WINDS OF HOT MASSIVE STARS

III Lecture: Quantitative spectroscopy of winds of hot massive stars

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Selected Topics in Astrophysics
Faculty of Mathematics and Physics
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1. Spectral diagnostics of stellar winds
2. Photospheric parameters determination
3. Terminal velocity determination
4. Mass-loss rates determination

Spectral diagnostics of stellar winds

- Important diagnostics - spectral lines
  - emission
  - absorption
  - P-Cygni

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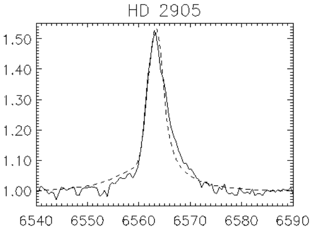
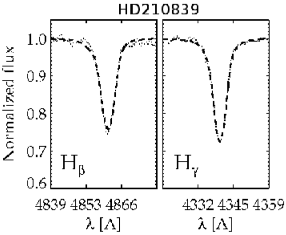
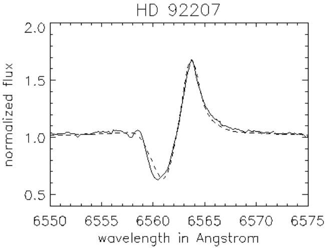
Optical lines

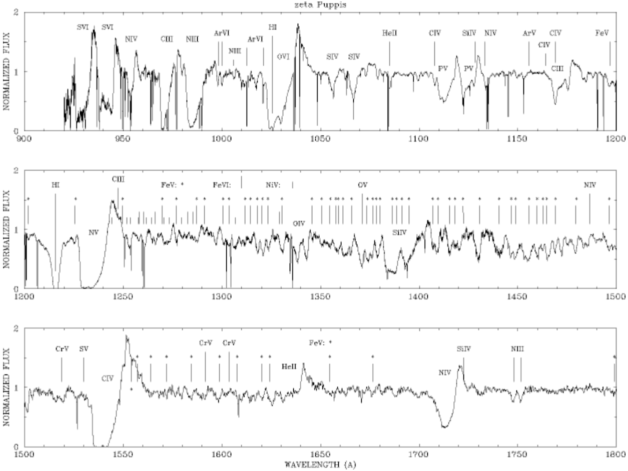






Spectral diagnostics of stellar winds

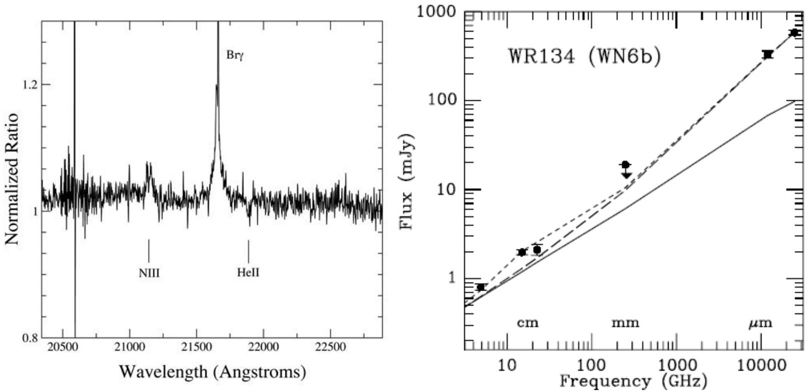
UV lines



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

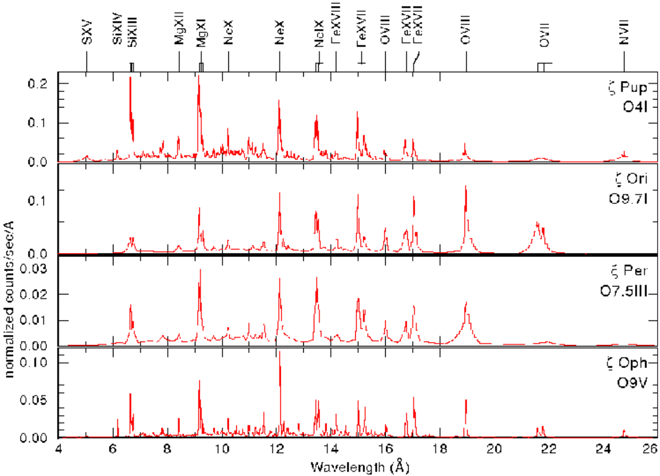
Spectral diagnostics of stellar winds

IR lines and radio continua



Spectral diagnostics of stellar winds

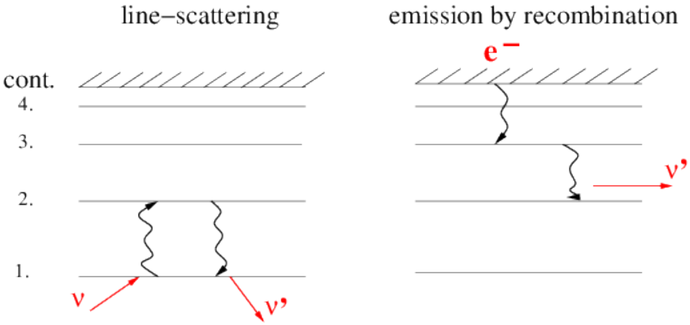
X-ray lines



Oskinova et al., 2008 - high resolution spectra obtained with Chandra HETGS/MEG

Spectral diagnostics of stellar winds

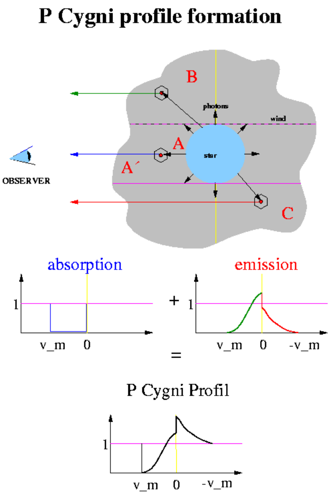
- Processes for line formation in winds:
  - Line scattering (e.g. P-Cygni UV resonance lines of C IV, N V, Si IV, O VI)
  - Line emission by recombination (e.g. H_α)
  - Line emission from collisional-excitation or photo-excitation
  - Pure absorption
- "Resonance line scattering" - line transition from the ground state of the atom



Formation of P-Cygni line profile

- P CYGNI PROFILE - signature of an expanding stellar atmosphere

Source: from homepage of J. Puls



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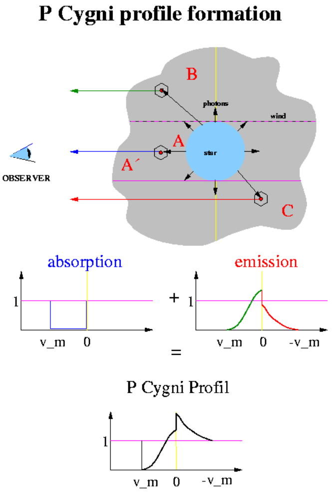
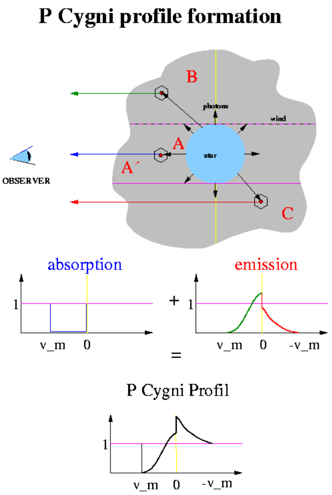


Formation of P-Cygni line profile

- P CYGNI PROFILE - signature of an expanding stellar atmosphere

  Source: from homepage of J. Puls
- The key effect is the Doppler-effect
- What can be investigate from P Cygni profiles?
  - Determination of the terminal velocity
  - Determination of the ion densities
  - Determination of the shape of the velocity field



Spectral diagnostics of stellar winds

- GLOBAL WIND PARAMETERS - $\dot{M}$, v_∞ and $\bar{\rho}$ (the average mass density)
- for stationary and spherically symmetric wind ⇒

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

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- "Observed wind properties" - the result of diagnostic techniques based on theoretical modeling

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Stellar atmospheric models + Hydrodynamic effects → Radiative transfer ⟹ Synthetic spectrum

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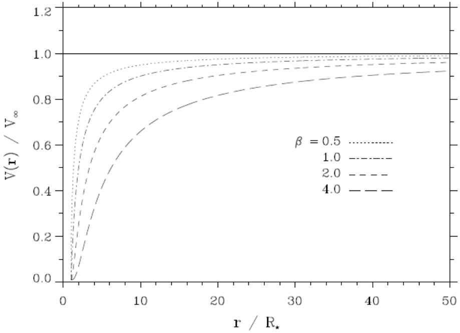
$$v(r) = v_\infty \left(1 - \frac{b}{r}\right)^\beta$$

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

- $v(R_*)$ is of the order of the isothermal sound speed



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

  - radiation field from the photosphere (lower boundary) - from a photospheric model
  - wind is in radiative equilibrium - the electron temperature is equal to or somewhat smaller than the effective temperature of the star (Kudritzki & Puls, 2000)
  - core-halo approximation
  - smooth transition between the quasi-hydrostatic photosphere and the wind
  - $\dot{M}$, v_∞, and β are treated as fitting parameters

Spectral diagnostics of stellar winds

- "Unified" non-LTE model atmosphere - used in more sophisticated and precise diagnostic methods (Gabler et al., 1989)
  - stellar and wind parameters are derived simultaneously and consistently

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- Current state-of-art wind models are based on:
  - the standard wind model assumptions
  - non-LTE
  - the radiative equilibrium approximation
  - $v(r)$ and $\rho(r)$ are derived from hydrodynamic calculations - THEORETICAL PARAMETERS or

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

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QUANTITATIVE SPECTROSCOPY - spectroscopic analyses using non-LTE model atmosphere codes (CMFGEN (Hillier & Miller, 1998); PoWR (Gräfener et al., 2002); FASTWIND (Puls et al., 2005))

Photospheric parameters determination

- Photosphere - the optical continuum is formed (below the sonic point)
- In the 1930s - the first model photospheric calculations were performed
  - radiative and hydrodynamic equilibrium
  - plane-parallel stratification
  - LTE
  - parametrized opacity
  - only H and He as atmospheric constituents

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- In the late 1960s - a new generation of atmospheric models were developed (Auer & Mihalas)
  - using efficient computational techniques (complete linearisation) for non-LTE model atmosphere calculations (e.g., Mihalas 1972, Mihalas at al. 1975, Kudritzki 1976, Hubeny 1988)

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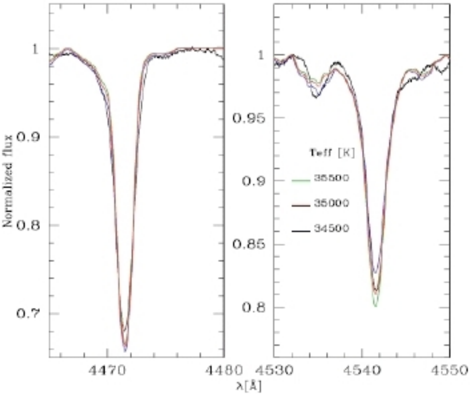
- In the late 1980s and 1990s - the models were improved to include metal opacities and line blanketing (e.g., Werner 1988, 1989; Anderson 1989, Hubeny & Lanz 1995)
  - metal line blanketing - effect caused by the presence of numerous metal lines in the UV region

Photospheric parameters determination

Reliable determination of stellar and wind parameters of hot massive stars can be achieved only with full blanketed non-LTE models (unified models) including the photosphere (quasi-static) and the supersonic wind (see review by Hubeny et al., 2003)

Photospheric parameters determination

- Determination of the effective temperature
  - $T_{\rm eff}$ is derived using the ionization balance method (e.g. Herrero et al. 1992, Puls et al. 1996, Martins et al. 2002)
  - He I λ 4471 and He II λ 4542 lines - the most reliable indicators for O and WR stars



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- Optical determination - uncertainties of 500 to 2000 K depending on the quality of the observational data and on the temperature itself
- For mid- and late-B stars ($T_{\rm eff}$< 2 700 K, He is almost neutral) - Si ionization balance: Si II 4124-31, Si III 4552-67-74, Si III 5738,
- For O stars near-IR spectra in the K-band can be used (He I lines at 2.058 and 2.112 μm, He II at 2.189 μm)

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- When only UV spectra are available, the determination of T_{eff} is more difficult - rely on the iron ionization balance (line forest from Fe IV 1600-1630 Å, V 1360-1380 Å, VI 1260-1290 Å)
- The relative strength of Fe line forests provides the best T_{eff} indicator (uncertainties are usually larger than optical determination)

Photospheric parameters determination

- Determination of the surface gravity
  - Derived from optical spectroscopy - the wings of the Balmer lines broadened by collisional processes (linear Stark effect), stronger in denser atmospheres, i.e. for higher $\log g$
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  - Hα, Hβ, Hγ are the main indicators
- In the near-IR - the Brackett lines (only the wings have to be considered since they are sensitive to collisional broadening)
- Brγ - the best gravity indicator in the K-band
- Br10 and Br11 (H-band) can be used as secondary indicators

Photospheric parameters determination

- Determination of the luminosity
  - derived from optical (or near-IR) photometry and bolometric corrections

$$\log \frac{L_{bol}}{\mathrm{L}_{\odot}} = -0.4\,(M_V + BC(T_{\mathrm{eff}}) - \mathrm{M}_{\odot}^{bol})$$

  - M_V - the absolute magnitude, BC(T_{eff}) - the bolometric correction at temperature T_{eff}, $\mathrm{M}_{\odot}^{bol}$ - the sun bolometric magnitude
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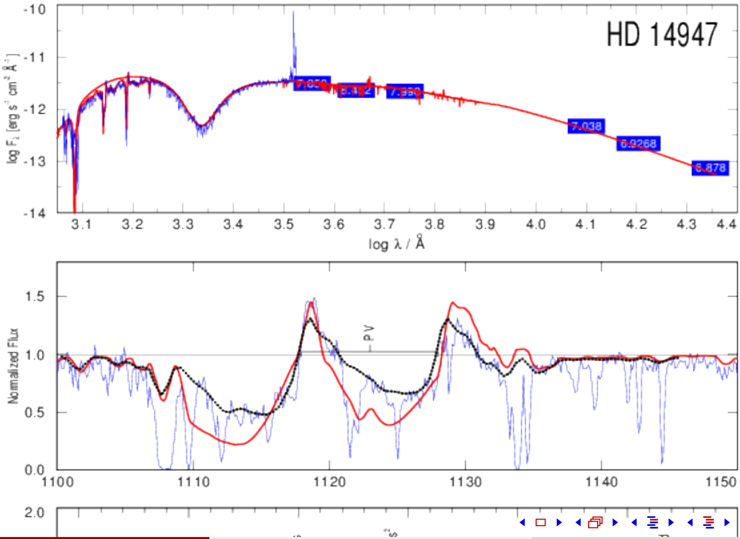
  - this method requires the use of calibrations of bolometric corrections
- Comparing directly absolute magnitudes (usually in the V band) to theoretical fluxes in the appropriate band convolved with the filter's response
- SED fitting - spectrophotometry ranging from the (far)UV to the infrared is used to adjust the global flux level of atmosphere model
- there is no need for bolometric corrections
- the reddening can be derived simultaneously
- the distance to the star must be known independently

Photospheric parameters determination

- Determination of the luminosity



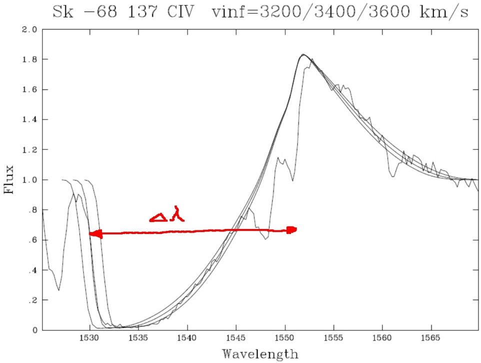
Photospheric parameters determination

- Determination of the surface abundaces
  - method consists in comparing synthetic spectra with different abundances to key diagnostic lines
  - optical studies of OB stars - determination of abundances of C, N, O, Si, Mg
- The main diagnostics are:
  - carbon: CII 4267, CII 6578-82 / CIII 4647-50, CIII 5696 / CIV 5802-12
  - nitrogen: NII 3995 / NIII 4510-15 / NIV 4058, NIV 5200 / NV 4605-20
  - oxygen: OII 4075, OII 4132, OII 4661 / OIII 5592
  - silicon: SiII 4124-31 / SiIII 4552-67-74, SiIII 5738 / SiIV 4089, SiIV 4116
  - magnesium: MgII 4481
- In O and B stars, the determination of surface abundances requires the knowledge of the micro-turbulence velocity - constrained from a few metallic lines
- Several iron line forests and few lines in the K-band and H-band can be used
- A determination of the abundances from the optical lines is necessary to correctly derive the wind properties

Formation of P-Cygni line profile

- Determination of the terminal velocity - by measuring the position of the "blue" absorption edge
- $\Delta\lambda$ - frequency of the blue edge minus frequency of the absorbed photon

$$v_\infty = \frac{\Delta\lambda}{\lambda_0} c$$

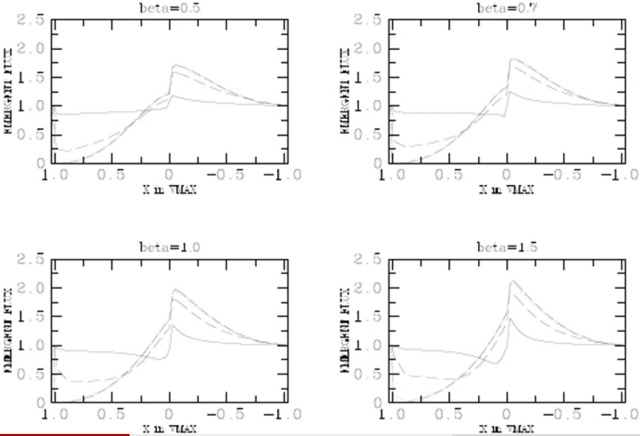


Terminal velocity determination

- The strongest saturated UV resonance lines can be used
  - measuring the frequency position of the blue edge of the profile
  - often the blue edges of the absorption trough of strong lines are not well defined - “softening” is interpreted as an indicator for existence of some extra velocity field, caused by additional small-scale or large-scale motions
  - the small-scale motions are usually referred to as “microturbulence”
  - thus, the value of v_∞ determined from the “softened” blue edge of the line profile is overestimated
  - “black troughs” (an extended region in the absorption part of saturated profiles with zero flux) - enhanced back-scattering in multiple non-monotonic velocity field
- Optical region - Balmer lines (Hα, Hβ, Hγ, Hδ) and He I
- for pure emission lines - the line width is related to the wind velocities

Terminal velocity determination

- Determination of the shape of the velocity field and the ion densities
  - The shallower the velocity field (larger β), the higher the emission
  - Large densities, the profiles become saturated
  - Saturated profiles - the profiles are no longer changing when the ion density is further increased



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- Saturated profiles - the profiles are no longer changing when the ion density is further increased
- Unsaturated profiles - profile never reaches zero intensity over its whole width
- Doublets - superposition of two profiles (certain ion may have two different ground states with very similar energies, both of which can be radiatively excited)

Mass-loss rates determination

- THEORETICAL $\dot{M}$ - from the hydrodynamical calculations

$$T_{eff}, L_*, R_* \Rightarrow \dot{M}, v_\infty$$

- "OBSERVED" $\dot{M}$ - non-LTE model + given v_β and $\rho(\dot{M}) \Rightarrow$ synthetic spectrum
  - ρ DEPENDENT DIAGNOSTIC (using the UV resonance lines)
  - ρ^2 DEPENDENT DIAGNOSTIC (using the recombination H_α, IR emission, or radio emission lines)

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PROBLEM!

- There is discrepancy between theoretical and observed mass-loss rates (e.g. Bouret et al., 2003, 2005; Fullerton et al., 2006; Puls et al., 2006)

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Clumping in hot star winds plays important role for:

- determination of mass-loss rates - the key parameter of hot, massive stars (see Puls et al., 2008)
- Clumping has to be take into account for reliable mass-loss rates determination

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Mass-loss rates determination

- The strengths of UV P-Cygni profiles
  - the most sensitive mass-loss rate diagnostics
  - intermediate region (10-100 $R_\odot$)
  - resonance lines from dominant ions; saturated (e.g., C IV, N V) and unsaturated (e.g., Si IV, P V)
  - linear dependence on density $\rho \propto \dot{M}/(r^2 v_\infty)$
  - the strength of the absorption and emission components constrain the total number of ions
  - the integrated line strength from unsaturated profiles to constrain $\dot{M}$

$$\tau_{\mathrm{rad}} \propto \dot{M}\, q_i\, A_e$$

$$q_i \sim 1$$

- only for dominant ion

$$\dot{M} \; < q_i >$$

$< q_i >$ - spatial average of the ion fraction

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$$\tau_{\text{rad}} \propto \dot{M}\, q_i\, A_e$$

$$q_i \sim 1$$

- only for dominant ion

$$\dot{M} \ < q_i >$$

$< q_i >$ - spatial average of the ion fraction

Stellar atmospheric models + Hydrodynamic effects → Radiative transfer
⟹ Synthetic spectrum

Mass-loss rates determination

- Thermal radio and FIR continuum emission
  - radio - outermost (above 100 $R_\odot$)
  - FIR - intermediate region (10-100 $R_\odot$)
  - free-free and bound-free transitions (scale with density square)
  - extremely sensitive to clumping in the wind

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- Hα emission
  - using non-LTE atmosphere codes
  - recombination lines (scale with density square)
  - sensitive to clumping
  - the innermost portion of the wind ($\lesssim 2R_\odot$)
  - overestimate the mass-loss rate of a clumped wind

Mass-loss rates determination