Research workshop on evolved stars

Spectral classification

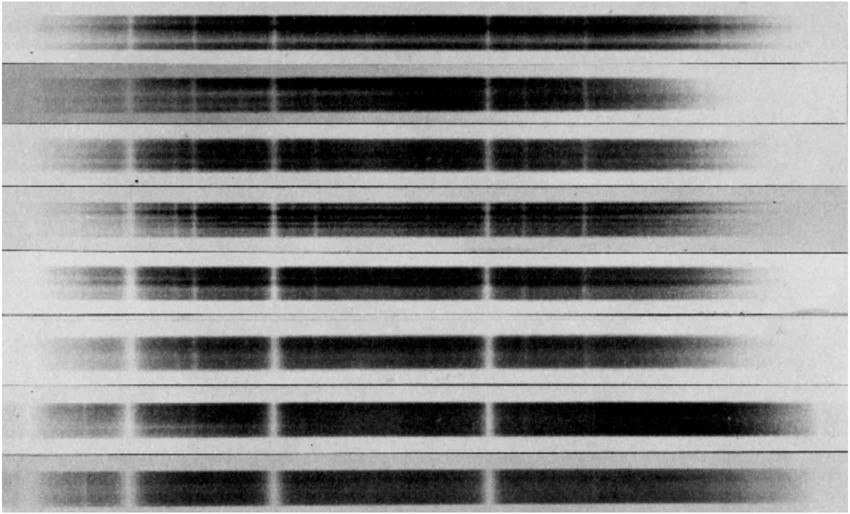
Matti Dorsch[1,2]

[1]University of Potsdam, [2]FAU Erlangen-Nürnberg

21. August 2023

Universität Potsdam

Classification: history



Classification: history

Mid/End of 19th century:

- ability to capture spectra of many of stars
- large number of stars, but small number of distinct spectra
- not much was known about physical origin of spectral lines

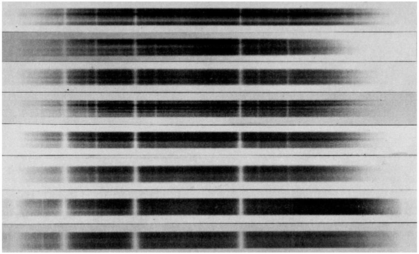


Figure: Spectra captured on photographic plates (negative!).

First strategy: find similar spectra → classes of spectra
order classes in some way
(A, B, C, D, ...; E. C. Pickering, W. Fleming 1890s)

Today's point of view

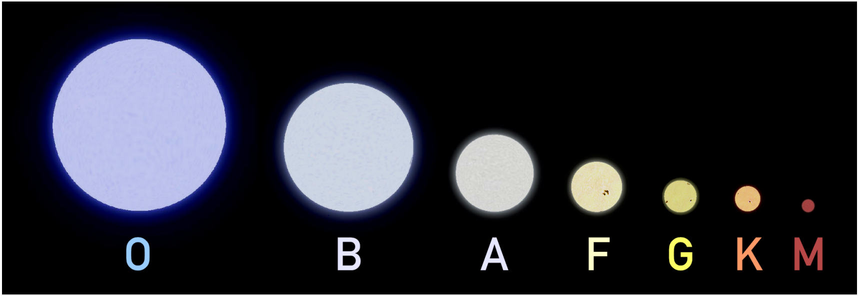


Figure: Spectral types O to M: schematic main sequence size and color.

- stars can be classified by the strengths of their absorption lines
- spectral lines depend mostly on atmospheric temperature (T_{eff})

$\rightarrow$ classes can be ordered by temperature
Annie Jump Cannon $\sim$1910

Line strengths

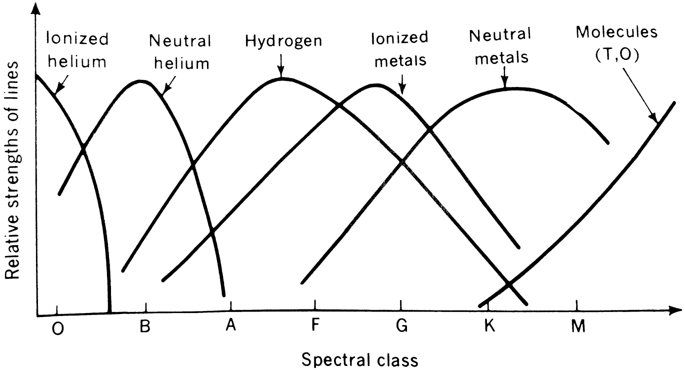


Figure: Relative line strengths with spectral class (G. Abell, 1964).

Why is that?

Line strengths: It's atomic physics!

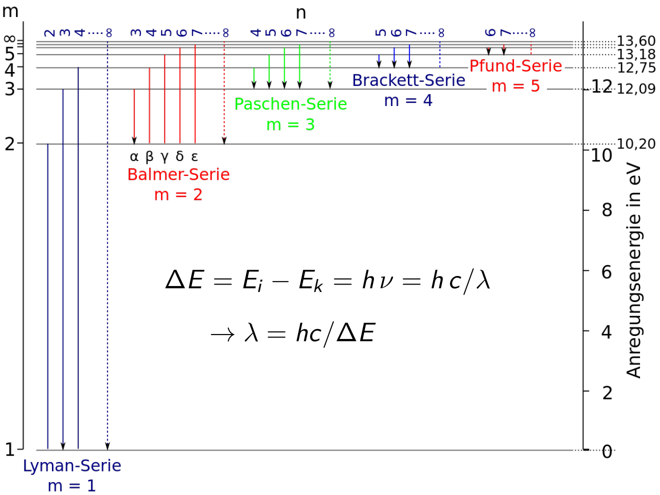


Figure: Hydrogen energy levels and transition series.

Line strengths: level populations

Absorption lines are only visible if the lower level is populated!

The ratio of populations of any two energy levels is given by the **Boltzmann equation**

$$\frac{n_i}{n_k} = \frac{g_i}{g_k} e^{-(E_i - E_k)/k_B T},$$

where n_i is the population of level i, E_i its energy with respect to the ground state, and g_i the statistical weight (number of possible states)

$$g_i = 2 \cdot J_i + 1,$$

where J_i is the total angular momentum quantum number.

$$\rightarrow \frac{N_i}{N_I} = \frac{g_i e^{-E_i/k_B T}}{\sum_k g_k e^{-E_k/k_B T}} = \frac{g_i e^{-E_i/k_B T}}{U_I}.$$

U_I is called the partition function.

Line strengths: ionization fractions

Lines from ionized species are only visible if enough atoms are ionized!

The number ratio of atoms in two subsequent ionization stages is given by the **Saha equation**:

$$\frac{N_{I+1}}{N_I} = \frac{2U_{I+1}}{n_\mathrm{e} U_I} \left(\frac{2\pi m_\mathrm{e} k_B T}{h^2} \right)^{3/2} e^{-\chi_I / k_B T}$$

where h is the Planck constant, m_e the electron mass, n_e the local electron density, and χ_I the ionization energy.

This can be combined with the condition of charge conservation to obtain the ionization fractions for all atoms.

Line strengths: ionization fractions

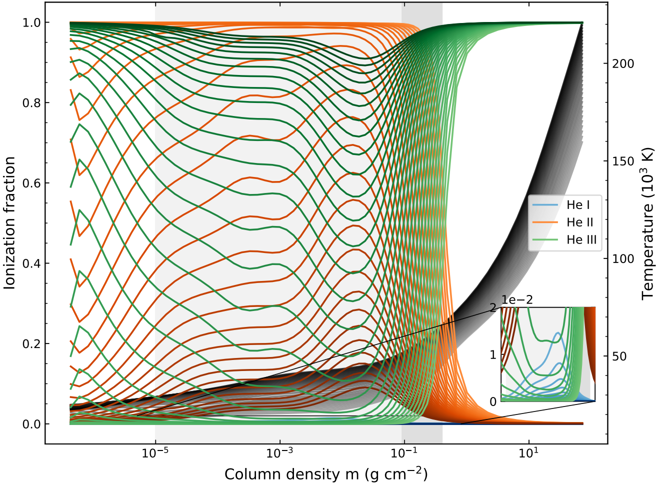


Figure: Ionization fractions for helium and $T_{\text{eff}} = 30\,000$ to $60\,000\,\text{K}$. The black curves show the temperature stratification (light = cooler).

Effective temperature

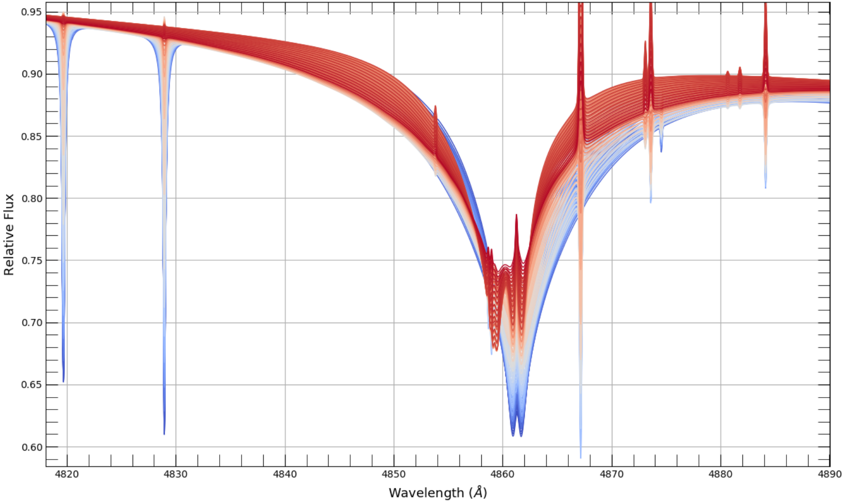


Figure: Synthetic spectra with T_{eff} from 35 000 to 48 000 K in steps of 1000 K, colored from blue (cooler) to red (hotter).

Line strengths

The combined effect.

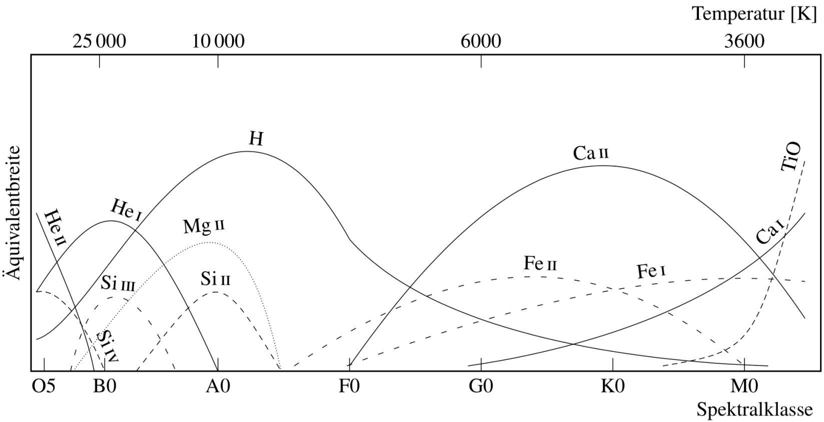
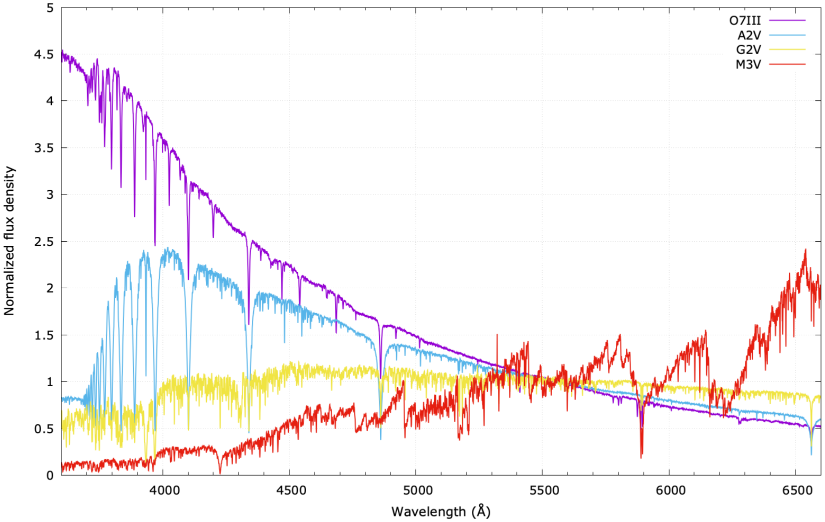
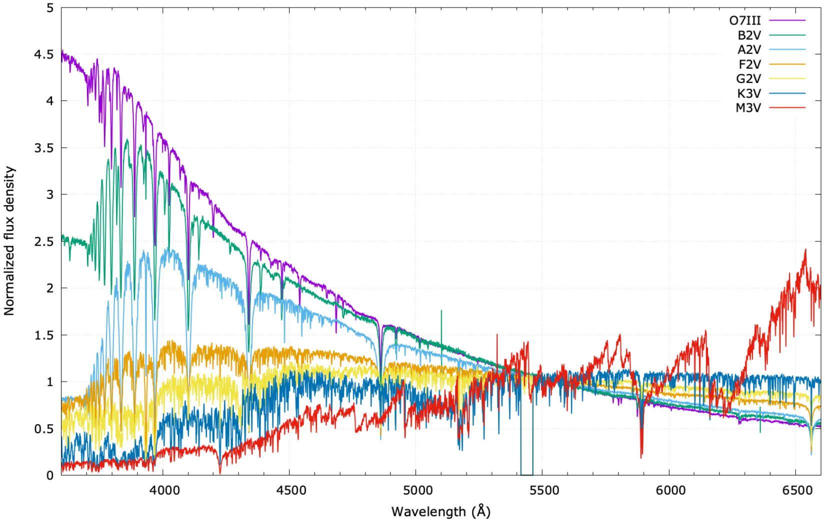


Figure: Line strengths depending on T_{eff}. The strengths are only comparable for a specific element (e. g. Ca).

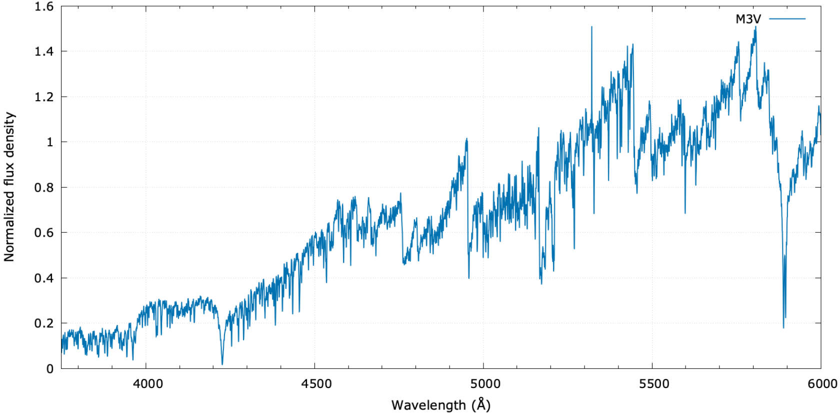
Overview O/A/G/M



Overview O/B/A/F/G/K/M

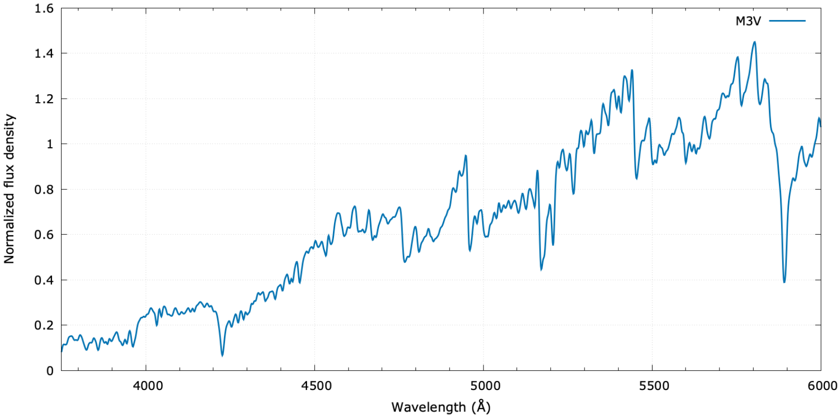


M



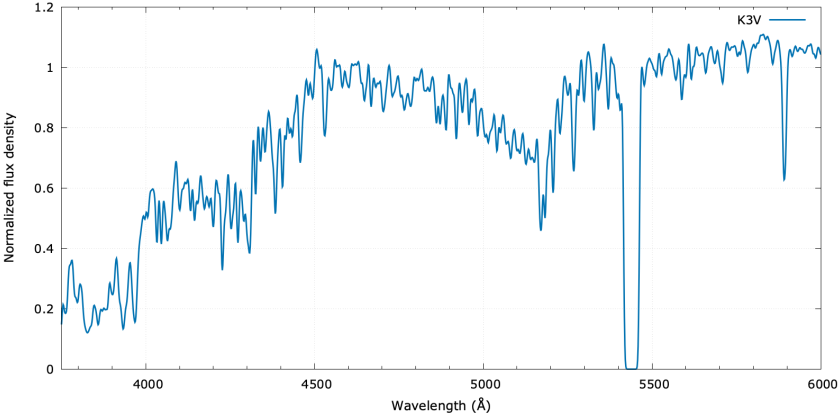
- very strong molecular bands: TiO, MgH...
- very strong Ca I 4226.73 Å, Na I 5890, 5896 Å

M



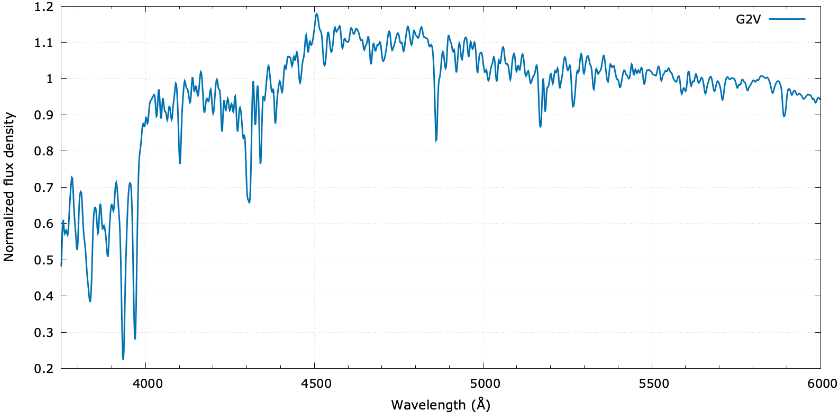
- very strong molecular bands: TiO, MgH...
- very strong Ca I 4227 Å, Mg I 5167, 5173, 5184 Å, Na I 5890, 5896 Å

K



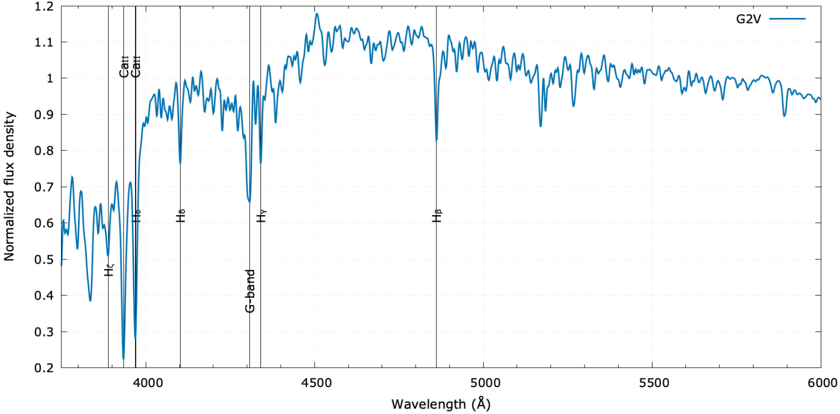
- strong Ca II 3934, 3968 Å, Mg I 5167, 5173, 5184 Å, Na I 5890, 5896 Å
- late: weak molecular bands
- early: weak G-Band at 4310 ± 10 Å

G



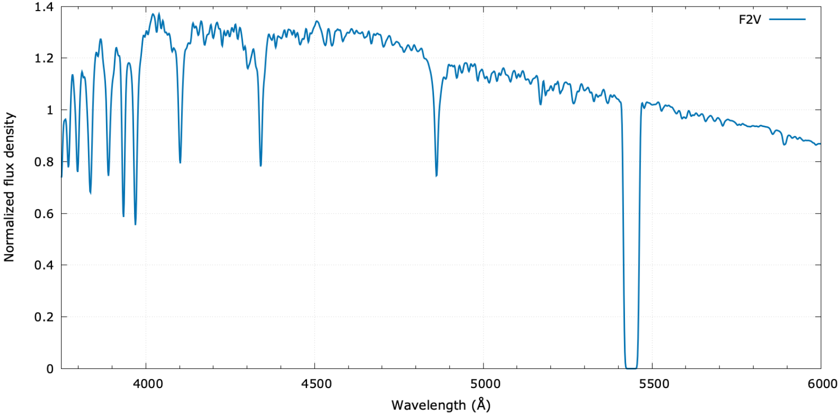
- **G-Band** at 4310 ± 10 Å (CH molecule)
- weak hydrogen lines, strong Ca II 3933.66, 3968.47 Å lines
- strong neutral metal lines (Fe I, ...)

G



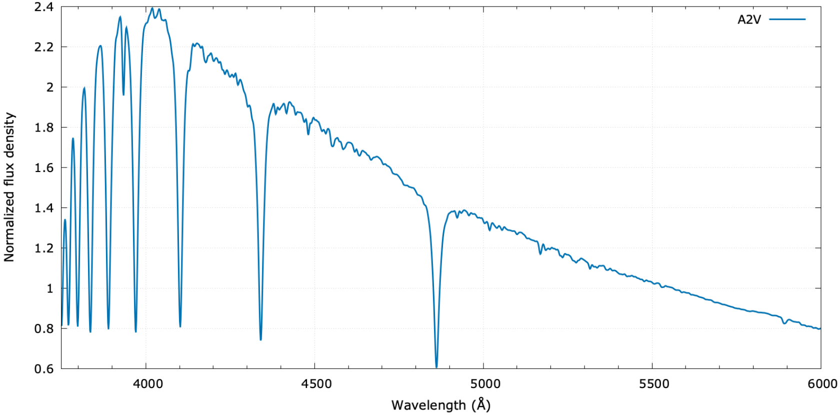
- **G-Band** at 4310 ± 10 Å (CH molecule)
- weak hydrogen lines, strong Ca II 3933.66, 3968.47 Å lines
- strong neutral metal lines (Fe I, ...)

F



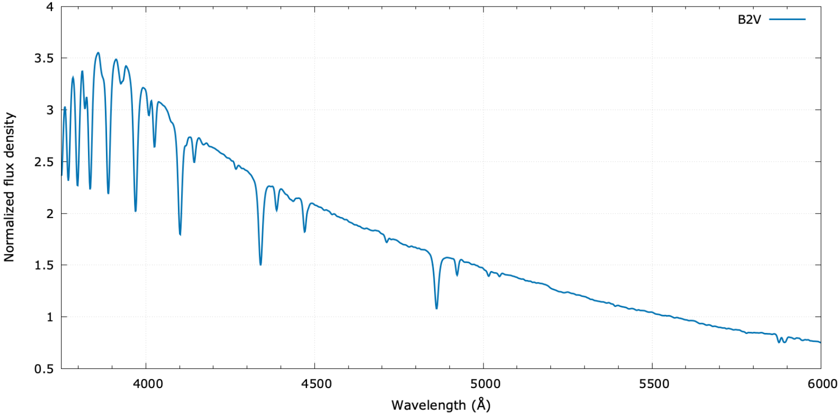
- Ca II lines and hydrogen lines have similar strength
- late: stronger Ca II, weak G-band becomes visible
- weaker neutral metal lines

A



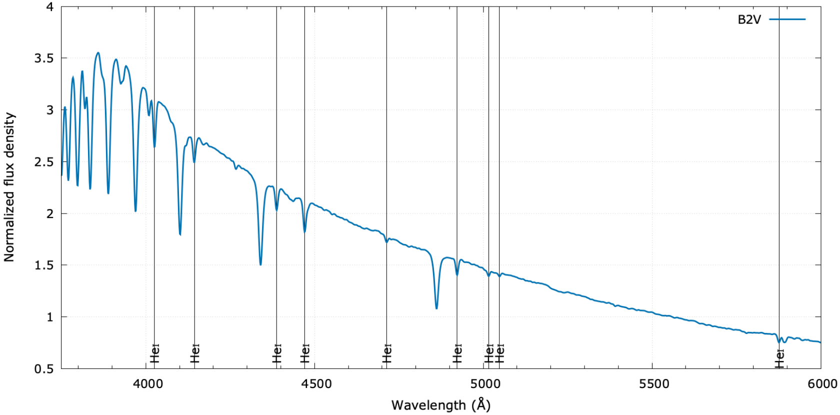
- very strong hydrogen lines, strong Balmer jump
- less and weaker neutral metal lines, weak Ca II
- ionized metal lines (e.g. Si II)

B



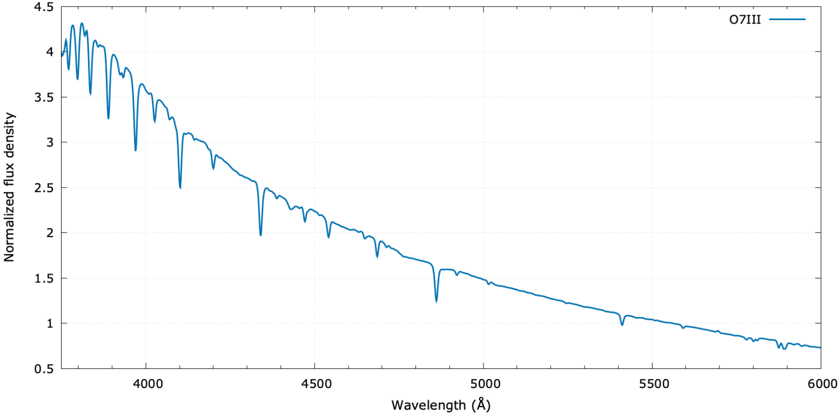
- weaker hydrogen lines, weaker Balmer jump
- neutral helium lines (He I 4026, 4144, 4388, 4471, 4713, 4922 Å)
- no ionized helium lines

B



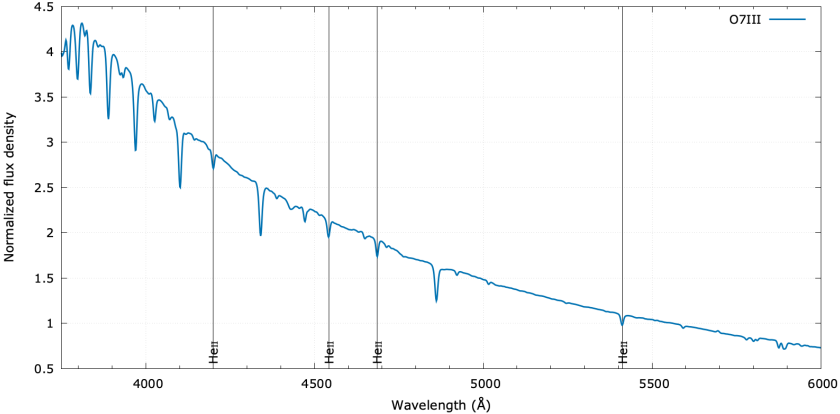
- weaker hydrogen lines, weaker Balmer jump
- neutral helium lines (He I 4026, 4144, 4388, 4471, 4713, 4922 Å)
- no ionized helium lines

O



- weak hydrogen lines
- neutral helium lines (He I 4026, 4144, 4388, 4471, 4713, 4922 Å)
- ionized helium lines (He II 4200, 4542, 4686, 5412 Å)

O



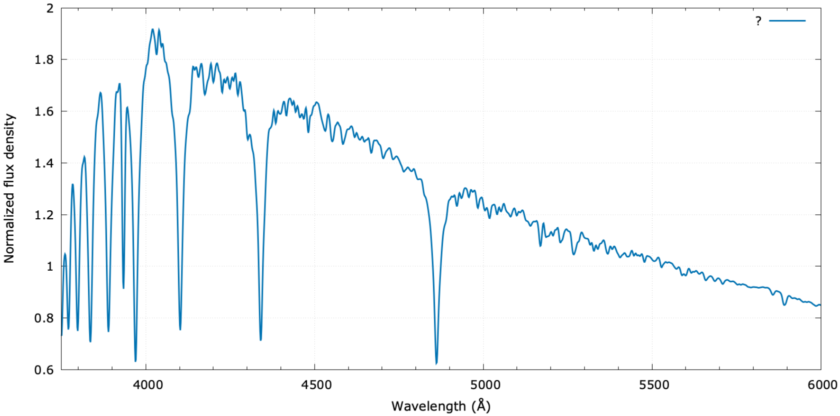
- weak hydrogen lines
- neutral helium lines (He I 4026, 4144, 4388, 4471, 4713, 4922 Å)
- ionized helium lines (He II 4200, 4542, 4686, 5412 Å)

Temperatures

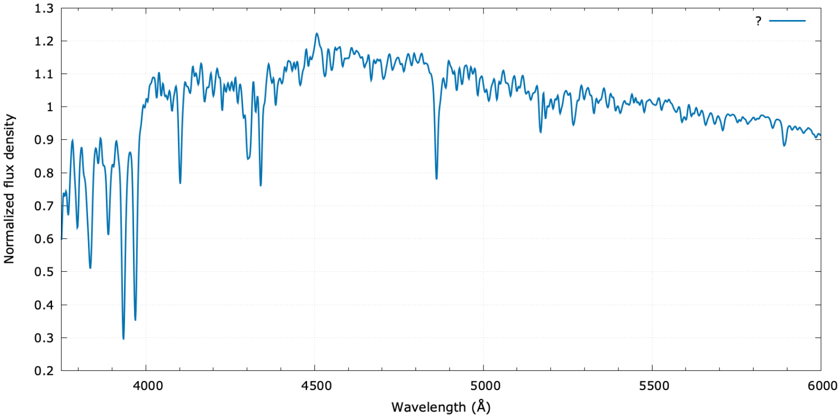
Main sequence effective temperatures (T_{eff}):

O	$>$32000 K
B	10500 - 32000 K
A	7400 - 10500 K
F	6000 - 7400 K
G	5300 - 6000 K
K	3900 - 5300 K
M	2400 - 3900 K

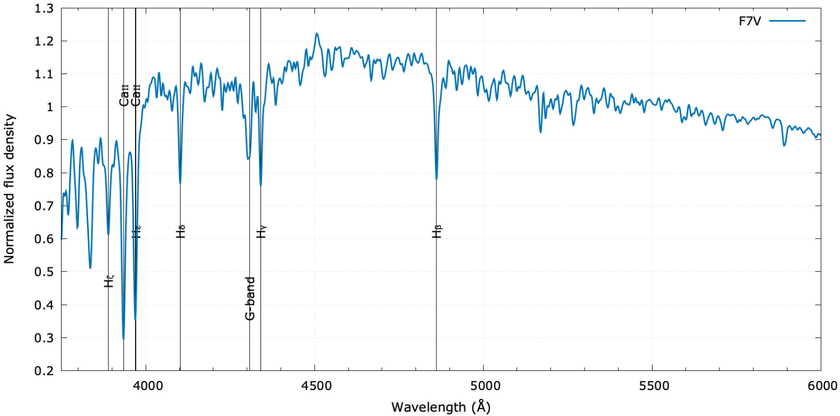
Examples (interactive!)



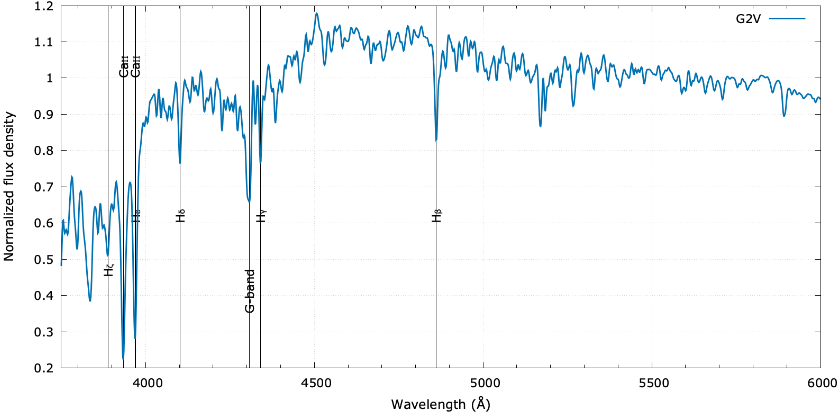
Examples (interactive!)



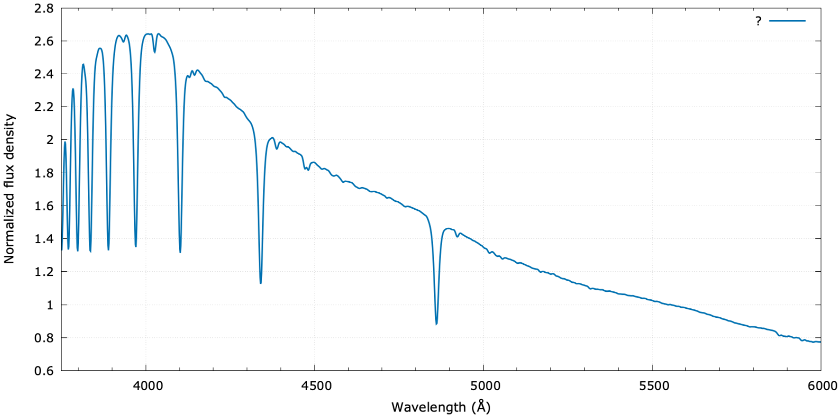
Examples (interactive!)



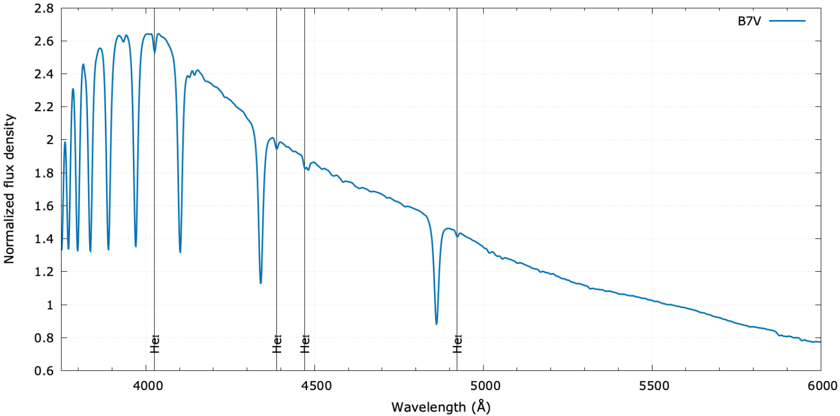
Examples (interactive!)



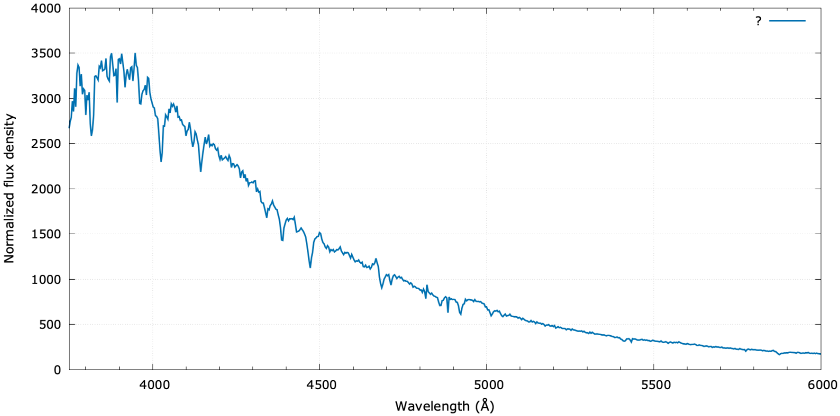
Examples (interactive!)



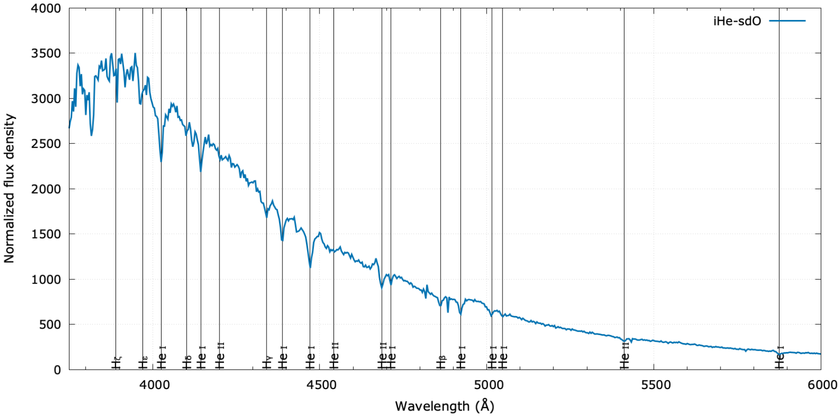
Examples (interactive!)



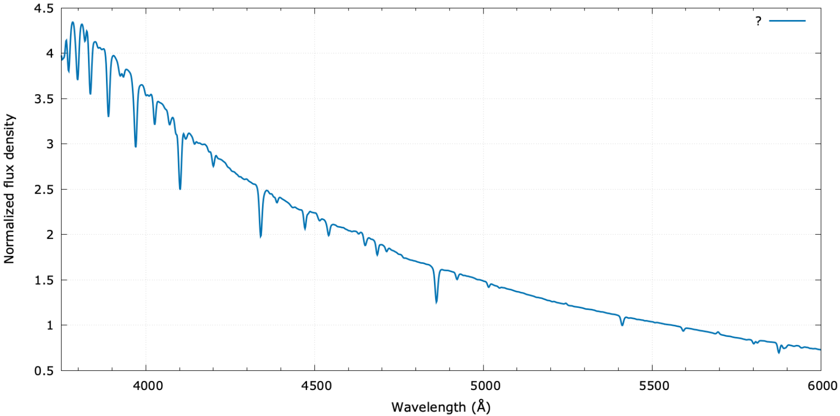
Examples (interactive!)



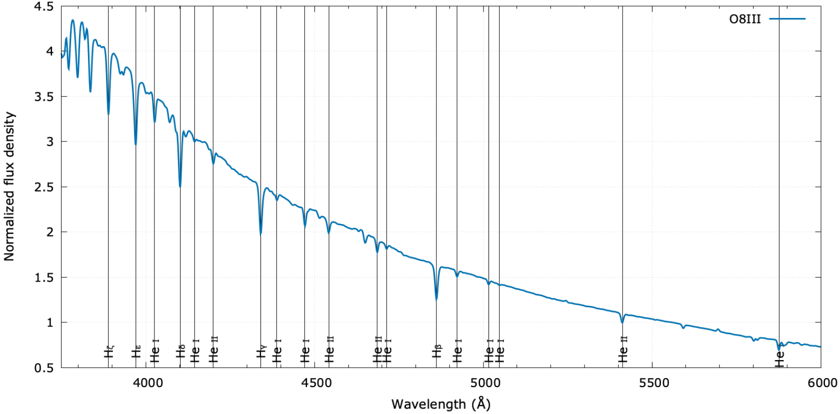
Examples (interactive!)



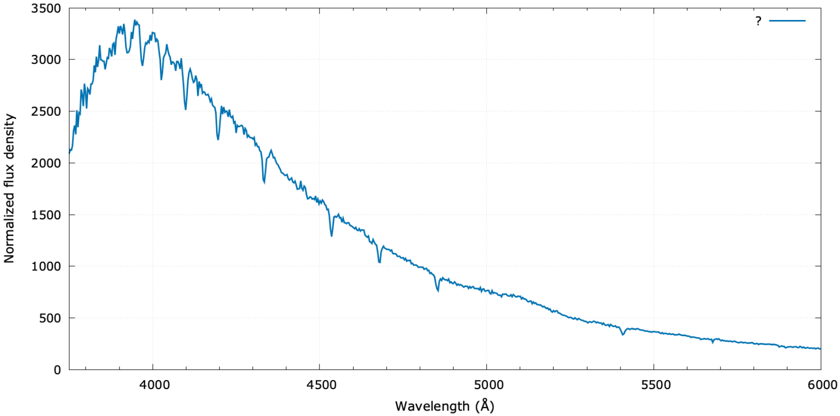
Examples (interactive!)



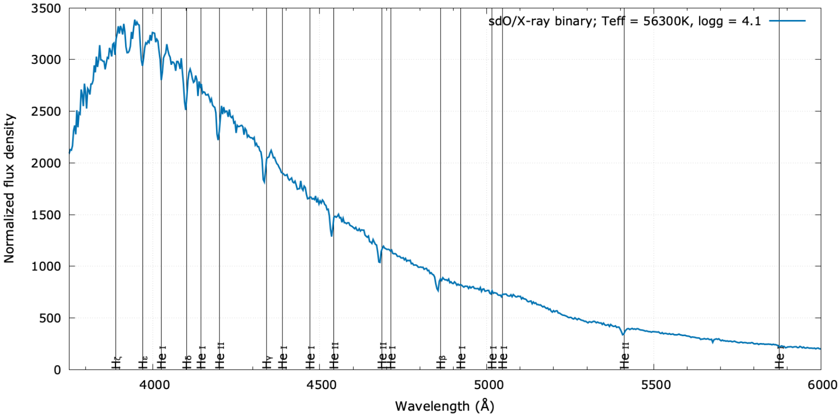
Examples (interactive!)



Examples (interactive!)



Examples (interactive!)



Luminosity classes - beyond the main sequence

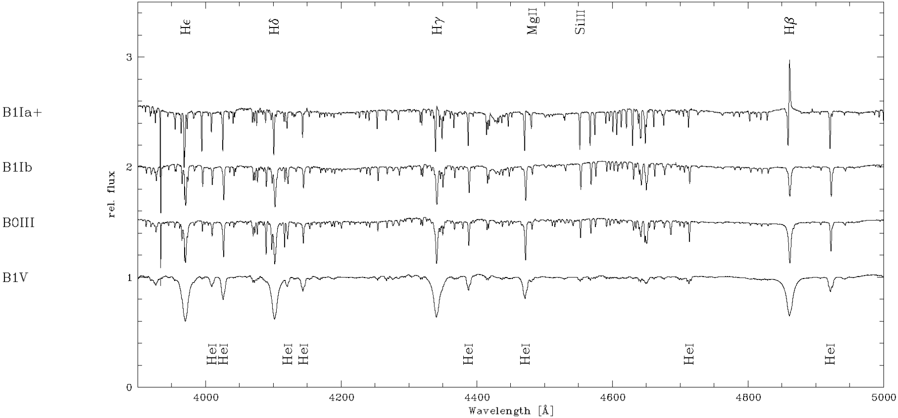


Figure: Luminosity classes.

Luminosity classes - beyond the main sequence

Classification: the MK(K) system (Morgan, Keenan, Kellman, 1943):

I	supergiant
II	bright giant
III	giant
IV	subgiant
V	main-sequence (dwarf)
sd- or -VI	subdwarf
D- or -VII	white dwarf

Luminosity classes are related to the atmospheric density; they do not correspond directly to the luminosity!

Luminosity classes - beyond the main sequence

... the difference is the surface gravity!

Luminosity classes - beyond the main sequence

... the difference is the surface gravity $g \rightarrow$ density in the atmosphere!

"the gravitational acceleration experienced at the surface at the equator"

$$\text{Usual units: } [g] = \text{cm / s}^2$$
$$\text{On earth: } \log g \approx 3.0$$
$$\text{Sun : } \log g \approx 4.0$$

Luminosity classes - beyond the main sequence

... the difference is the surface gravity $g \rightarrow$ density in the atmosphere!

Two main effects:

- different metal lines: ionization (Saha equation)

Luminosity classes - beyond the main sequence

... the difference is the surface gravity $g \rightarrow$ density in the atmosphere!

Two main effects:

- different metal lines: ionization (Saha equation)

$$\frac{N_{I+1}}{N_I} = \frac{2U_{I+1}}{n_\mathrm{e} U_I} \left(\frac{2\pi m_\mathrm{e} k_B T}{h^2} \right)^{3/2} e^{-\chi_I / k_B T}$$

- line width: 3 main types of broadening effects for hot stars

Luminosity classes - beyond the main sequence

... the difference is the surface gravity $g \rightarrow$ density in the atmosphere!

Two main effects:

- different metal lines: ionization (Saha equation)

$$\frac{N_{I+1}}{N_I} = \frac{2U_{I+1}}{n_\mathrm{e} U_I} \left(\frac{2\pi m_\mathrm{e} k_B T}{h^2} \right)^{3/2} e^{-\chi_I / k_B T}$$

- line width: 3 main types of broadening effects for hot stars
  - natural broadening: $\Delta E \gtrsim \hbar / \Delta t$, de-excitation on short timescales Δt; $\Delta t \approx 10^{-8}\,\mathrm{s} \rightarrow \Delta\lambda \approx 10^{-4}\,\text{Å}$

Luminosity classes - beyond the main sequence

... the difference is the surface gravity $g \rightarrow$ density in the atmosphere!

Two main effects:

- different metal lines: ionization (Saha equation)

$$\frac{N_{I+1}}{N_I} = \frac{2U_{I+1}}{n_\mathrm{e} U_I} \left(\frac{2\pi m_\mathrm{e} k_B T}{h^2} \right)^{3/2} e^{-\chi_I / k_B T}$$

- line width: 3 main types of broadening effects for hot stars
  - natural broadening: $\Delta E \gtrsim \hbar / \Delta t$, de-excitation on short timescales Δt; $\Delta t \approx 10^{-8}\,\mathrm{s} \rightarrow \Delta\lambda \approx 10^{-4}\,\mathrm{Å}$
  - thermal Doppler broadening:
    Maxwell velocity distribution, depends on T_local

Luminosity classes - beyond the main sequence

... the difference is the surface gravity $g \rightarrow$ density in the atmosphere!

Two main effects:

- different metal lines: ionization (Saha equation)

$$\frac{N_{I+1}}{N_I} = \frac{2U_{I+1}}{n_\mathrm{e} U_I} \left(\frac{2\pi m_\mathrm{e} k_B T}{h^2} \right)^{3/2} e^{-\chi_I / k_B T}$$

- line width: 3 main types of broadening effects for hot stars
  - natural broadening: $\Delta E \gtrsim \hbar / \Delta t$, de-excitation on short timescales Δt; $\Delta t \approx 10^{-8}\,\mathrm{s} \rightarrow \Delta\lambda \approx 10^{-4}\,\text{Å}$
  - thermal Doppler broadening:
    Maxwell velocity distribution, depends on T_local
  - pressure broadening: change of atomic level energies due to electric fields of colliding particles: (linear) Stark effect

Line broadening

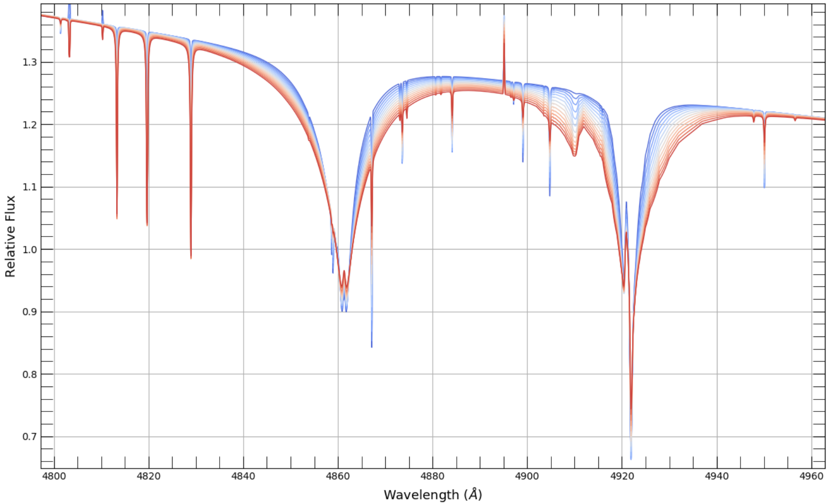


Figure: synthetic spectra with $\log g$ from 4.7 to 6.0 in steps of 0.1, colored from blue (low) to red (high).

Summary

Very simplified:

Line strengths $\rightarrow$ effective temperature T_{eff}

Line widths $\rightarrow$ surface gravity $\log g$

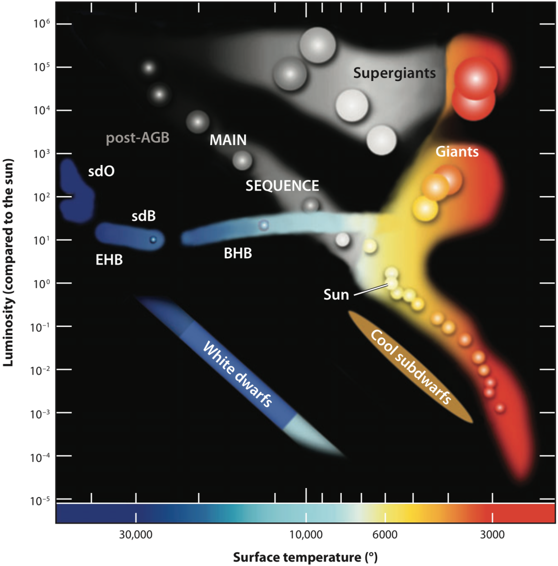
How can we use this information?

Theoretical Hertzsprung-Russell diagram

Hertzsprung-Russell diagram (HRD)

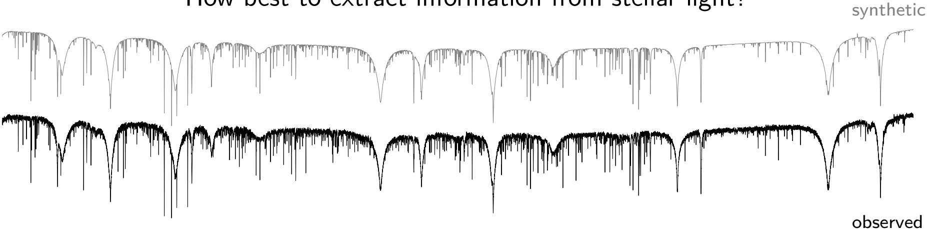
Luminosity:
$L = 4\pi\sigma R^2 T_{\mathrm{eff}}^4$

T_{eff} from spectroscopy
$R = \Theta/(2\varpi)$ from parallax



Atmospheric models

How best to extract information from stellar light?



- Compare observed spectra to synthetic spectra
  $\rightarrow$ Need to model the region, where the spectrum is formed:

  The stellar photosphere

- Compute model atmospheres for set of atmospheric parameters:
  - Effective surface temperature $T_{\rm eff}$
  - Surface gravity $g = GM/R^2$
  - Helium abundance
  - Metal abundances

Atmospheric models: no details!

Atmospheric structure: Basic equilibria

- Hydrostatic equilibrium *"F(Gravity) = F(Pressure)"*
- Radiative equilibrium *"Emitted energy = Absorbed energy"*
- Particle conservation *"Total Number of e^- and atoms = const."*

Spectrum synthesis: Radiative transfer equation

$$\mathrm{d}I_\nu = -\kappa_\nu I_\nu \mathrm{d}s + \eta_\nu \mathrm{d}s$$

Intensity at specific λ = Absorption at λ + Emission at λ

Determined by scattering and radiative processes:

$\rightarrow$ free-free, bound-free, **bound-bound**:

$\rightarrow$ Depend on n_e, $T(s)$

$\rightarrow$ Depend on T_eff, $\log g$, chemical abundances, ...

- Local thermal equilibrium (LTE)
  "Local plasma not coupled to other volumes"
- Or more general: statistical equilibrium (non-LTE)
  "Atomic level pop. do not change in time"

TLUSTY/SYNSPEC

- Complex model atmospheres with TLUSTY; per depth point:
  - Temperature
  - Electron density
  - Mass density
  - Energy level occupation numbers
- Synthetic spectra with SYNSPEC
- χ^2 minimization with SPAS
  - Effective temperature T_{eff}
  - Surface gravity $\log g$
  - Abundance of one element
  - v_{rad}, $v_{\mathrm{rot}} \sin i$

Table: Model grids for determining atmospheric parameters.

		T_{eff} (K)			$\log g$ (cgs)			$\log N_{\mathrm{He}}/N_{\mathrm{H}}$			
Grid	Elements	min.	max.	step	min.	max.	step	min.	max.	step	N_{models}
He-sdO	HHeCNSi^c	30 000	60 000	1000	4.70	6.40	0.1	−1.0	+3.4	0.2	6272

Model fits

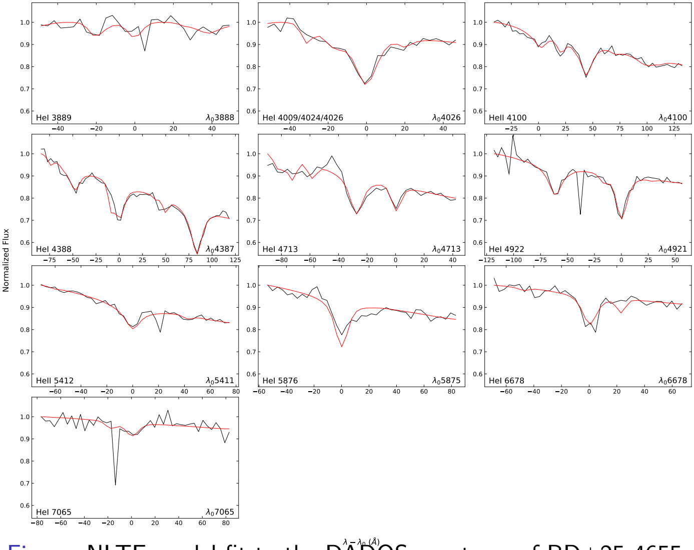
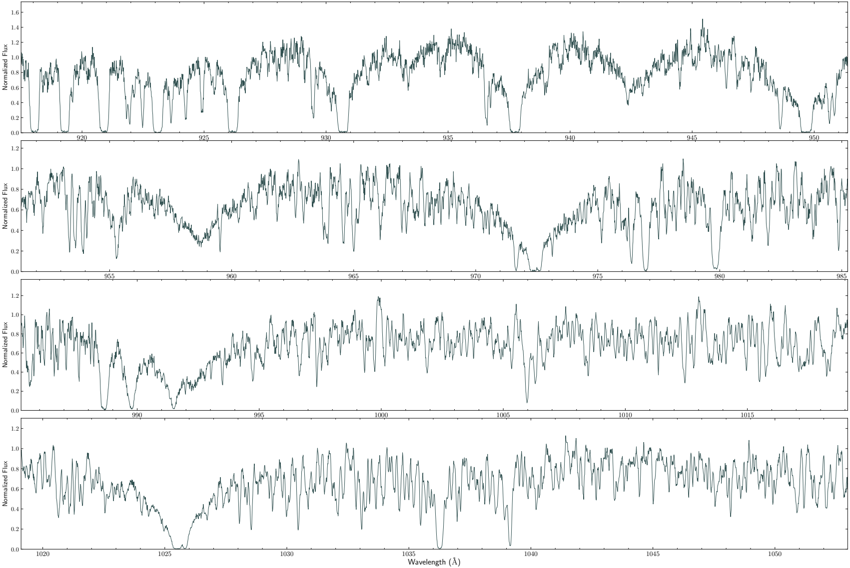
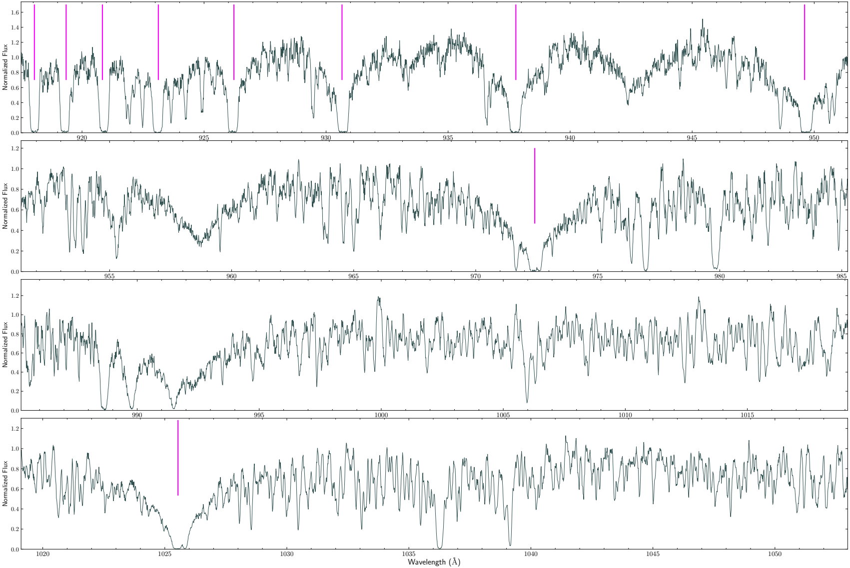


Figure: NLTE model fit to the DADOS spectrum of BD+25 4655.

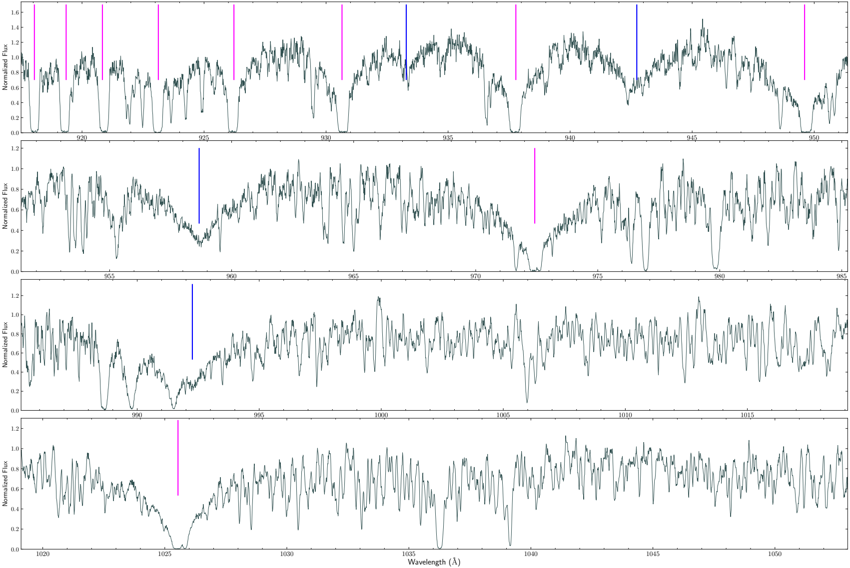
Synthectic spectra example



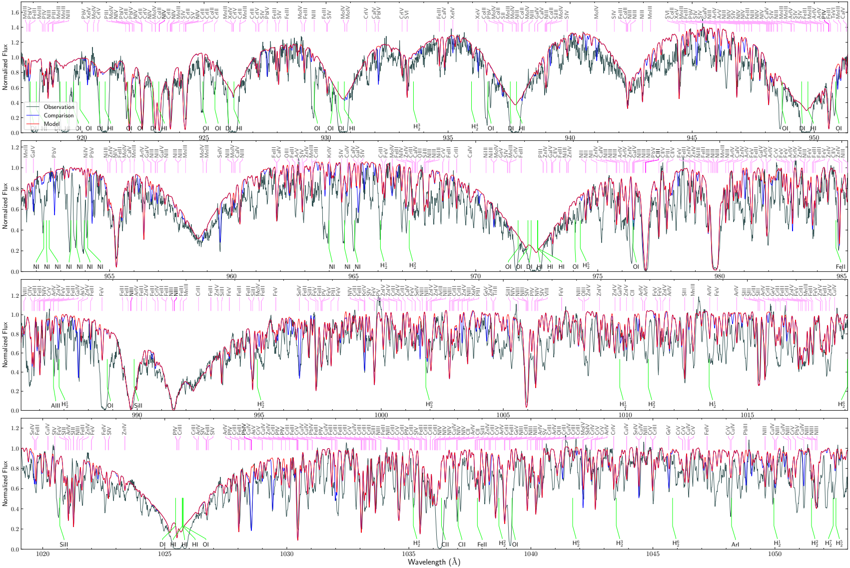
Synthectic spectra example



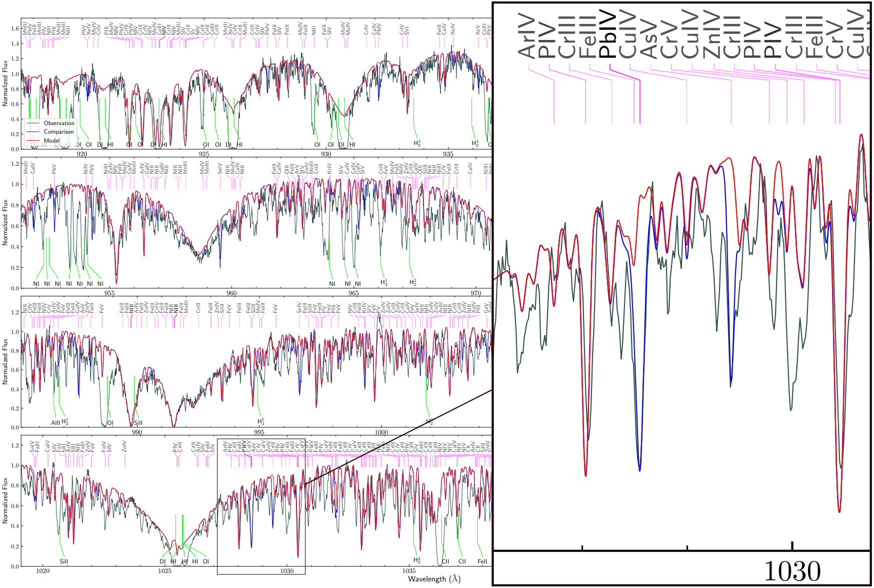
Synthectic spectra example



Synthectic spectra example



Synthectic spectra example



Thank you!

Questions?