From starlight to spectra and inference of stellar properties

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July 21, 2025

Astronomický ústav AV ČR

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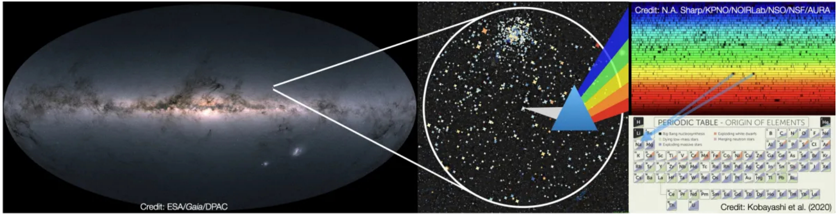


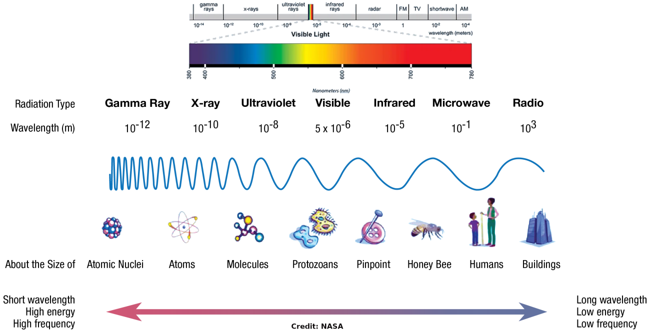
Outline

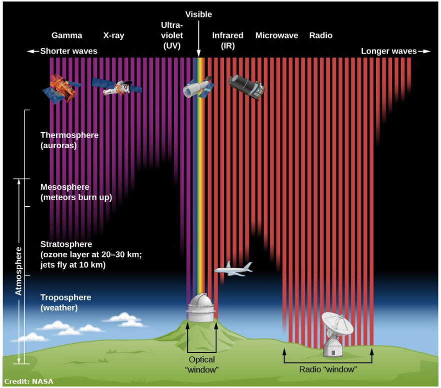
1. Who I am?
2. Introduction to stellar spectroscopy
3. Spectral types and stellar classification
4. Quantitative stellar spectroscopy
5. Stellar atmosphere models

Who I am?

- I obtained my BSc and MSc in astrophysics from the University of Belgrade in Serbia.
- I obtained my Ph.D. in Theoretical Physics and Astrophysics from Charles University in Prague.
- I had two postdocs at the ASU in Ondřejov.
- Currently, I am the head of the Stellar Physics Department at ASU.
- Research interests: **Massive hot stars and their winds**, radiative transfer in inhomogeneous medium (e.g. clumping), quantitative spectroscopy - modelling and analyzing massive star spectra, studding the line profile variability of massive stars, stellar evolution of low metallicities stars.
- **PoWR code** - Potsdam stellar atmosphere code (e.g., Hamann & Gräfener 2003, 2004; Sander et al. 2015) for simulating the spectra of hot stars, particularly Wolf-Rayet (WR) and OB-type stars.

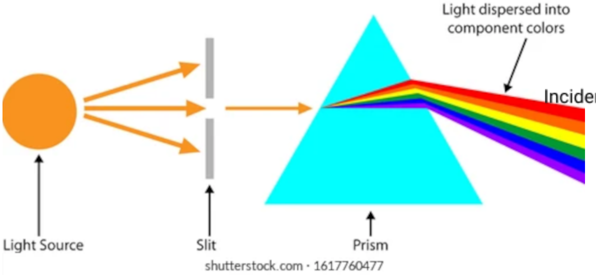
- **Definition**
  - Spectroscopy is the study of the interaction between electromagnetic radiation (light) with matter in stars and analyzing the resulting spectra to infer various stellar properties.





Introduction to Stellar Spectroscopy

- **Definition**
  - The technique of splitting light (i.e., electromagnetic radiation) into its constituent wavelengths, i.e., a spectrum.
  - **Dispersive elements**: **Prism** and **Grating**.



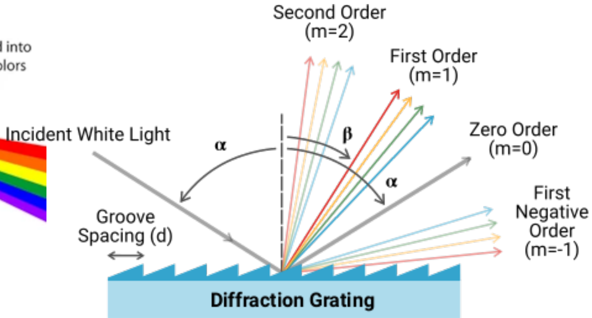
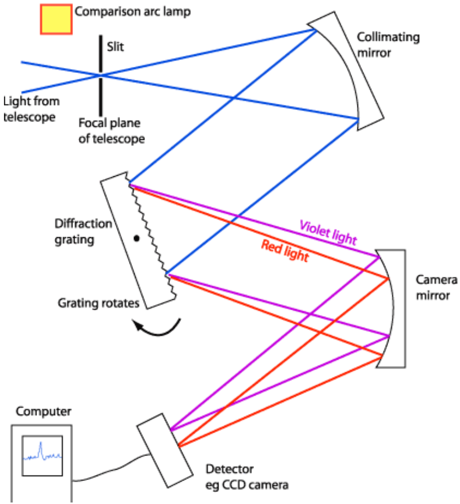


Image taken from https://www.meetoptics.com.

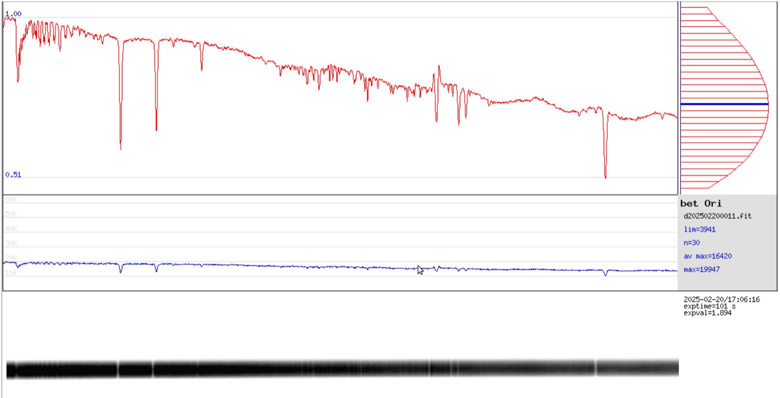
Introduction to Stellar Spectroscopy

- **A Schematic Diagram of a Slit Spectrograph** (Image taken from https://www.findlight.net).



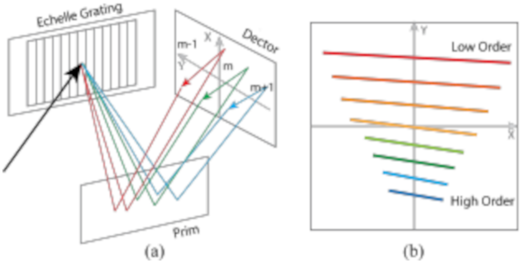
Introduction to Stellar Spectroscopy

- Spectra taken with single order spectrograph attached to 2m Perek Telescope at Ondřejov observatory, in Czech Republic.



Introduction to Stellar Spectroscopy

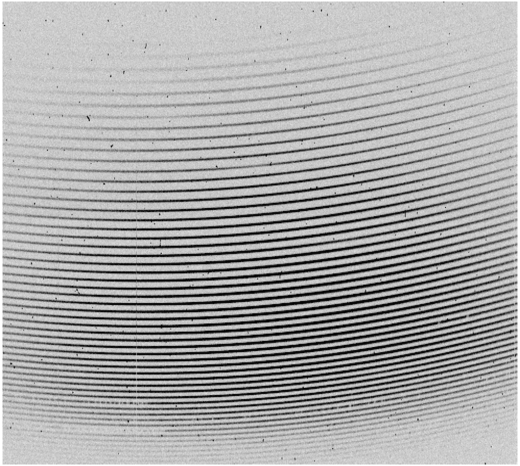
- **Échelle Grating** - For high resolution astronomical work échelle is the preferred choice over a grating used in low order.
- The reasons for this are:
  - Two dimensional format that permits broad spectral coverage.
  - Allows compact spectrograph design.
- Échelle has a large groove spacing and is used at high order number, thus it is necessary to use a cross-disperser to separate the orders, or to use a filter to isolate a single orders.



Credit: Image taken from Shen et al. 2018.

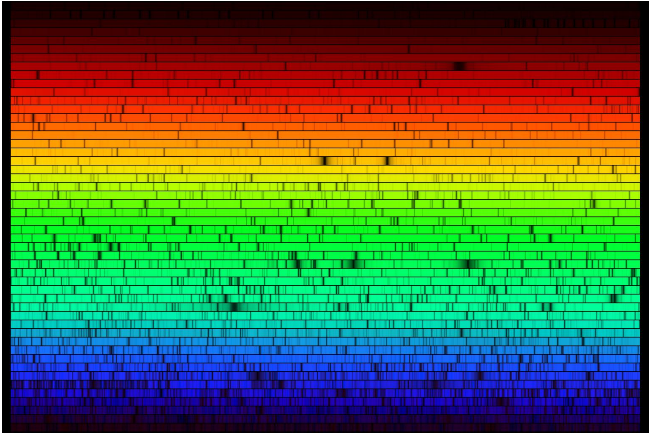
Introduction to Stellar Spectroscopy

- Spectra taken with Ondřejov Échelle spectrograph (OES) attached to 2m Perek Telescope at Ondřejov observatory, in Czech Republic.



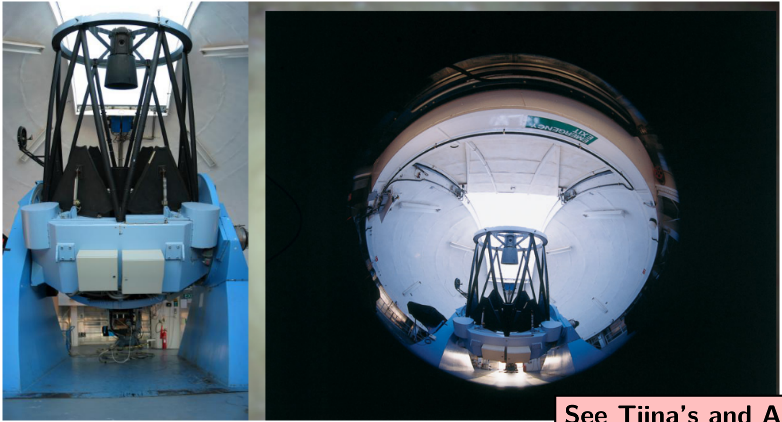
Introduction to Stellar Spectroscopy

- Solar spectrum covering almost the entire optical range, obtained using the HIRES echelle spectrograph on the 10 m Keck telescope, Hawaii.



Introduction to Stellar Spectroscopy

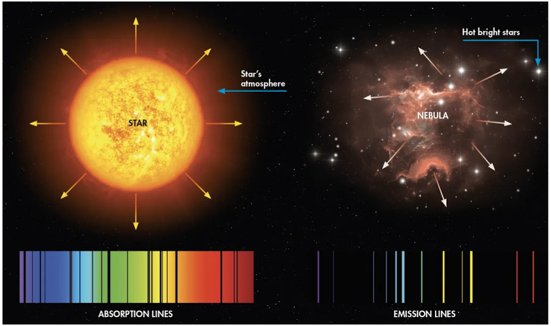
- **FIES** - The spectrograph is a cross-dispersed Echelle spectrograph attached to the Nordic Optical Telescope (NOT) at La Palma in the Canary Islands.

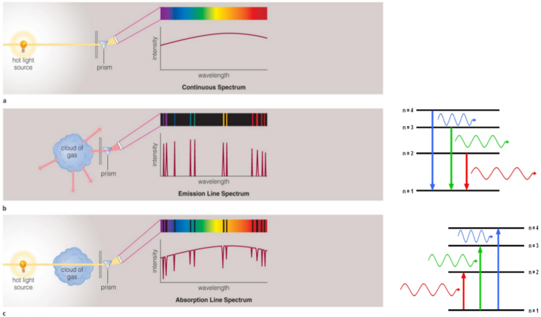


See Tiina's and Andres's talks!

Credit: NOT.

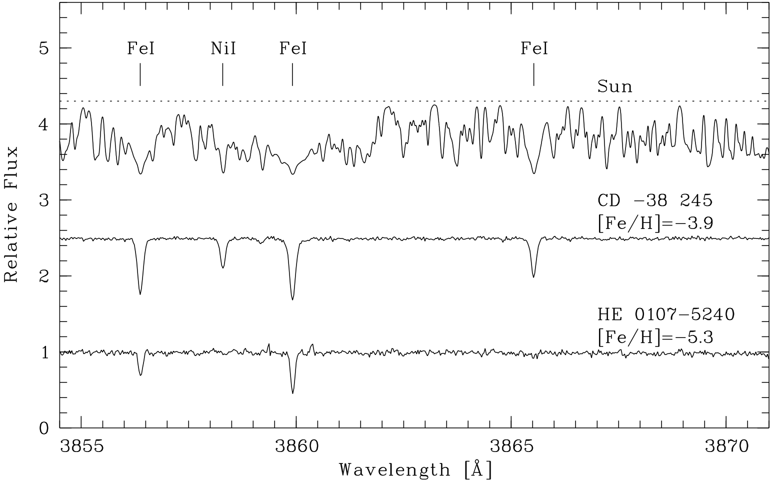
- **Types of Spectra**
  - **Continuous Spectrum** - Emitted by a dense, hot object (e.g., a star's photosphere) that radiates light at all wavelengths without gaps, resembling a blackbody curve.
  - **Absorption Line Spectrum** - Formed when light from a continuous source passes through a cooler gas, causing absorption of light by he atoms and molecules within the gas.
  - **Emission line Spectrum** - Starlight can also heat up a cloud of gas, exciting the atoms and molecules within the gas, and causing it to emit light.





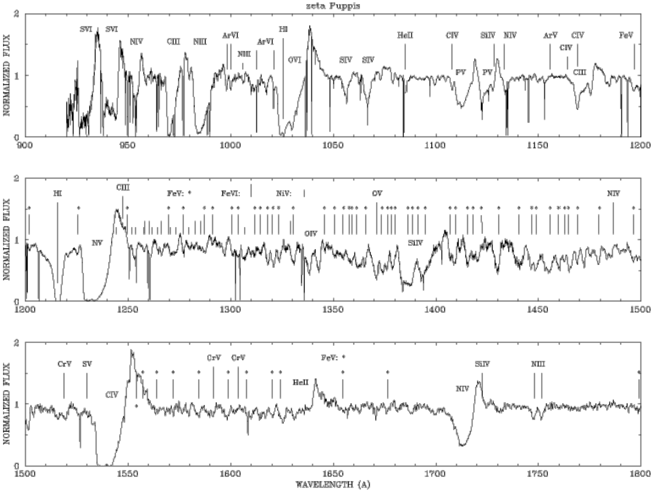
Spectral Types and Stellar Classification

- Spectral comparison of the Sun with the metal-poor stars CD 38° 245 and HE 01075240
(figure taken from Christlieb et al. 2004).



Spectral Types and Stellar Classification

- Supergiant ζ Puppis observed with Copernicus and IUE (figure taken from Pauldrach et al. 1994).



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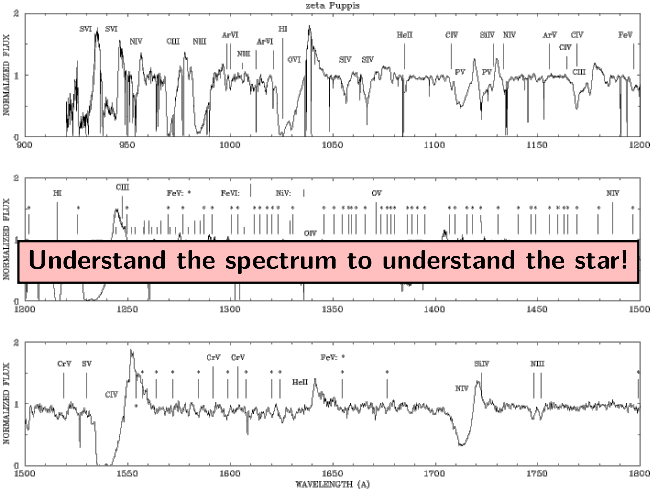
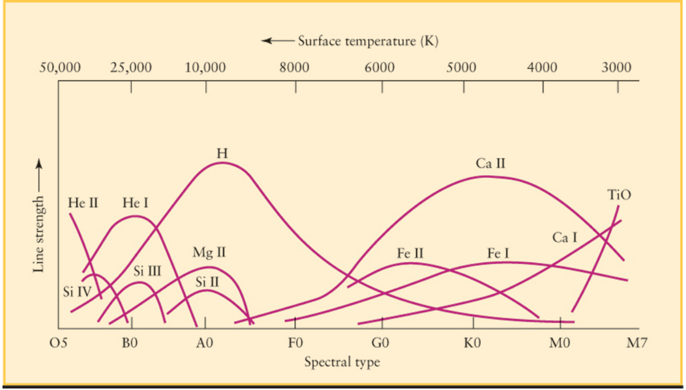


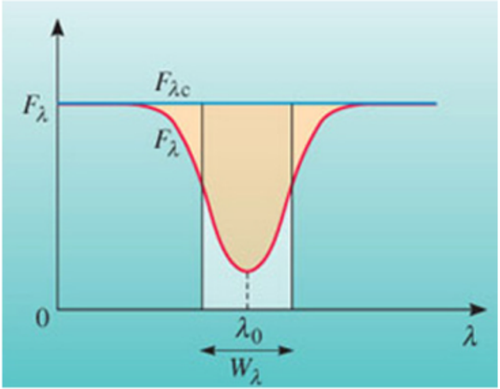
Spectral Types and Stellar Classification

- **Stellar Classification**
  - The classification is based on the relative strengths and shape of spectral lines which are mainly sensitive to stellar **surface temperatures**.
  - The lines of each atom or molecule are strongest at particular temperature.



Spectral Types and Stellar Classification

- **Stellar Classification**
  - The classification is based on the relative strengths and shape of spectral lines which are mainly sensitive to stellar **surface temperatures**.
  - The lines of each atom or molecule are strongest at particular temperature.
  - Comparing line strengths, we can measure a star's surface temperature!



Equivalent width

(Line strength)

$$W_\lambda = \int (1 - F_\lambda / F_{\lambda c}\, d\lambda)$$

See Camila's talk!

Spectral Types and Stellar Classification

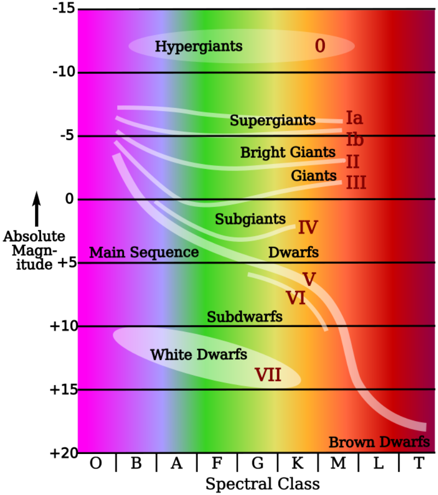
- **Stellar Classification - Harvard Classification System**
  - Standard Stellar Types (O, B, A, F, G, K, and M).
  - Subtypes - Subclasses numbered 0 to 9 (Sun is stellar type G2).

Class	Effective temperature[1][2][3]	Vega-relative "color label" [4][nb 1]	Chromaticity[5] [6][7][nb 2]	Main-sequence mass[1][8] (solar masses)	Main-sequence radius[1][8] (solar radii)	Main-sequence luminosity[1][8] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[9]
O	≥ 30,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000–30,000 K	blue white	deep blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellow white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96–1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	orange	pale yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	2,400–3,700 K	red	light orange red	0.08–0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Credit: Wikipedia.

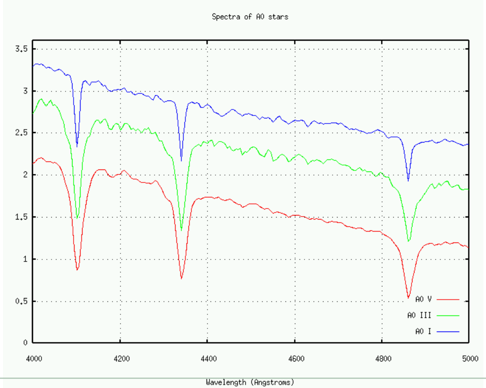
Spectral Types and Stellar Classification

- Stellar Luminosity Classes - Yerkes classification System



Stellar surface gravity

$$g = \frac{G \cdot M_*}{R_*^2}$$



Spectral Types and Stellar Classification

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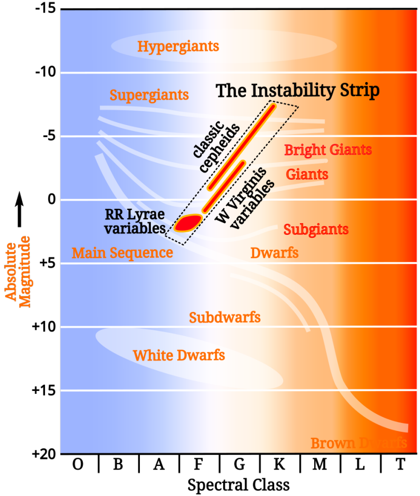

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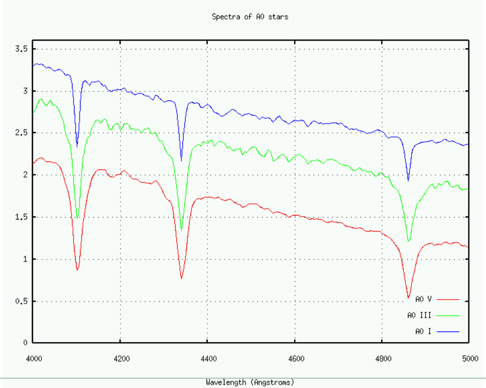
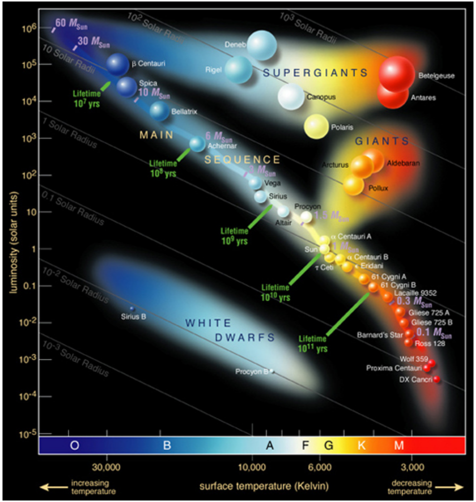


Spectral Types and Stellar Classification

- **Hertzsprung–Russell diagram** shows stars at different evolutionary stages.



Mass-Luminosity Relation

$$\frac{L_*}{L_\odot} = \left(\frac{M_*}{M_\odot}\right)^a$$

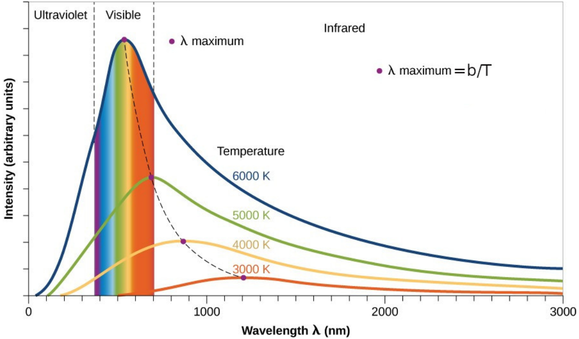
$$1 < a < 6$$

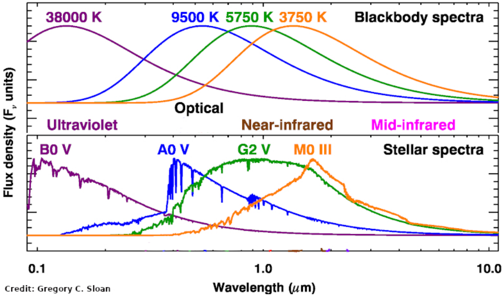
$a = 3.5$ - for the stars on the main sequence

See Gabriele's talk!

- **Planck function and Stefan-Boltzmann law**

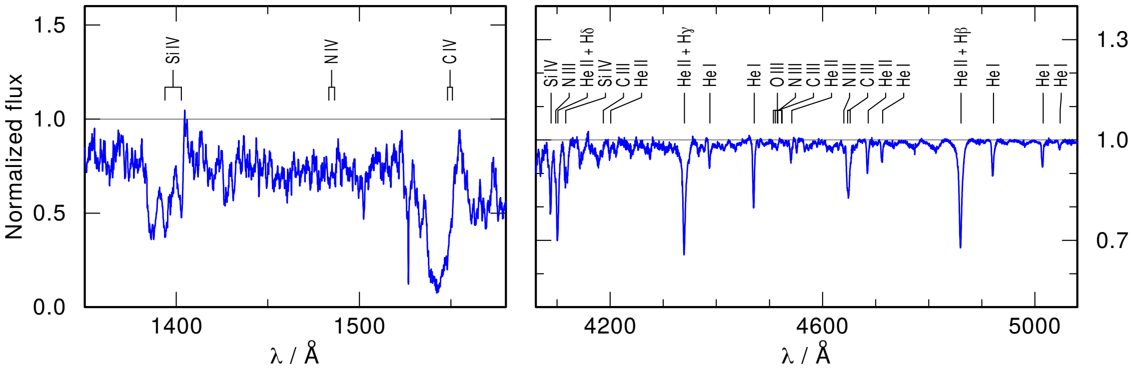
$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda k_B T}-1} \qquad L = \int_0^\infty L_\lambda d\lambda = \int_{d\Omega}\int_A B_\lambda d\lambda dA d\Omega = 4\pi R^2 \sigma_B T^4$$





Wien's displacement law

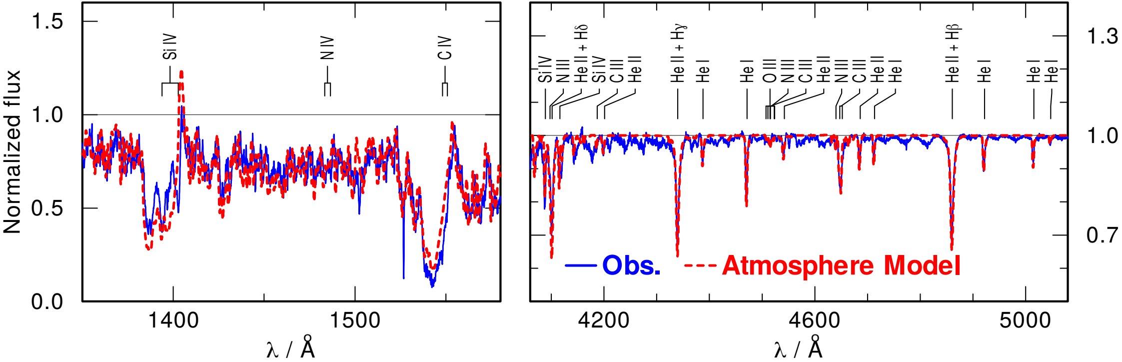
- **Quantitative Spectroscopy** - a technique from which we can extract information about the physical properties and surface chemical composition of stars.
- Determination of physical parameters that (uniquely and completely?) characterize a star.



Credit: A. Sander.

Quantitative Stellar Spectroscopy

- **Quantitative Spectroscopy** - a technique from which we can extract information about the physical properties and surface chemical composition of stars.
- Determination of physical parameters that (uniquely and completely?) characterize a star.
- Only a proper modeling of the stellar atmosphere can reproduce the emergent spectrum.



Credit: A. Sander.

Quantitative Stellar Spectroscopy

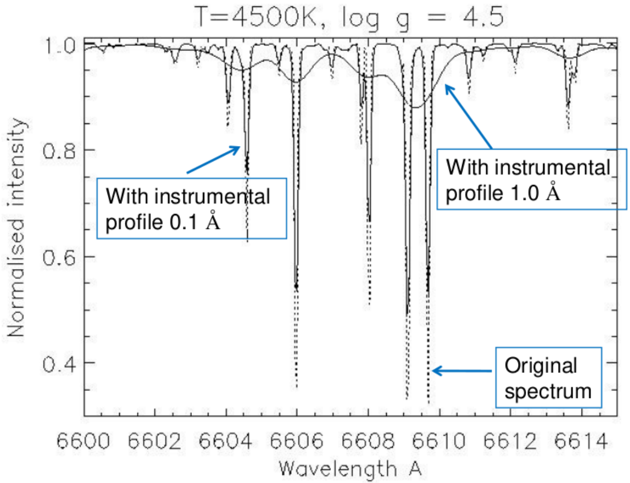
- **Ingredients**
  - **Observed spectra and their processing**
  - Theoretical (synthetic) spectra (model atmosphere/line formation codes)
  - Grid of models
- **What should we worry about?**
  - Information encoded in the observed data (both quantity and quality)
    - How many spectra we need (single spectra or time series spectra)
    - Spectral range coverage
    - Signal-to-noise ratio (SNR)
    - Resolution (R)

Quantitative Stellar Spectroscopy

- **Resolving power (R)** - Tells how small details we can resolve in the spectrum.
- It is defined as $\lambda/\Delta\lambda$.
- Examples
  - $R = 1000$ at $6500\ \mathring{A}$ gives $\Delta\lambda = 6.5\ \mathring{A}$ or 300 km/s
  - $R = 10000$ at $6500\ \mathring{A}$ gives $\Delta\lambda = 0.65\ \mathring{A}$ or 30 km/s
  - $R = 100000$ at $6500\ \mathring{A}$ gives $\Delta\lambda = 0.065\ \mathring{A}$ or 3 km/s
- At the given R, the resolution in velocity doesn't change with wavelength.
  - $R = \lambda/\Delta\lambda = c/\Delta \mathrm{v}$
- For seeing detailed structures in spectra the spectral resolution has to be high.
- For study the composition of stellar atmosphere and determination of element abundances we need high resolution spectroscopy.

Quantitative Stellar Spectroscopy

- **Lines get "diluted" with low resolution.**

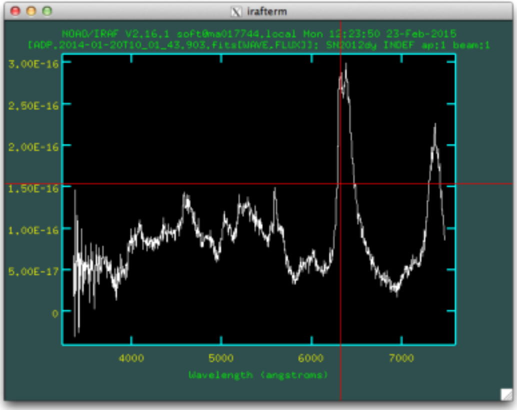


Credit: H. Korhonen.

Choose an instrument wisely!

Quantitative Stellar Spectroscopy

IRAF - commonly used software



Processing of the observed spectrum

- Reducing spectra
- Normalize spectra
- Correct the observed spectrum for:
  - Telluric (atmospheric) lines
  - Interstellar lines - diffuse interstellar bands (DIBs)
  - Cosmic rays

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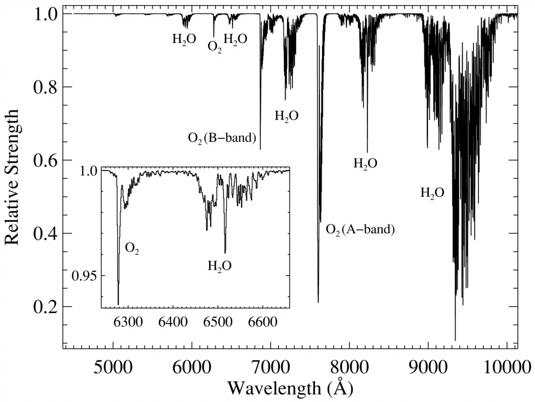

Figure taken from Matheson et al. 2000, AJ, 120, 1499 - Ttelluric absorption lines at KPNO.

Quantitative Stellar Spectroscopy

Processing of the observed spectrum

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`Molecfit` - A general tool for removal of atmospheric absorption features.

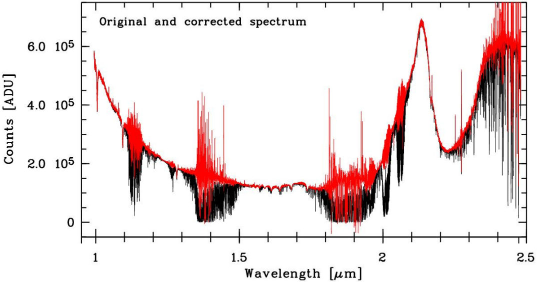

Figure taken from Kausch et al. 2015, A&A 576, A78 - Telluric absorption corrected spectrum (red) and the original spectrum (black)

Quantitative Stellar Spectroscopy

Processing of the observed spectrum

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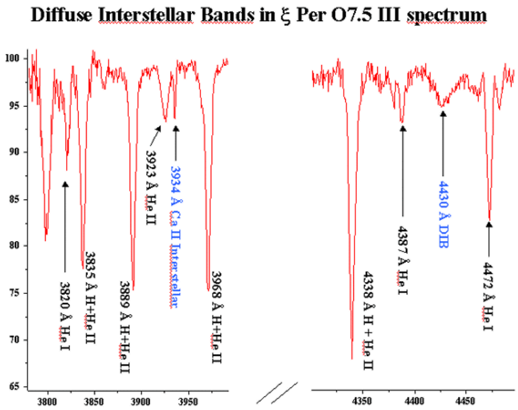

Credit: Paolo Valisa.

Quantitative Stellar Spectroscopy

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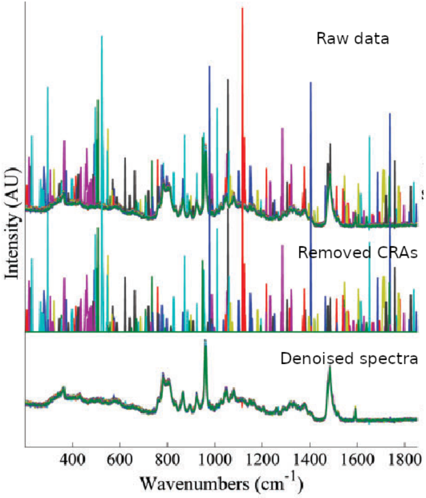


Image taken from Sinead & Hennelly 2019

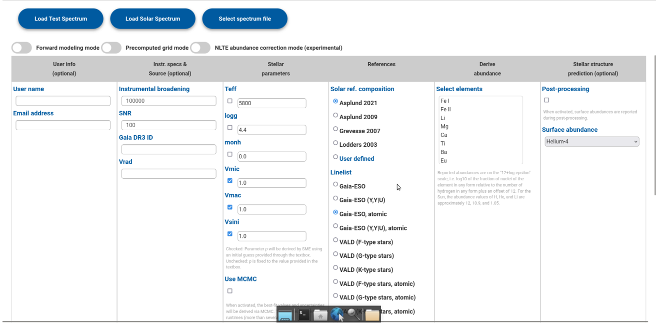
Quantitative Stellar Spectroscopy

- **Ingredients**
  - Observed spectra and their processing
  - **Theoretical spectra (model atmosphere/line formation codes**
  - Comparison metrics (grid of models)
- **What should we worry about?**
  - Physics incorporated in the models (i.e., assumptions/simplifications)
  - Atomic data
  - Grid of models
  - Uncertainties/Errors
- **Calculation of the grid of the models**
  - Define the parameter space (free parameters)
  - Define the range of values for free parameters
  - Fix some parameters

Quantitative Stellar Spectroscopy

Spectroscopy Made Easy (SME) (Valenti & Piskunov, 1996, 2017)

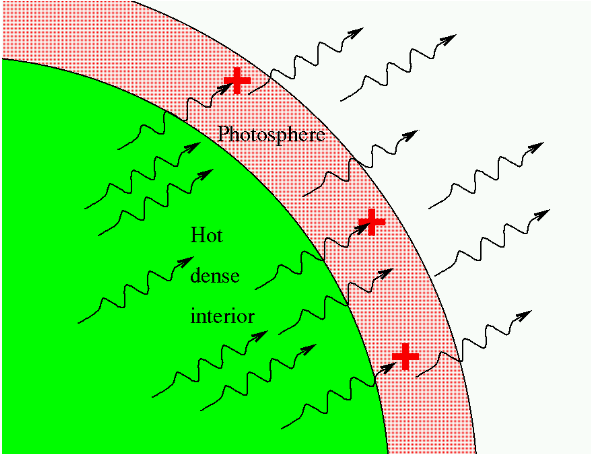
- **PySME** (Wehrhahn et al. 2022) - create high-resolution synthetic spectra, based on a range of stellar parameters, a linelist and a model atmosphere. It can also be used the other way around. Give PySME an observation and it will determine the best fit stellar parameters for that spectrum.
- **webSME** - Pipeline preview available at **http://pipeline.chetec-infra.eu** (developed by Johannes Puschnig).



See Andreas's talk!

Stellar atmosphere models

- **Stellar Atmosphere** is all we really see from a star.
- Emergent radiation gives the only information about the star we have to understand how the emergent stellar radiation forms.
- Radiation is influenced by stellar atmosphere => solution of radiative transfer equation is necessary.
- **Radiative Transfer** describes how radiation propagates through the stellar atmosphere, interacting with gas particles via absorption, emission, and scattering.



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Stellar atmosphere models

Tasks in stellar atmosphere modelling

- Prediction of emergent radiation (the only observable quantity).
- Understanding of physical processes in stellar atmospheres.

Model formulation

- For given basic parameters: R_* , M_* , L_* ($T_{\rm eff}$, $\log g$), $\dot{M}$, v_∞.
- Spatial dependence of quantities $T(\vec{r})$, $\rho(\vec{r})$, $\vec{v}(\vec{r})$, $n_e(\vec{r})$, $n_i(\vec{r})$, $J(\nu, \vec{r})$, ...
- Solving the set of equations describing stellar atmospheres.
- Computation of a synthetic stellar spectrum.

Atomic and Molecular Data

- Accurate determination of stellar parameters depends on adequate atomic and molecular data. Completeness of this data is crucial for atmospheric and abundance analysis.

Stellar atmosphere models

Approximations in stellar atmosphere modelling

- **Geometry approximations (symmetries)**
  - one-dimensional (1-D) atmosphere (types: plane-parallel or spherically symmetric)
- **Stellar atmosphere structure**
  - Photosphere (quasi-static, continuous spectrum)
  - Stellar wind (moving extending atmosphere)
- **Physical approximations**
  - Stationary medium ($\partial/\partial t = 0$)
  - Static medium ($\vec{v} = 0$)
- **Equilibrium distributions**
  - Local thermodynamic equilibrium (**LTE**)
    - particle velocities - Maxvell eq.
    - energy levels population –Saha-Bolzmann eq.
    - radiation field - Planck eq.
  - Kinetic (statistical) equilibrium (**NLTE**)
    - particle velocities - Maxvell eq.
    - energy levels population –kinetic (statistical) equilibrium equations
    - radiation field - radiative transfer eq.

Equations of model stellar atmospheres

radiative transfer equation ($I_{\mu\nu}$)

$$\mu \frac{\mathrm{d}I_{\mu\nu}}{\mathrm{d}z} = -\chi_\nu I_{\mu\nu} + \eta_\nu \qquad \mu \frac{\partial I_{\mu\nu}}{\partial r} + \frac{1-\mu^2}{r}\frac{\partial I_{\mu\nu}}{\partial \mu} = \eta_\nu - \chi_\nu I_{\mu\nu}$$

radiative equilibrium equation (T)

$$4\pi \int_0^\infty (\chi_\nu J_\nu - \eta_\nu)\, \mathrm{d}\nu = 0$$

hydrostatic equilibrium equation (ρ)

$$\frac{\mathrm{d}p}{\mathrm{d}m} = g - \frac{4\pi}{c}\int_0^\infty \frac{\chi_\nu}{\rho} H_\nu \,\mathrm{d}\nu$$

kinetic (statistical) equilibrium equations (n_i)

$$n_i \sum_l (R_{il} + C_{il}) + \sum_l n_l (R_{li} + C_{li}) = 0$$

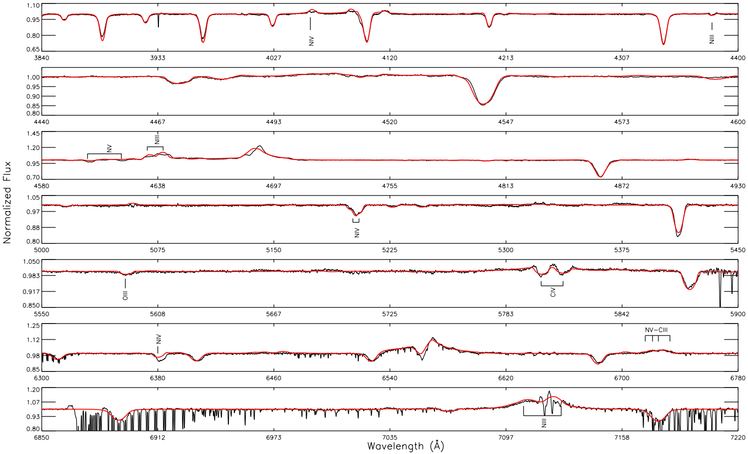
Stellar atmosphere models

- Solution of equations of model stellar atmosphere
  - System of nonlinear integrodifferential equations
  - Analytic solution impossible
  - Numerical solution
    - Complete linearization method (multidimensional Newton-Raphson method)
    - Accelerated Λ-iteration method (Jacobi iteration method)
- Recommendation: **Theory of Stellar Atmospheres: An Introduction to Astrophysical Non-equilibrium Quantitative Spectroscopic Analysis**, **Ivan Hubeny & Dimitri Mihalas, 2014**.

See Arũnas's talk!

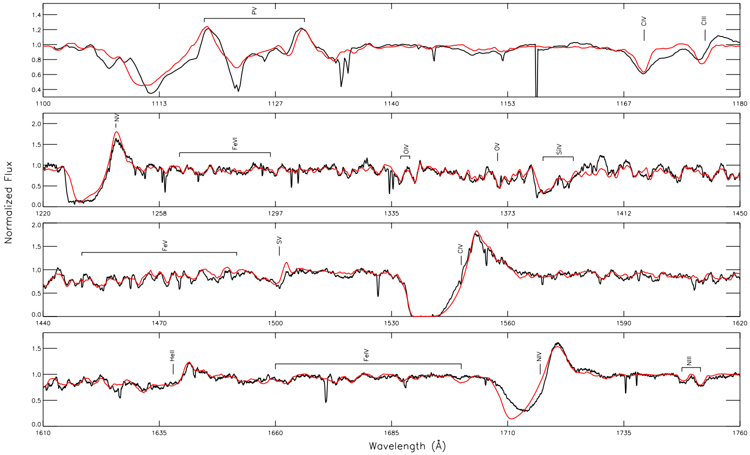
Stellar atmosphere models

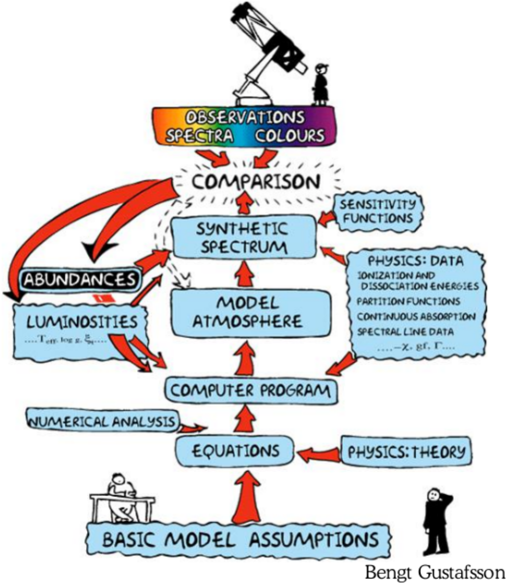
- **Supergiant ζ Puppis** observed with FEROS (Bouret et al., 2012). CMFGEN (Hillier 1990; Hillier & Miller 1998) synthetic spectra in red.



Stellar atmosphere models

- **Supergiant ζ Puppis** observed with Copernicus and IUE (Bouret et al., 20212). CMFGEN (Hillier 1990; Hillier & Miller 1998) synthetic spectra in red.





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Thank you for your attention!

Have a fun with modelling!