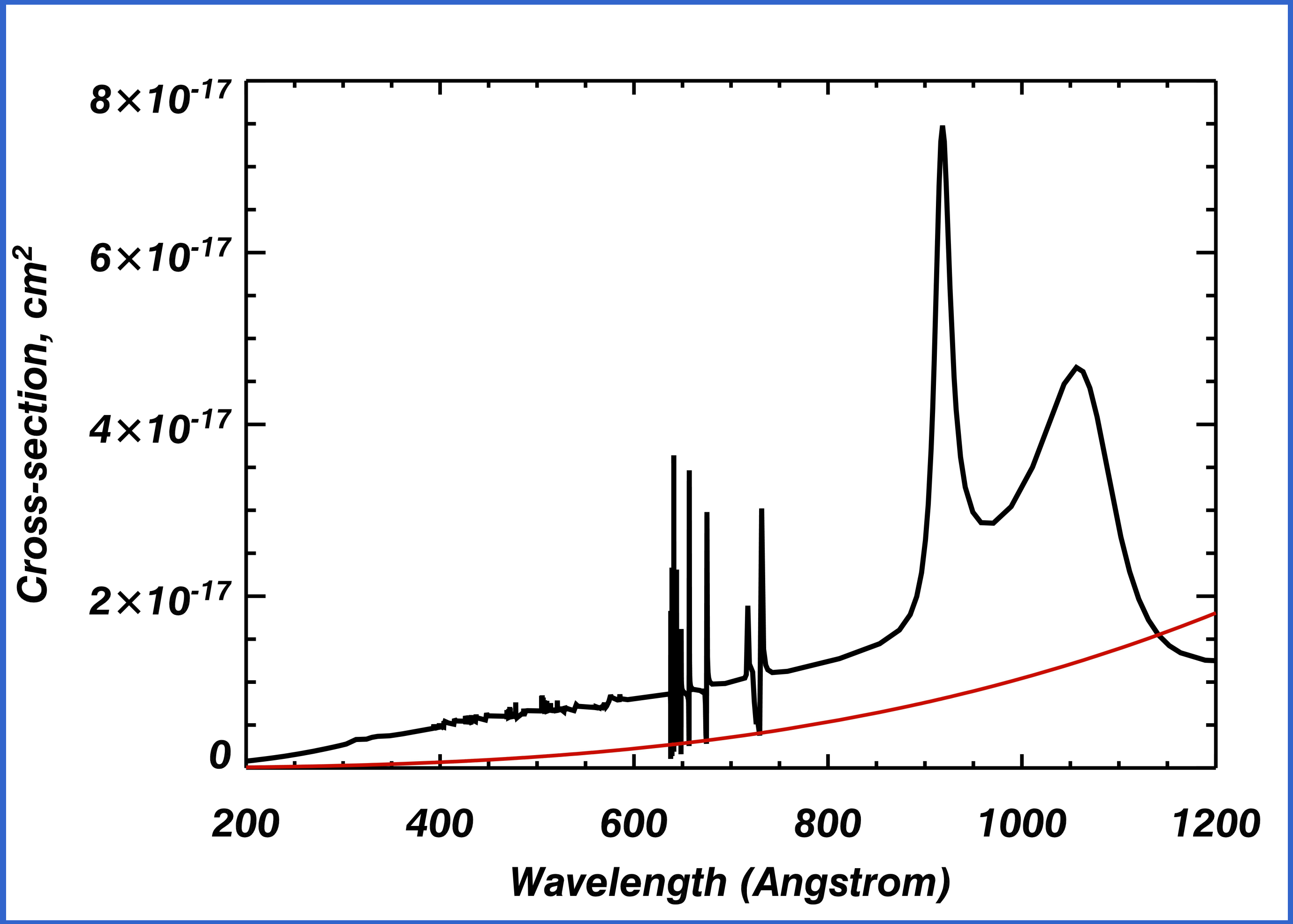
The aim of the project is to compute accurate atomic data required for opacity calculations, including energy levels, transition frequencies, oscillator strengths and absorption cross-sections.

Cross-sections were computed for the lowest-lying electron states in H, He, Li, Be, B, C, N, O, F, Ne, Na, Mg, Al, Si, S, Ar, and Ca have been included in STERNE3.

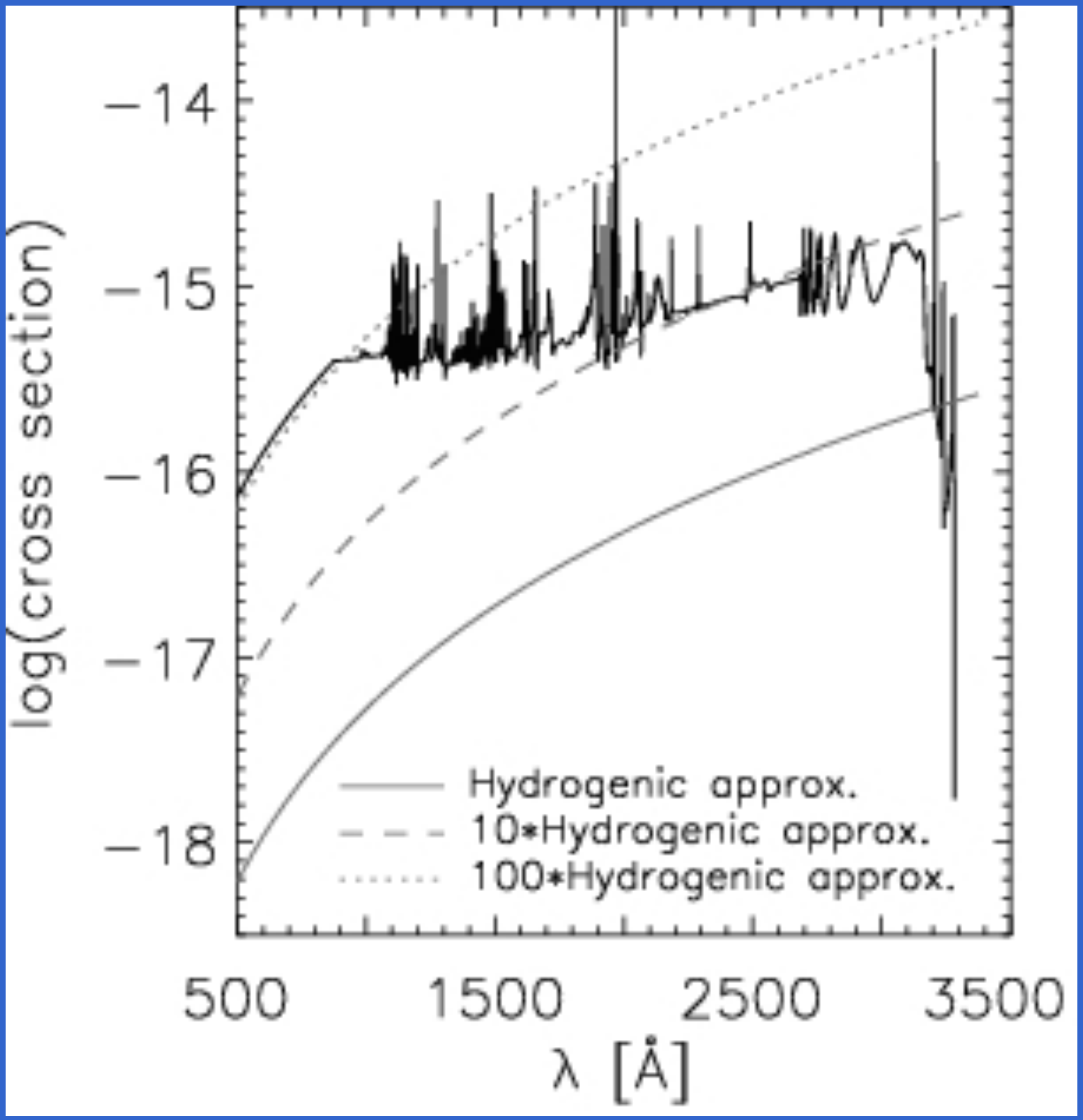
The IRON Project (IP) is carrying out new calculations for the iron group elements.

Cross-sections for Fe I, Fe II, Fe II have been included in STERNE3.

Comparison: Absorption cross-sections

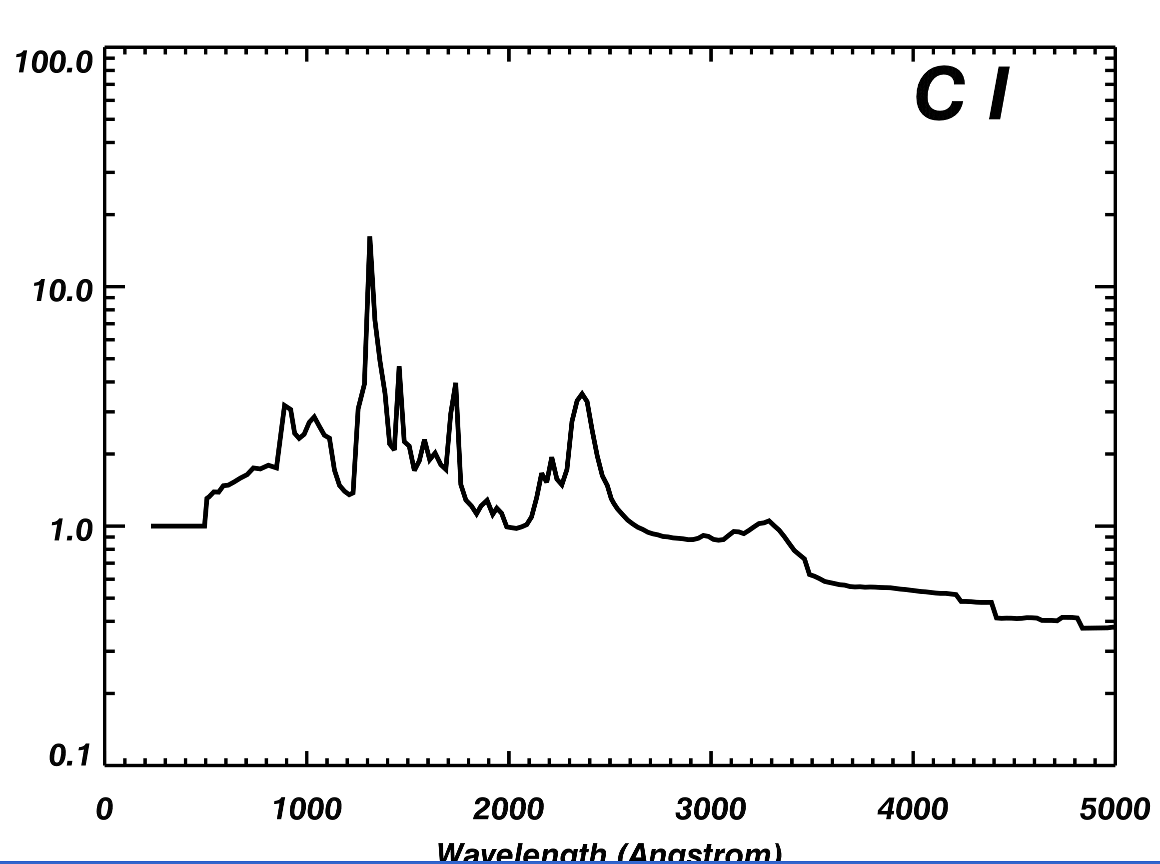


OP C I cross-section compared to the hydrogenic approximation (red curve).

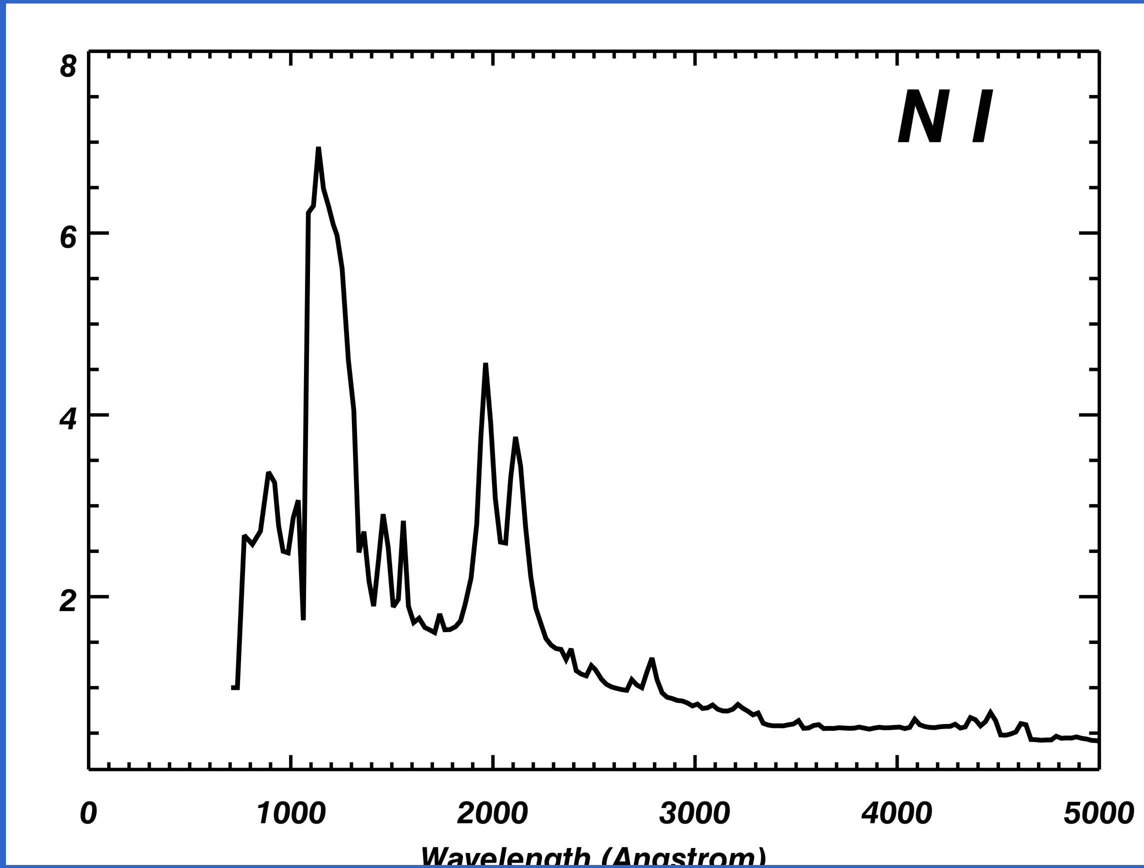


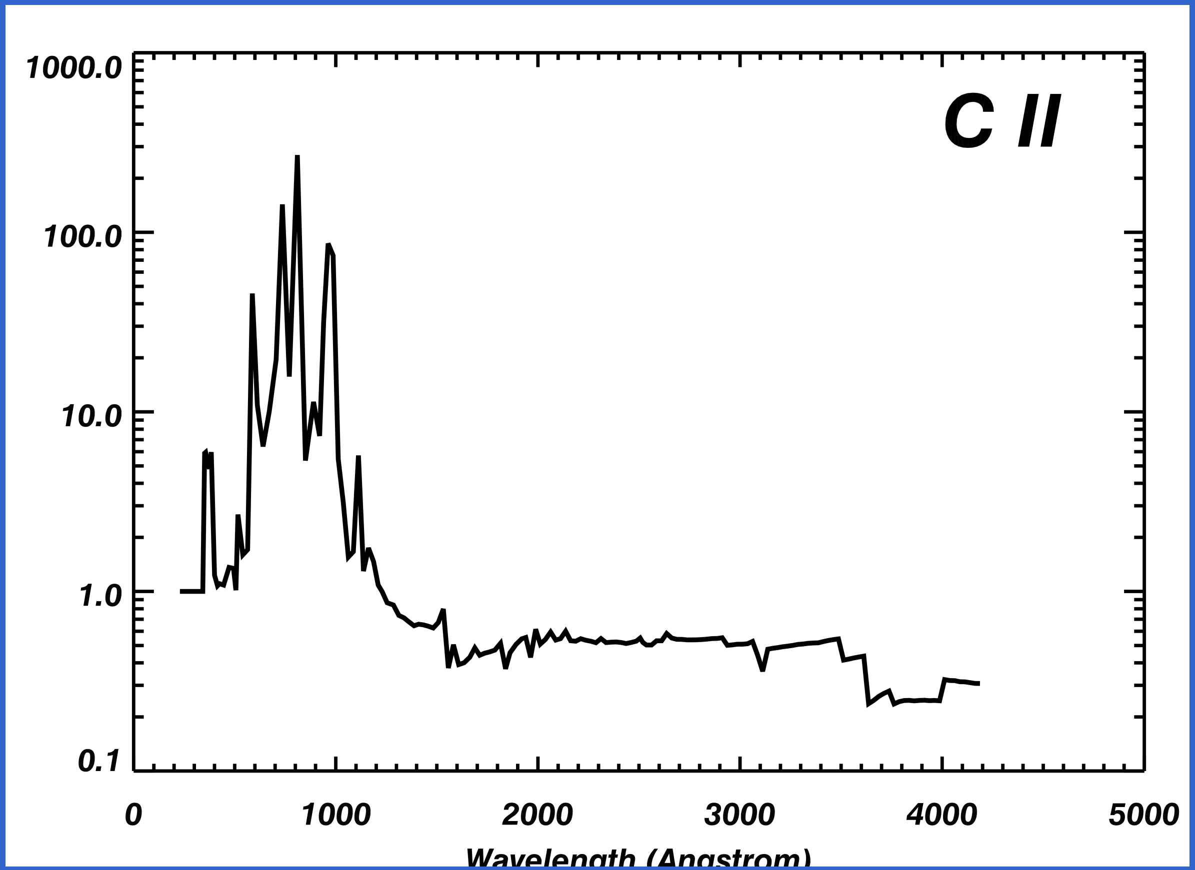
IP Fe I cross-section compared to the hydrogenic approximation.

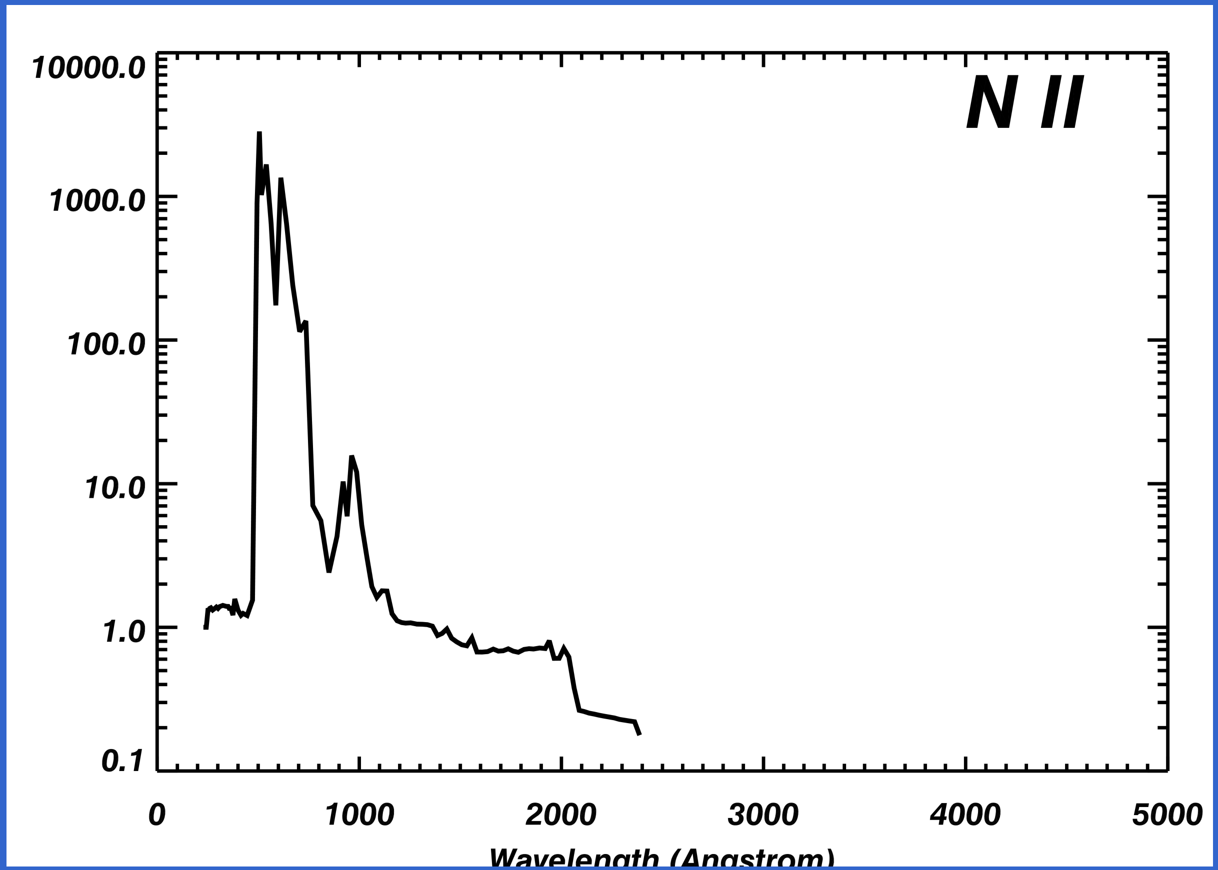
Comparison: Opacity



$$\frac{\kappa^{bf}_{STERNE3}}{\kappa^{bf}_{STERNE2}}$$

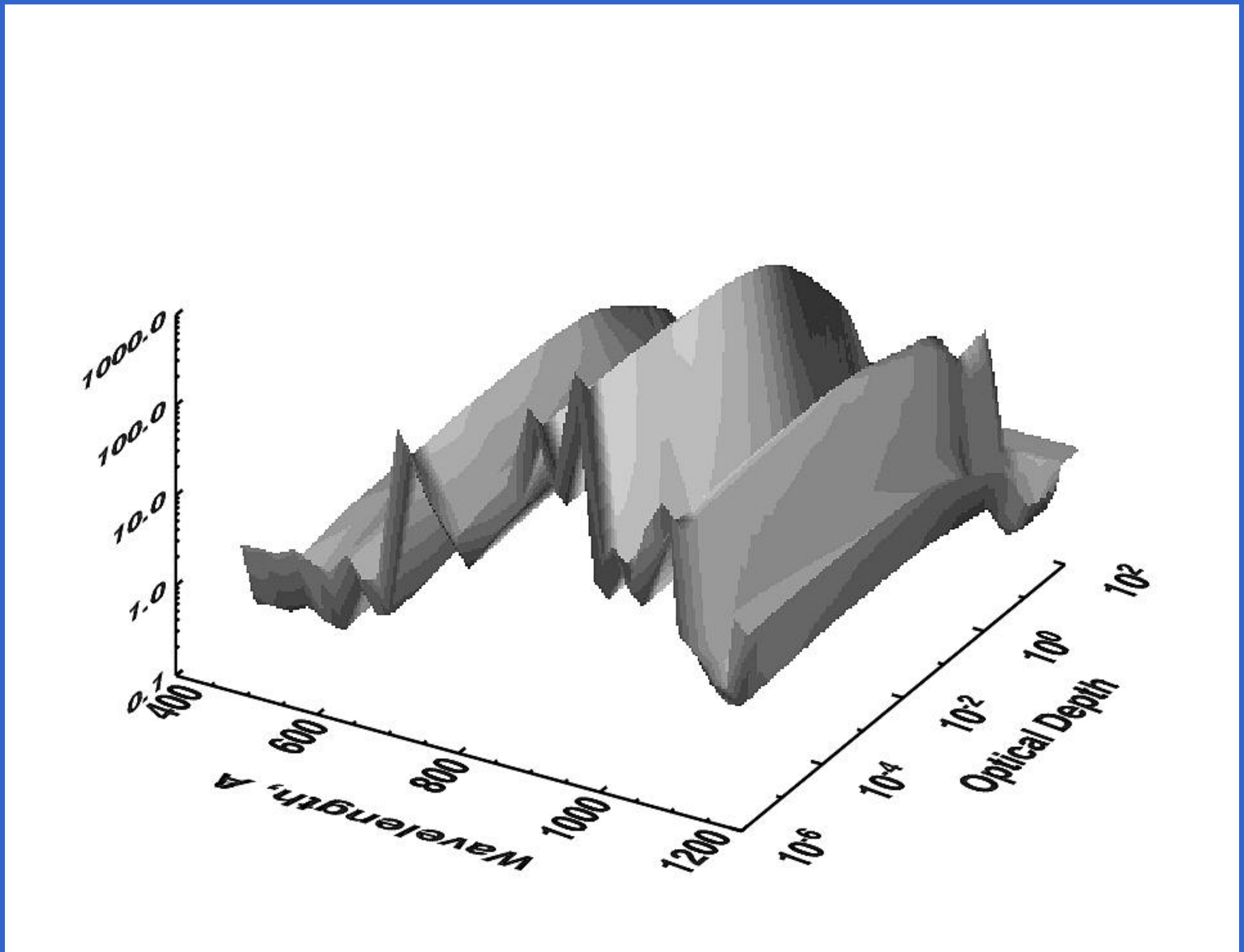




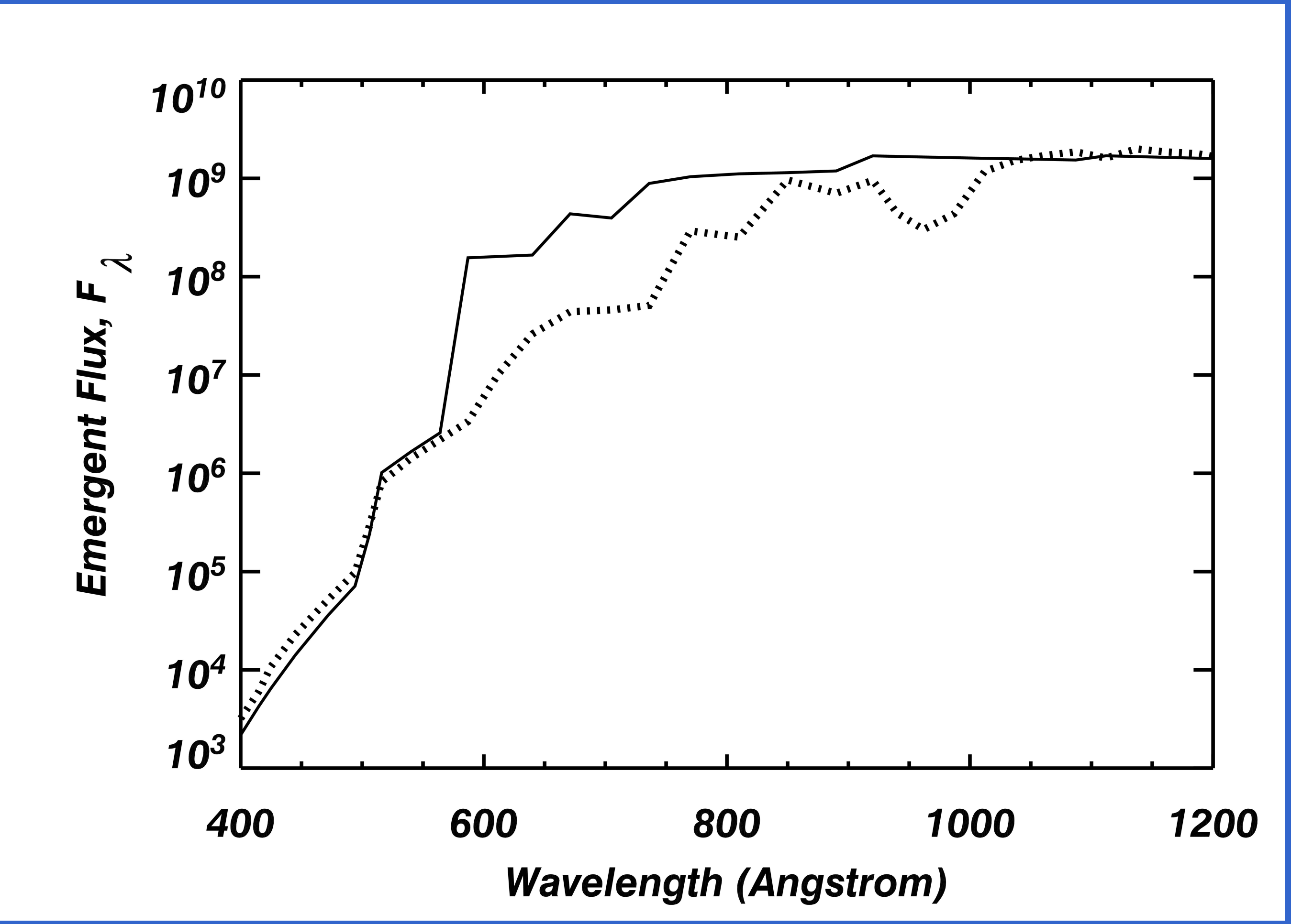


Results

An increase in the CII opacity when using the OP cross-sections leads to an increase in the continuum opacity at λ > 1000 angstroms.



Ratio of CII opacity computed with the OP cross-sections to the opacity computed using the Peach data.



Effect of the CII opacity on the emergent flux. The dotted line represents the model with the new opacities. T_{eff} = 20 000 K

A2. Chemical Diffusion

In complete chemical equilibrium, the diffusive velocities for each chemical species, i, must be zero.

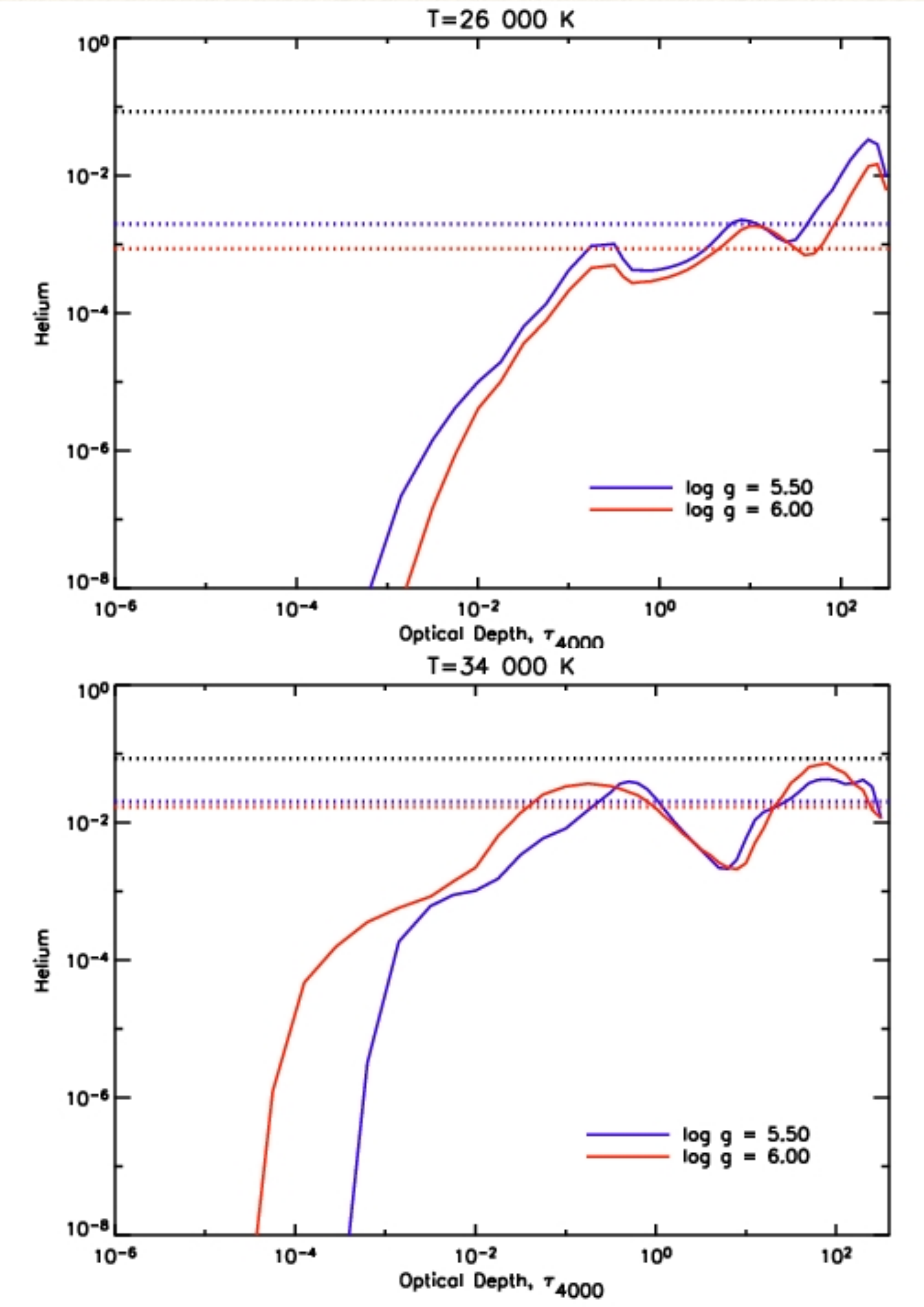
To satisfy this requirement, the specific density of each element, ρ_i, must satisfy the following equation:

$$\left(1-\frac{A_1\left(Z_i^{eff}+1\right)}{A_i\left(Z_1^{eff}+1\right)}\right)g=\frac{1}{\rho_i}\frac{4\pi}{c}\int_0^\infty \kappa_{\nu i}H_\nu d\nu$$

where $\kappa_{\nu i}$ represents the specific opacity. A is the atomic mass and Z the effective charge of each ion.

Thus, under the diffusion approximation, the chemical composition is a function of the local opacity only, and not of the initial composition.

Chemical equilibrium for hot subdwarfs



← Helium abundance vs depth in atmosphere

→ H and He line profiles for homogeneous and stratified atmospheres