QUANTITATIVE SPECTROSCOPY OF MASSIVE HOT STARS

Lecture I: Basics of QS

Brankica Kubátová

Astronomický ústav AV ČR

Selected chapters on astrophysics

Astronomical Institute
Faculty of Mathematics and Physics, Charles University

November 16, 2022, Prague

Outline of the course

Lectures

1. **Basics of the quantitative spectroscopy (November 16)**
2. **Spectral diagnostics of massive, hot stars I (November 23)**
3. **Spectral diagnostics of massive, hot stars II (November 30)**
4. **NLTE model atmospheres codes (PoWER code)(December 1)**

Outline of the course

Lectures

1. **Basics of the quantitative spectroscopy (November 16)**
2. **Spectral diagnostics of massive, hot stars I (November 23)**
3. **Spectral diagnostics of massive, hot stars II (November 30)**
4. **NLTE model atmospheres codes (PoWER code)(December 1)**

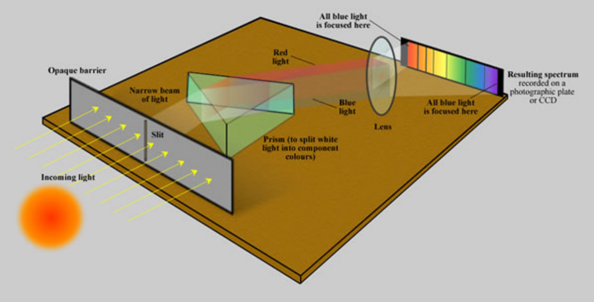
Literatures

1. **Quantitative spectroscopy of hot stars** - **Kudritzki, R. P. ; Hummer, D. G.**, Annual Rev. Astron. Astrophys., Vol. 28, p. 303-345 (1990)
2. **A Modern Guide to Quantitative Spectroscopy of Massive OB Stars** - **Sergio Simón-Díaz**, Springer International Publishing, pp. 155-187 (2020)

Spectroscopy

What it is?

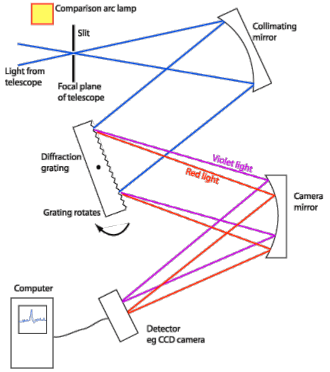
- Spectroscopy is the study of the interaction between matter and electromagnetic radiation
- The technique of splitting light (i.e., electromagnetic radiation) into its constituent wavelengths i.e., a spectrum



Credit: COSMOS - The SAO Encyclopedia of Astronomy

Spectroscopy

Spectrograph



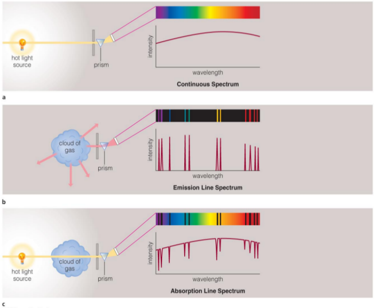
A Schematic Diagram of a Slit Spectrograph

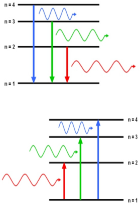
Credit: James B. Kaler, in "Stars and their Spectra," Cambridge University Press, 1989

Spectroscopy

Types of a spectra

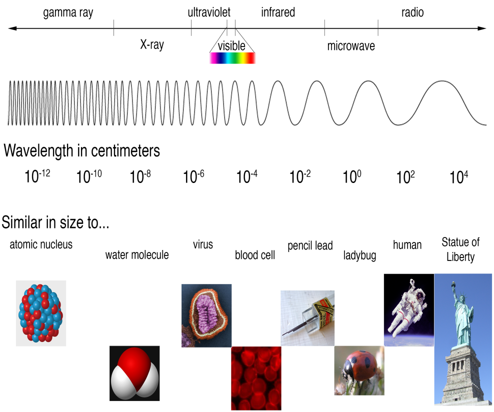
- **Continuous Spectrum** - stellar photosphere is blackbody with T_{eff}
- **Emission line Spectrum** - requires atoms or ions in an excited state
- **Absorption Line Spectrum** - cooler material in front of hotter material





Spectroscopy

Electromagnetic radiation



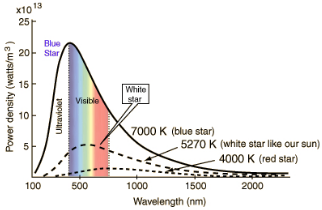
Credit: NASA's Imagine

Spectroscopy

Electromagnetic radiation

Wien's displacement law

For massive, hot stars the peak radiation is in UV spectral region



$$\lambda_{max} T = b$$

$$b = 0.29\ \text{cm K}; \quad T = 30\,000\ \text{K} \Rightarrow$$

$$\lambda_{max} = 960\ \text{Å}$$

Spectroscopy

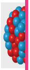
Electromagnetic radiation

Wavel

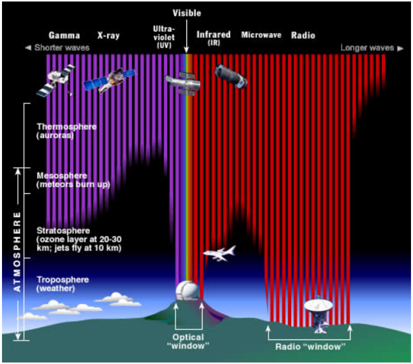
10

Similar

atomic



Earth Atmosphere



Credit: NASA's Imagine

Spectroscopy

Electromagnetic radiation

IUE

International Ultraviolet Explorer
120 to 340 nm

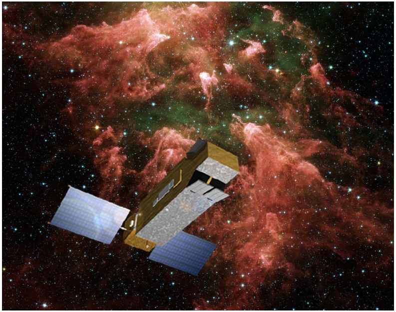
Credit: NASA's Imagine

Spectroscopy

Electromagnetic radiation

FUSE

The Far Ultraviolet Spectroscopic Explorer
90 to 120 nm



Credit: NASA's Imagine

Spectroscopy

Electromagnetic radiation

HST

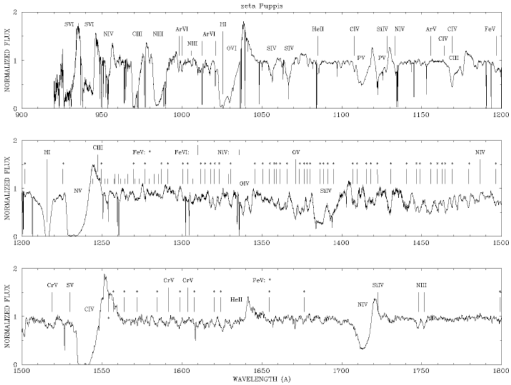
The Hubble Space Telescope
115–2500 nm

Credit: NASA's Imagine

Spectroscopy

UV spectra

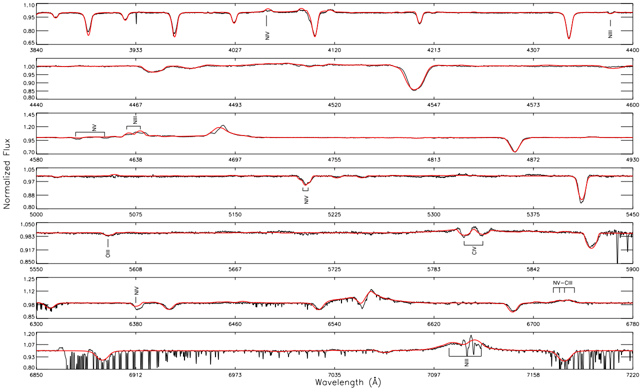
- **Merged spectrum of Copernicus and IUE UV high-resolution observations of the supergiant ζ Puppis (Pauldrach et al., 1994)**



Spectroscopy

Optical spectra

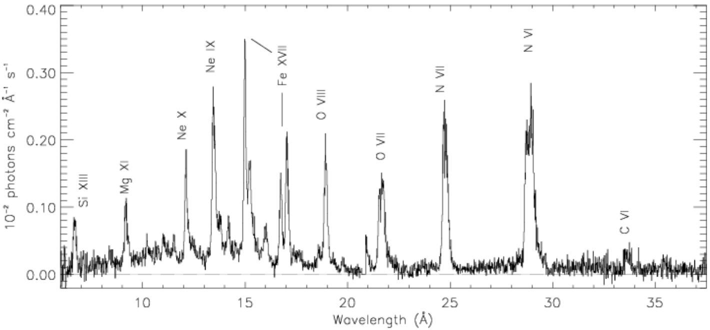
- ζ Pup observed with FEROS (Bouret et al., 2012)



Spectroscopy

X-ray spectra

- ζ Pup observed with XMM-Newton (Kahn et al., 2001)



Spectroscopy

SED of O-type stars

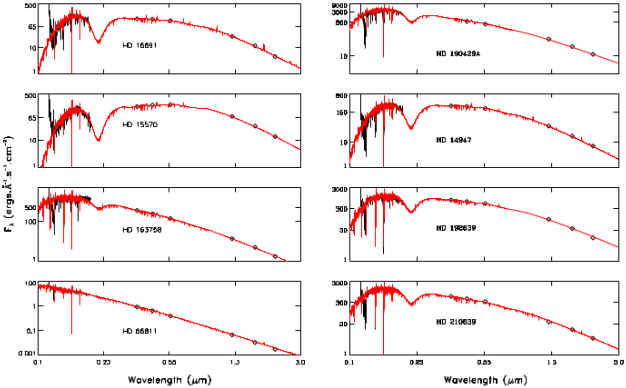
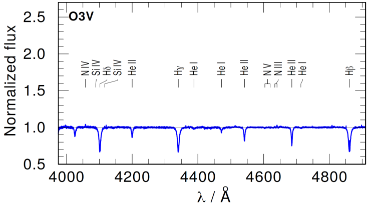


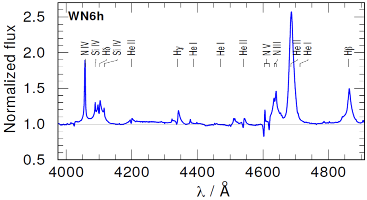
Fig. 1. Synthetic SEDs (in red) compared to flux calibrated + UBVJHK photometry for the target stars (in black). The distance, $E(B-V)$ and luminosity were iterated to reach agreement between models and observations (see Sect. 4.1). For plotting purpose, the fluxes were scaled by a factor 10^{14} for all stars but HD 66811 and HD 210839, where factors 10^{9} and 10^{13} were used, respectively.

Credit: Bouret et al., 2012

Spectroscopy

Spectra of O- and W-R-type stars





Credit: A. Sander

Spectroscopy

What Do Spectra Tell Us?

- Identify the type of the object
- Chemical composition
- Temperature, Preassure
- Chemical abundances
- Velocity (Radial and Rotational)
- Properties of the star and wind
- Strength of Magnetic field
- Physical changes in the star
- Material around stars
- Accretion disk
- To study the interstellar medium

Spectroscopy

What Do Spectra Tell Us?

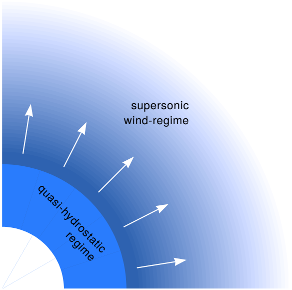
- Identify th... of the object
- Chemic...
- Tempe...
- Chem...
- Velo...
- Properties o...
- Strength of Magneti...
- Physical changes in the star
- Material around stars
- Accretion disk
- To study the interstellar medium

- All the information we gather about stars is derived from analysis of their radiation (spectra)
- Spectroscopy is a tool for unlocking the secrets of star light

Stellar atmosphere

Why to study stellar atmospheres?

- **The stellar atmosphere is all we really see from the star**
- Its spectrum is (usually) the only information we get
  $\Rightarrow$ Understand the spectrum to understand the star
- Only a proper modeling of the atmosphere can reproduce the emergent spectrum

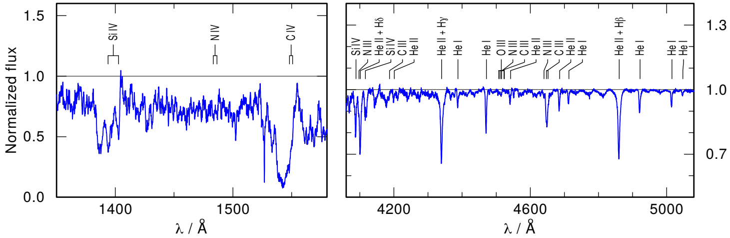


Credit: A. Sander

Stellar atmosphere

Why to study stellar atmospheres?

- **The stellar atmosphere is all we really see from the star**
- **Its spectrum is (usually) the only information we get**
  ⇒ Understand the spectrum to understand the star
- **Only a proper modeling of the atmosphere can reproduce the emergent spectrum**

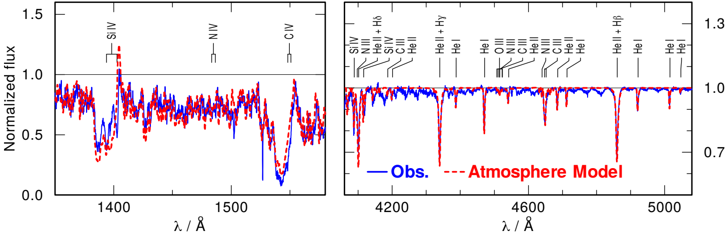


Credit: A. Sander

Stellar atmosphere

Why to study stellar atmospheres?

- **The stellar atmosphere is all we really see from the star**
- **Its spectrum is (usually) the only information we get**
  ⇒ Understand the spectrum to understand the star
- **Only a proper modeling of the atmosphere can reproduce the emergent spectrum**



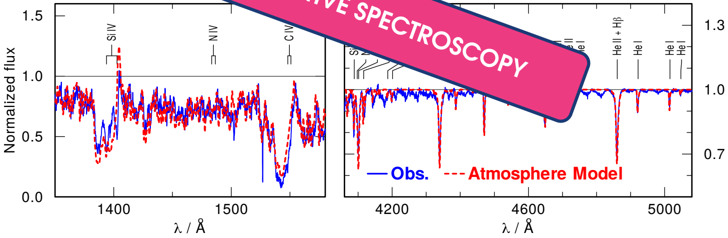
Credit: A. Sander

Stellar atmosphere

Why to study stellar atmospheres?

- The stellar atmosphere is all we really see from the star
- Its spectrum is (usually) the only information we get
  $\Rightarrow$ Understand the spectrum to understand the star
- Only a p… deling of the atmosphere can reproduce the eme…

QUANTITATIVE SPECTROSCOPY



Credit: A. Sander

QUANTITATIVE SPECTROSCOPY

What is QS?

- Determination of physical parameters that (uniquely and completely?) characterize an astronomical object
- QS is approached as an inversion problem $\mathbf{d}_{\mathrm{obs}} = \mathbf{F}(\mathbf{p})$
- The process of calculating from a set of observations the causal factors that produced them

QUANTITATIVE SPECTROSCOPY

What is QS?

- Determination of physical parameters that (uniquely and completely?) characterize an astronomical object
- QS is approached as an inversion problem $d_{obs} = F(p)$
- The process of calculating from a set of observations the causal factors that produced them

QUANTITATIVE SPECTROSCOPY

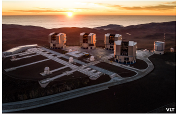
What is QS?

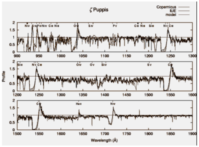
- Determination of physical parameters that (uniquely and completely?) characterize an astronomical object
- QS is approached as an inversion problem $d_{obs} = F(p)$
- The process of calculating from a set of observations the causal factors that produced them

QUANTITATIVE SPECTROSCOPY

What is QS?

- Determination of physical parameters that (uniquely and completely?) characterize an astronomical object
- QS is approached as an inversion problem $d_{obs} = F(p)$
- The process of calculating from a set of observations the causal factors that produced them





QUANTITATIVE SPECTROSCOPY

What is QS?

- Determination of physical parameters that (uniquely and completely?) characterize an astronomical object
- QS is approached as an inversion problem $\mathbf{d}_{\text{obs}} = \mathbf{F}(\mathbf{p})$
- The process of calculating from a set of observations the causal factors that produced them

The ingredients

- Observed data (spectra)
- Theoretical spectra (model atmosphere/line formation codes)
- Comparison metrics (grid of models)

QUANTITATIVE SPECTROSCOPY

What is QS?

- Determination of physical parameters that (uniquely and completely?) characterize an astronomical object
- QS is approached as an inversion problem $d_{obs} = F(p)$
- The process of calculating from a set of observations the ...

What should we worry about?

- Information encoded in the observed data
  (both quantity and quality, i.e., spectral range coverage, SNR, ...)
- Physics incorporated in the models
  (i.e., assumptions/simplifications)
- Atomic data
- Comparison metrics (grid of models)
- Uncertainties/Errors

QUANTITATIVE SPECTROSCOPY

Processing of the observed spectrum

- To correct the observed spectrum for interstellar lines and nebular contamination
- To correct the observed spectrum for cosmic rays and telluric lines
- To improve the normalization

QUANTITATIVE SPECTROSCOPY

Processing of the observed spectrum

- To correct the observed spectrum for interstellar lines and nebular contamination
- To correct the observed spectrum for cosmic rays and telluric lines
- To improve the normalization

Calculating the grid of the models

- Define the free parameters (parameter space)
  - No wind (4d) – T_{eff}, $\log g$, He
  - With wind (8d) – T_{eff}, $\log g$, He, β, R_*, v_∞, $\dot{M}$
  - + wind clumping, + elemental abundances ...
- Define the range of values for the various free parameters
- Fix some parameters

QUANTITATIVE SPECTROSCOPY

Processing of the observed spectrum

- To correct the observed spectrum for interstellar lines and nebular contamination
- To correct the observed spectrum for cosmic rays and
-

Calc

-
- ters
-

QS tools in the OB literature

	Mokien+2005	Lefever+2006	Simón-Díaz +2011	Irrgang+2014
Targets	O Stars	B Stars	O Stars	B stars
Metrics	MD	MD	MD	MD
Models	FASTWIND	FASTWIND	FASTWIND	ADS
Parameters	6	7	6	13
Method	GA	Grid	Grid	Grid
# of models	7000/star	$3x10^5$	$2x10^5$	$\sim 2x10^6$
Comment	on the fly	Grid	Grid	Grid

MD – Minimum distance.
GA – Genetic algorithm.
ADS – Atlas + Detail + Surface

Credit: Miguel A. Urbaneja

QUANTITATIVE SPECTROSCOPY

Martins at al., 2015

"Surface abundances of Galactic ON stars"

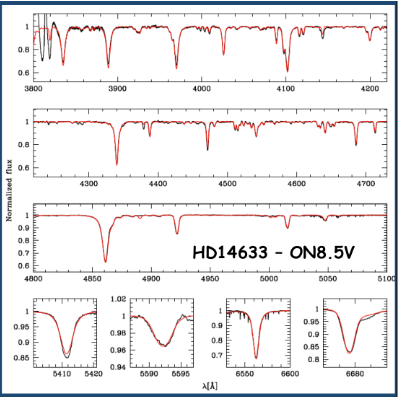
Observations: high-resolution, high SNR optical spectra.

Parameters: Teff, logg, He/H, CNO.

Comment: No wind analysis ("reasonable" values adopted).

Models: CMFGEN (Hillier & Miller 1998).

Sample size: 12 stars.



QUANTITATIVE SPECTROSCOPY

Najarro, Hanson & Puls (2011)

"L-band spectroscopy of Galactic OB-stars"

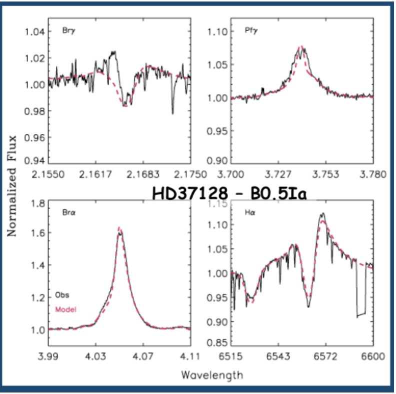
Observations: optical spectra, H-,K- and L-band.

Parameters: Teff, logg, He/H, β, Q, … (#11)

Comment: clumping law with 4 parameters.

Models: CMFGEN (Hillier & Miller 1998).

Sample size: 10 stars.



Stellar Atmospheres Models

Stellar parameters

- Effective temperature T_{eff} [K]
- Surface gravity $\log g$
- Helium abundance $Y = H/He$
- Stellar luminosity L_* $[L_\odot]$
- Stellar radii R_* $[R_\odot]$
- Micro-turbulent Velocity
- Chemical Abundances

Stellar Atmospheres Models

Stellar parameters

- Effective temperature T_{eff} [K]
- Surface gravity $\log g$
- Helium abundance $Y = H/He$
- Stellar luminosity L_* $[L_\odot]$
- Stellar radii R_* $[R_\odot]$
- Micro-turbulent Velocity
- Chemical Abundances

Wind parameters

- Terminal velocity v_∞ [km/s]
- Mass-loss rate $\dot{M}$ $[M_\odot/yr]$
- Beta parameter β

Stellar Atmospheres Models

Stellar parameters

- Effective temperature T_{eff}
- Surface gravity $\log g$
- Helium abundance $Y = $ H
- Stellar luminosity $L_* \ [L_\odot]$
- Stellar radii $R_* \ [R_\odot]$
- Micro-turbulent Velocity
- Chemical Abundances

Photospheric models

- DETAIL/SURFACE (Butler & Giddings, 1985)
- TLUSTY/SYNSPEC (Hubeny, 1988)

Wind parameters

- Terminal velocity v_∞ [km/s]
- Mass-loss rate $\dot{M} \ [M_\odot/yr]$
- Beta parameter β

Stellar Atmospheres Models

Stellar parameters

- Effective temperature T_{eff}
- Surface gravity $\log g$
- Helium abundance $Y = H$
- Stellar luminosity $L_* \ [L_\odot]$
- Stellar radii $R_* \ [R_\odot]$
- Micro-turbulent Velocity
- Chemical Abundances

Wind parameters

- Terminal velocity v_∞ [km
- Mass-loss rate $\dot{M} \ [M_\odot/yr]$
- Beta parameter β

Photospheric models

- DETAIL/SURFACE (Butler & Giddings, 1985)
- TLUSTY/SYNSPEC (Hubeny, 1988)

Photospheric + Wind models

- CMFGEN (Hillier & Miller, 1998)
- FASTWIND (Puls et al., 2005)
- PoWR (Hamann & Gräfener, 2004)
- WM-basic (Pauldrach el al., 2001)

Stellar Atmospheres Models

Stellar parameters

- Effective temperature T_{eff}
- Surface gravity $\log g$
- Helium abundance $Y = H$
- Stellar luminosity L_* $[L_\odot]$
- Stellar radii R_* $[R_\odot]$
- Micro-turbulent Velocity
- Chemical Abundances

Wind parameters

- Terminal velocity v_∞ [km
- Mass-loss rate $\dot{M}$ $[M_\odot/yr]$
- Beta parameter β

Photospheric models

- DETAIL/SURFACE (Butler & Giddings, 1985)
- TLUSTY/SYNSPEC (Hubeny, 1988)

Photospheric + Wind models

- CMFGEN (Hillier & Miller, 1998)
- FASTWIND (Puls et al., 2005)
- PoWR (Hamann & Gräfener, 2004)
- WM-basic (Pauldrach el al., 2001)

Stellar Atmospheres Models

What has to be included?

- **Extreme non-LTE situation**
- Model atoms for H, He, C, N, Fe, etc. (atomic data)
- Line blocking/blanketi
- Modeling two regimes (core) + Supersonic wi
- Inhomogeneities
- Other physical effects

non-LTE

- Intense radiation field + Low densities in lines and continuum forming regions
  ⇒ Collisions are less important in hot star atmospheres

Stellar Atmospheres Models

What has to be included?

- **Extreme non-LTE situation**
- **Model atoms for H, He, C, N, Fe, etc. (atomic data)**
- Line blocking/blanketing
- Modeling two regimes: Hydrostatic part (core) + Supersonic wind (halo)
- Inhomogeneities
- Other physical effects

Stellar Atmospheres Models

What has to be included?

- Extreme non-LTE situation
- Model atoms for H, He, C, N, Fe, etc. (atomic data)
- Line blocking/blanketing
- Modeling two regimes
  (core) + Supersonic wi
- Inhomogeneities
- Other physical effects

Atomic data

- Collisional cross sections
  - OPAL PROJECT (Iglesias & Rogers 1996)
  - OPACITY PROJECT (Seaton et al. 1992)
  - IRON PROJECT (Hummer et al. 1993, Witthoeft & Badnell 2008)
- Super-level approach - simplified treatment of iron-group atoms (Anderson 1985, 1989)

Stellar Atmospheres Models

What has to be included?

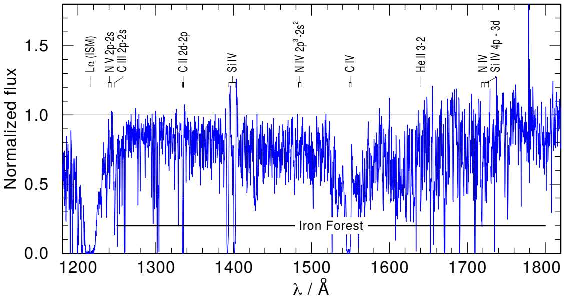
- **Extreme non-LTE situation**
- **Model atoms for H, He, C, N, Fe, etc. (atomic data)**
- **Line blocking/blanketing**
- Modeling two regimes: Hydrostatic part (core) + Supersonic wind (halo)
- Inhomogeneities
- Other physical effects

Stellar Atmospheres Models

What has to be included?

- Extreme non-LTE situation
- Model atoms for H, H
  data)
- Line blocking/blo
- Modeling two reg
  (core) + Superson
- Inhomogeneities
- Other physical ef

Blanketing and blocking



Credit: A. Sander

Stellar Atmospheres Models

What has to be included?

- Extreme non-LTE situation
- Model atoms for H, He
  data)
- Line blocking/
- Modeling two
  (core) + Supe
- Inhomogeneit
- Other physica

Blanketing and blocking

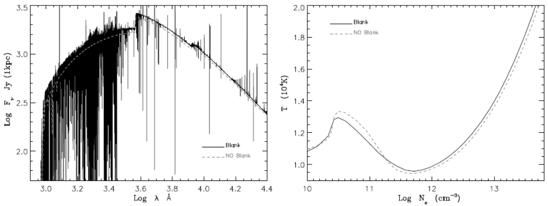


Figure 2: Effects of line blanketing (solid: blanketed model, dashed: model without blanketing) on the flux distribution ($\log F_\nu$ (Jansky) vs. $\log \lambda$ (Å), left panel) and temperature structure ($T(10^4$ K) vs. $\log n_e$, right panel) in the atmosphere of a late B-hypergiant. Blanketing blocks flux in the UV, redistributes it towards longer wavelengths and causes back-warming. From Puls et al. (2008).

Credit: J. Puls

Stellar Atmospheres Models

What has to be included?

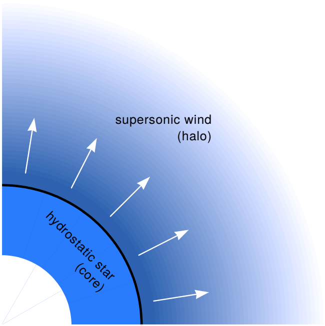
- Extreme non-LTE situation
- Model atoms for H, He, C, N, Fe, etc. (atomic data)
- Line blocking/blanketing
- Modeling two regimes: Hydrostatic part (core) + Supersonic wind (halo)
- Inhomogeneities
- Other physical effects

Stellar Atmospheres Models

What has to be included?

- Extreme non-LTE situation
- Model atoms for l
  data)
- Line blocking/bla
- Modeling two reg
  (core) + Supersor
- Inhomogeneities
- Other physical ef

Modeling two regimes



Credit: A. Sander

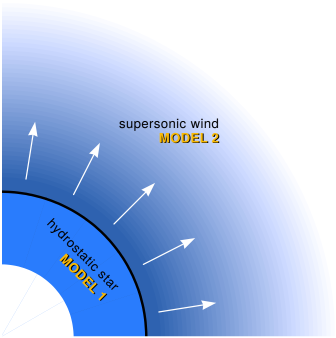
Stellar Atmospheres Models

What has to be included?

- Extreme non-LTE situa
- Model atoms for l
  data)
- Line blocking/bla
- Modeling two reg
  (core) + Supersor
- Inhomogeneities
- Other physical ef

Modeling two regimes

- Traditional core-halo approach: Two separate models



Credit: A. Sander

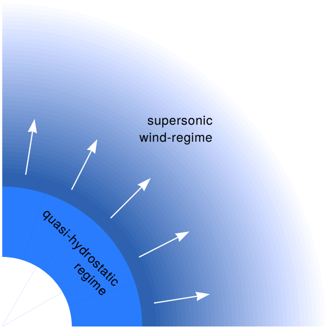
Stellar Atmospheres Models

What has to be included?

- Extreme non-LTE s
- Model atoms for l
  data)
- Line blocking/bla
- Modeling two reg
  (core) + Supersor
- Inhomogeneities
- Other physical ef

Modeling two regimes

- Modern approach, since ≈ 1990s:
  Unified model atmospheres
  (e.g. Hamann & Schmutz 1987, Gabler et al., 1989)



Credit: A. Sander

Stellar Atmospheres Models

What has to be included?

- Extreme non-LTE situation
- Model atoms for H, He, C, N, Fe, etc. (atomic data)
- Line blocking/bla
- Modeling two reg (core) + Supersor
- Inhomogeneities
- Other physical ef

Wind clumping

- Simplification: Clumping factor $D \implies \rho_{\mathbf{cl}} = D\rho_{sw}$; void inter-clump medium; monotonic velocity field
- Microclumping approach - clumps are optically thin at all frequencies (FASTWIND; CMFGEN ; PoWR)
- 3-D description of clumping from other codes

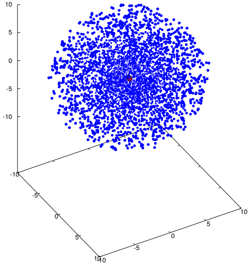
Stellar Atmospheres Models

What has to be include

- Extreme non-LTE s
- Model atoms for l data)
- Line blocking/bla
- Modeling two reg (core) + Superson
- Inhomogeneities
- Other physical ef

Wind clumping

- Simplification: Clumping factor $D \implies \rho_{cl} = D\rho_{sw}$; void inter-clump medium; monotonic velocity field
- Microclumping approach - clumps are optically thin at all frequencies (FASTWIND; CMFGEN ; PoWR)
- 3-D description of clumping from other codes



Šurlan et al., 2012

Stellar Atmospheres Models

What has to be included?

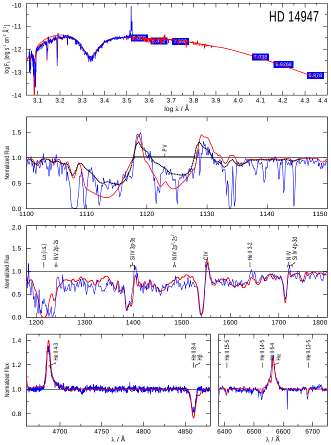
- Extreme non-LTE situation
- Model atoms for H, He, C, N, Fe, etc. (atomic data)
- Line blocking/blanketin
- Modeling two reg (core) + Supersor
- Inhomogeneities
- Other physical ef

Other physical effects

- Magnetic field
- Rotation
- Pulsation ...

Application - an example

The best fit



Example from Šurlan et al., 2013

Application - an example

Diagnostic lines

	UV	Optical	near-IR
T_{ef}	Fe IV/V/VI	He I 4471 / He II 4542 Si II 4124 / Si III 4552 / Si IV 4116	He I 2.112 / He II 2.189
$\log g$	–	Hβ, Hγ, Hδ	Brγ
v_∞	N V 1240, Si IV 1393-1403 C IV 1548-1550, N IV 1718	Hα, Hβ, Hγ, He I 4471 (if strong wind)	He I 2.058, He I 2.112, Brγ (if strong wind)
$\dot{M}$	N V 1240, Si IV 1393-1403 C IV 1548-50, N IV 1718	Hα, He II 4686	Brγ
f (clumping)	O V 1371, N IV 1718 P V 1118-1128	Hα, He II 4686	Br10, Br11
Surface abundances	Fe IV/V/VI	C III 4637-40, C IV 5812, N III 4510-15, N IV 5200, O II 4661, O III 5592...	N III 2.247-2.251 Mg II 2.138-2.144 Si II 1.691-98 Fe II 1.688, Fe II 2.089
Magnetic f eld	–	He I 4026, He I 4712 He II 4200, He II 4542, O III 5592, C IV 5812	–

From Martins et al., 2011

THANK YOU FOR YOUR ATTENTION!

Brankica Kubátová

E-mail: brankica.kubatova@asu.cas.cz
Hompage: http://stelweb.asu.cas.cz/ brankica/