QUANTITATIVE SPECTROSCOPY OF MASSIVE HOT STARS

Lecture II: Spectral Diagnostics I

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Selected chapters on astrophysics

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Massive, hot stars

Basic properties

- **Spectral type - OB-type**
  Massive stars in short-lived transition phase (BSGs, B(e)SGs, ASGs, YHGs, LBVs, and WR
- **Massive - $M_{init} \gtrsim 8$ ($M_\odot$)**
- **Hot - $T_{eff} \gtrsim 20\,000$ (K)**
  → high surface brightness
  → strong radiation in UV
- **Extremely luminous - $L \gtrsim 3000$ ($L_\odot$)**
- **Short lifetimes**
  Unofficial motto: "Live fast, die young"
- **Ends in a supernova explosion or gamma-ray burst**
  Remnant: neutron star or black hole
- **Very rare** (small fraction of the stellar population)

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H-R diagram

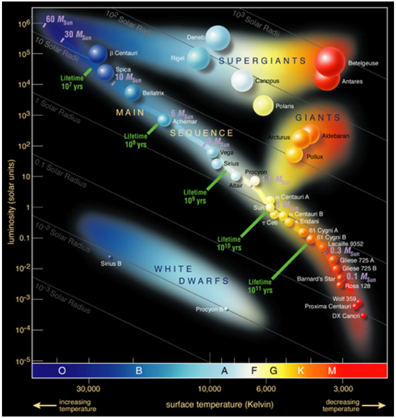

Photo: eso.org

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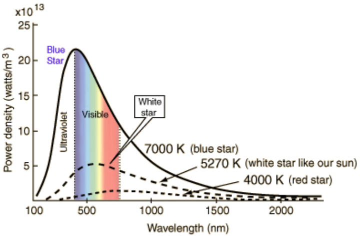
Peak radiation in the UV

Wien's displacement law



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

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

$\lambda_{max} = 960\ \text{Å}$

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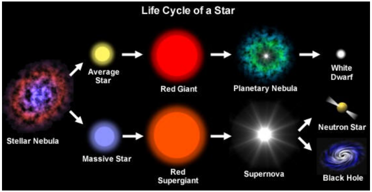
Life Cycle of a Star



Credit: NASA

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Orion's Belt

The Orion's Belt including the Flame Nebula (left) and Horsehead Nebula (lower left).

Credit: ESO/ESA/NASA

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Hot, massive stars

Why to study them?

- Can be seen at large distances
- Enrich ISM with heavier elements (i.e., metals)
- Influence the chemical and structural evolution of galaxies
  - Heat-up, ionize, or facilitate chemical reactions in ISM
  - Provide kinetic energy and momentum into ISM
  - Trigger, regulate and terminate star formation in stellar clusters
- The most likely source for reionizing the early universe

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The “Bubble Nebula”

Credit: NASA/ESA.

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Wind parameters

Global and local parameters

- GLOBAL WIND PARAMETERS
  - Mass-loss rate $\dot{M} \sim 10^{-7} - 10^{-5}\ M_\odot/yr$
  - Terminal velocity v_∞ up to ~ 5000 km/s
  - Average mass density $\overline{\rho}$
- For stationary and spherically symmetric wind $\Rightarrow$

$$\dot{M} = 4\pi r^2 \rho(r)\, v(r) = \text{const.}$$

$$\overline{\rho} = \frac{\dot{M}}{4\pi R_*^2 v_\infty}$$

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Wind parameteras

Observed and theoretical parameters

- "Observed" wind parameters - the result of diagnostic techniques based on theoretical modelling

non-LTE model + given $v(r)$ and $\rho(r) \Rightarrow$ synth. spectrum $\Rightarrow$ comp. with obs.

- Theoretical (predicted) wind parameters - the result of hydrodynamical calulations $T_{\rm eff}$, L_*, R_*, chem. comp. $\Rightarrow v(r), \rho(r), \dot{M}, v_\infty$

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Problem!

- Discrepance between teoretical and "observed" mass-loss rates (e.g. Bouret et al., 2003, Martins et al., 2005, Puls al., 2006)
- Different mass-loss diagnostics result in different mass-loss rates (e.g. Bouret et al., 2003, 2005; Fullerton et al., 2006; Puls et al., 2006)

Line-driven Winds

Principle of wind driving

1. The photons are scattered in lines of ions of heavier elements (e.g., ions of C , N , O , Si , Ne , P , S , Ni , Fe -group elements etc.)
   - physical process: momentum and energy transfer by absorption and scattering - "Resonance line scattering"
2. The outward accelerated ions transfer their momenta to the bulk plasma of the wind (hydrogen and helium - mostly passive component)
   - physical process: Coulomb collisions
3. Pioneering works of Lucy & Solomon (1970) and Castor, Abbott, & Klein (1975, CAK) serve as a basis for present hot star wind theory

Line-driven Winds

Principle of wind driving

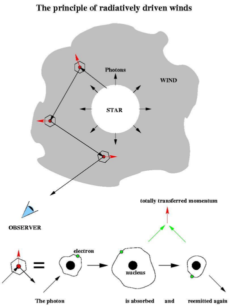
1. Th… el… el… -group

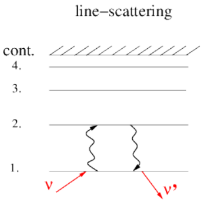
2. Th… a to th… mostly po…

3. Pi… tor, Ab… ent hot st…

Resonance line scattering

- Line transition from the ground state of the atom





Credit: J. Puls

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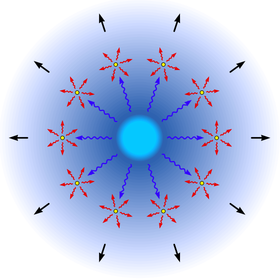
Absorptions mainly from radial directions

but isotropic re-emission ⇒ Radial net outflow



Credit: A. Sander

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Wind model assumptions

Wind model

- "Standard model" - a stationary, spherically symmetric smooth stellar wind
- Density distribution from equation of continuity

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v(r)}$$

- The β velocity law - assumption predicted by the theory of radiation-driven winds (see Castor et al, 1975; Pauldrach et al, 1986)

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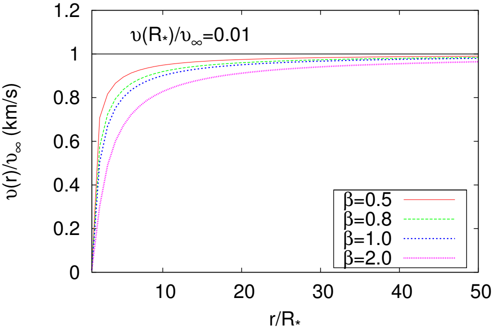
$$v(r) = v_\infty \left(1 - \frac{b}{r}\right)^\beta$$

$$b = R_* \left\{1 - \left(\frac{v(R_*)}{v_\infty}\right)^{1/\beta}\right\}$$

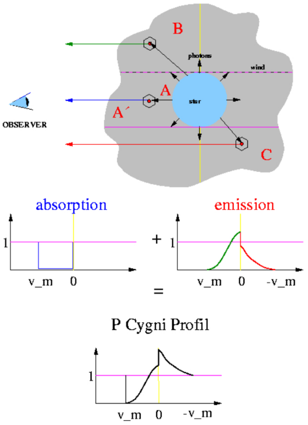
Wind model assumptions

The β velocity law



Spectral signature of mass loss

P-Cygni profile formation



Credit: J. Puls

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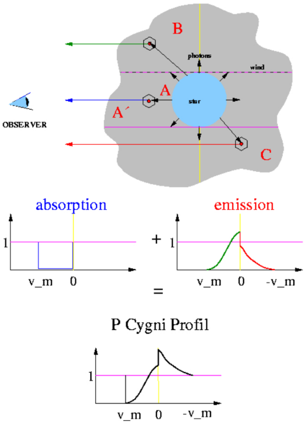

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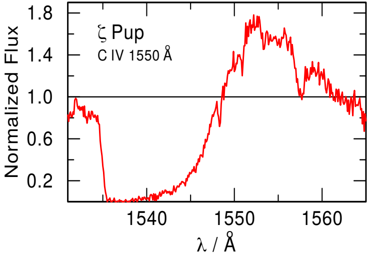
What can be inferred?

- The terminal velocity



$$v_\infty = \frac{\Delta\lambda}{\lambda} \cdot c$$

Credit: A. Sander

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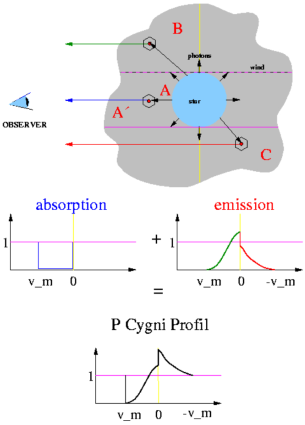

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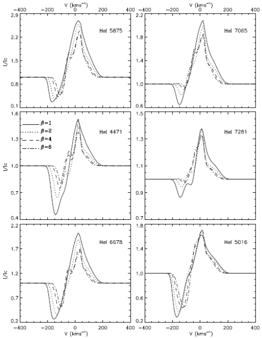
What can be inferred?

- The shape of the velocity field



From Najarro et al., 1997

Small-scale wind structures

Wind clumping

- STABILITY ANALYSIS OF STELLAR WINDS - Lucy & Solomon 1970; MacGregor et al. 1979; Abbott 1980; Carlberg 1980; Owocki & Rybicki 1984; Owocki & Puls 2002, Krtička & Kubát 2002, and other papers
  - line-deshadowing instability (LDI) is an intrinsic property of the line-driving mechanism
- RADIATION HYDRODYNAMICAL SIMULATIONS of the nonlinear growth of the LDI
  - 1D spherically symmetric wind - Feldmeier (1995), Feldmeier et al. (1997), Owocki et al. (1988), Runacres & Owocki (2002)
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Theoretical predictions

- Small perturbation of driving force tends to grow and steepens into shocks - SHOCK COMPRESSION
- CLUMPS - regions with different density than the surrounding wind matter

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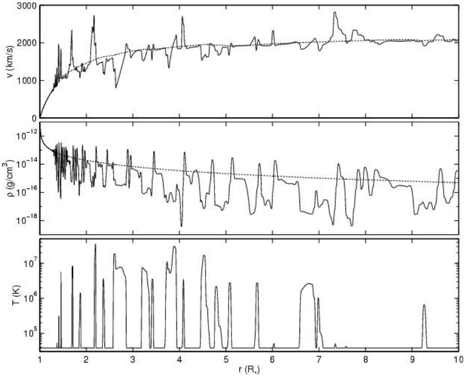

From Runacres & Owocki (2002)

Stelar Atmospheres Models

Stellar parameters

- Efective temperature T_{eff} [K]
- Surface gravity $\log g$
- Helium abundance Y=H/He
- Stellar luminosity L_* $[L_\odot]$
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By fitting the SED

- Distance (global scaling)
- Interstellar Extinction (Reddening) "color exces" $E_{(B-V)}$

Spectroscopic analysis

Steps to perform

1. Acquisition of the observed spectrum.
2. Pre-processing of the spectrum, including a first qualitative visual assessment, the continuum normalization and the radial velocity correction.
3. Determination of the line-broadening parameters. This is the basic step to have access to projected rotational velocities.
4. Identification of the stellar atmosphere code and atomic models best suited for the analysis of the star under study.
5. Creation of a grid of stellar atmosphere models.
6. Identification of the analysis strategy best suited to extract information from the observed spectrum of the star under study.
7. Determination of the main set of spectroscopic parameters accessible through the analysis of the observed piece of spectrum (*stellar parameters determination).*
8. Determination of surface abundances of interest (*chemical abundance analysis).*

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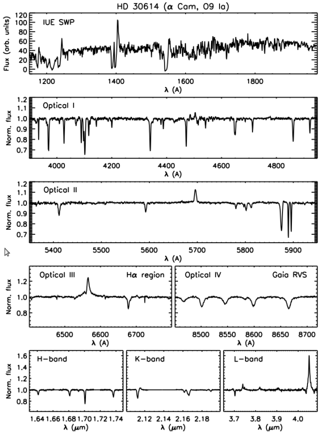

Fig. 4 Panchromatic view of the O9 Ia star HD 30614 (α Cam). The figure has been created combining observations obtained with different spectrographs attached to several ground based telescope facilities (optical and IR) and the IUE space mission (UV). Spectra kindly provided by F. Najarro & M. Garcia (Centro de Astrobiolgía, Madrid).

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8. Determination of surface abundances of interest (*chemical abundance analysis*).

Spectroscopic analysis

Steps to perform

1. Acquisition of the observed spectrum.
2. Pre-processing of the spectrum, including a first qualitative visual assessment, the continuum normalization and the radial velocity correction.
3. Determination of the line-broadening parameters. This is the basic step to have access to projected rotational velocities.
4. Identification of the stellar atmosphere code and atomic models best suited for the analysis of the star under study.
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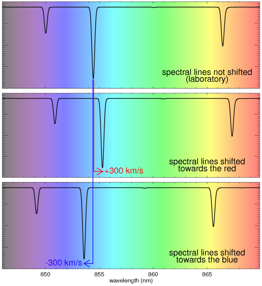
Radial velocity correction

Radial velocity

- The observed spectrum must be corrected by Doppler shift to ensure that all diagnostic lines are located in the laboratory position.
- Standard techniques
  - Identification of the core of one or several diagnostic lines.
  - Cross-correlation with a template.



Line-broadening parameters

Rotational velocity

- Inferring the projected component of the equatorial rotational velocity ($v\sin i$) by disentangling the effect that rotation produces on the line-profile from anz other broadening effect.
- Selection of the best suited lines for the line broadening analysis - a well isolated photospheric metal line than a hydrogen or helium line are better to use.
- Methods
    - The combined use of the Fourier transform and a goodness-of-fit methods
    - Synthetic line resulting from a stellar atmosphere code – is convolved with a rotational and a macroturbulent profile

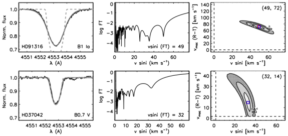


Fig. 5 Combined FT+GOF line-broadening analysis of the Si III λ4552 Å line in the early-B dwarf HD 37042 (bottom) and the early-B supergiant HD 91316 (top). [Left panels] The best fitting synthetic profile (solid gray) and the profile corresponding to $v \sin i$(FT) and $v_{mac} = 0$ (dashed gray) are over plotted to the observed profile (solid black). [Middle panels] Fourier transform of the observed profile. [Right panels] χ^2-2D-map resulting from the GOF analysis.

Line-broadening parameters

Micro-turbulence velocity

- Form of turbulence that varies over small distance scales
- Mechanisms that can cause broadening of the absorption lines in the stellar spectrum
- Varies with the effective temperature and the surface gravity
- Velocity fields with a scale that is shorter than the mean free path of the photons in the atmosphere
- The microturbulent velocity is defined as the microscale non-thermal component of the gas velocity in the region of spectral line formation

Line-broadening parameters

Micro-turbulence

- Convection - the mechanism believed to be responsible for the observed turbulent velocity field
- In massive stars the sub-surface convection zones can excite turbulence at the stellar surface through the emission of acoustic and gravity waves (Cantiello et al., 2009; Langer et al., 2009)
- The strength of the microturbulence can be determined by comparing the broadening of strong lines versus weak lines
- Microturbulenceis usually treated in model atmospheres as a free parameter (ξ_t) that allows to re-establish agreement among abundances derived from different lines

$$\xi_t(r) = \xi_t^{min} + (\xi_t^{max} - \xi_t^{min}) \cdot \frac{v(r)}{v_\infty}$$

Line-broadening parameters

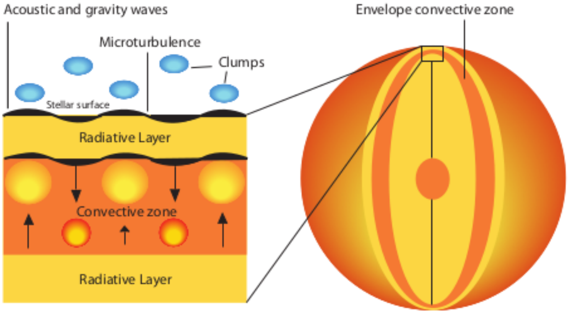


Figure 1: Schematic representation of the physical processes connected to subsurface convection. Acoustic and gravity waves emitted in the convective zone travel through the radiative layer and reach the surface, inducing density and velocity fluctuations. In this picture microturbulence and clumping at the base of the wind are a consequence of the presence of subsurface convection.

From Cantinello et al., 2009

Line-broadening parameters

Macro-turbulence

- Howarth et al., 1997 - OB stars from IUE spectroscopy: important line broadening mechanism in addition to rotation
- Refers to velocity fields with a scale longer than the mean free path of the photons
- Macroturbulence of the order of several tens of km/s
- Aerts & De Cat, 2003 - take into account pulsational velocity fields; pulsational broadening in the line-prediction code
- Pulsational velocity broadening due to the collective effect of numerous low-amplitude gravity mode oscillations offers a natural and appropriate physical explanation for the occurrence of macroturbulence in hot massive stars

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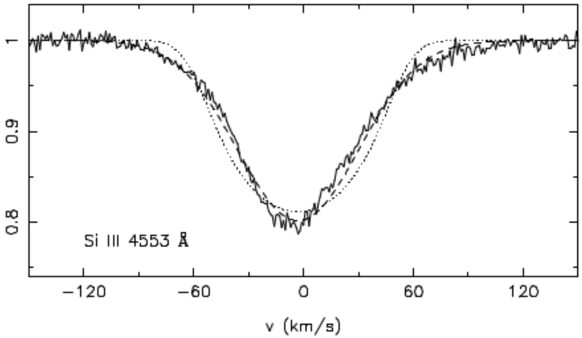

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THANK YOU FOR YOUR ATTENTION!

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