WINDS OF HOT MASSIVE STARS

III Lecture: Quantitative spectroscopy of winds of hot massive stars

[1]Brankica Šurlan
[1]Astronomical Institute Ondřejov

Selected Topics in Astrophysics
Faculty of Mathematics and Physics
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Prague

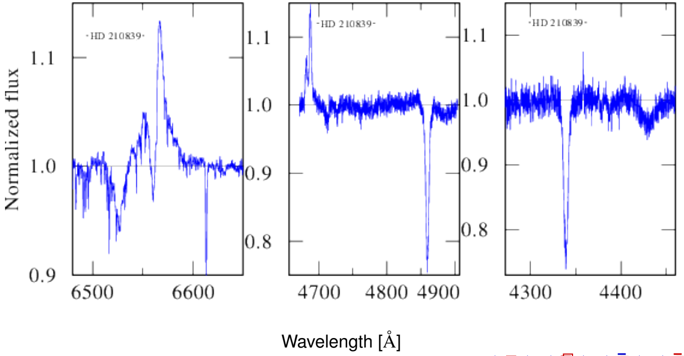
1. Spectral diagnostics of stellar winds
2. Photospheric parameters determination
3. Terminal velocity determination
4. Mass-loss rates determination

Spectral diagnostics of stellar winds

- Spectral lines - important diagnostics
  - emission
  - absorption
  - P-Cygni

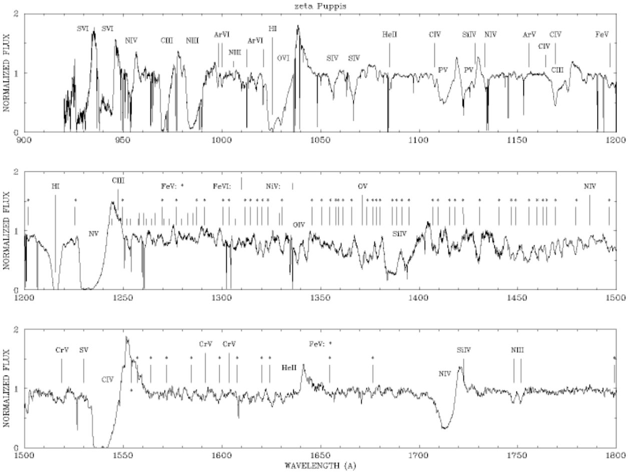
Spectral diagnostics of stellar winds

- Spectral lines - important diagnostics
  - emission
  - absorption
  - P-Cygni
- Optical lines - H_α, He II, H_β, and H_γ(from Šurlan et al., 2013, observations taken at the Perek 2-m Telescope of the Ondřejov Observatory)



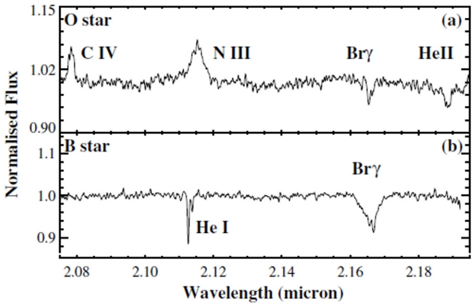
Spectral diagnostics of stellar winds

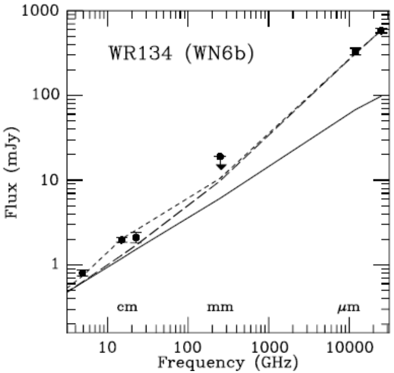
- Ultraviolet (UV) lines (from Pauldrach et al., 1994 - Merged spectrum of Copernicus and IUE UV high-resolution observations of the supergiant ζ Puppis)



Spectral diagnostics of stellar winds

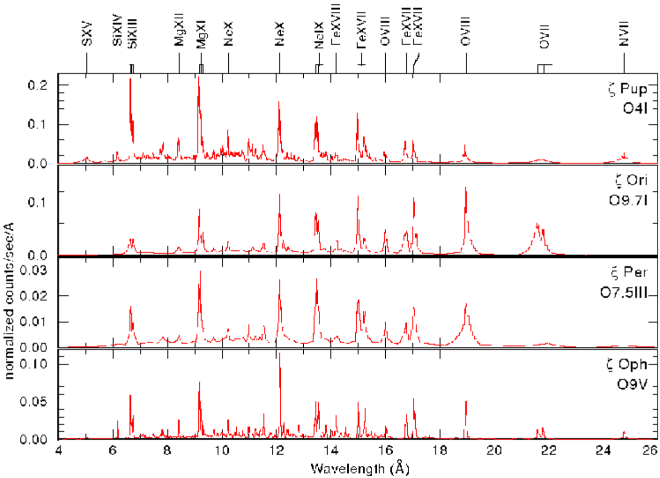
- Infrared (IR) lines (from Bik et al., 2005) and radio continua (from Nugis et al., 1998)





Spectral diagnostics of stellar winds

- X-ray lines (from 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

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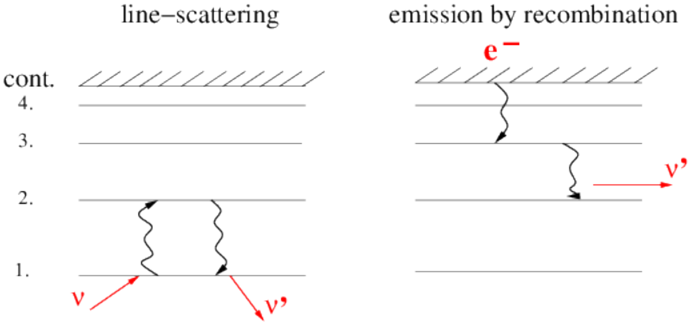
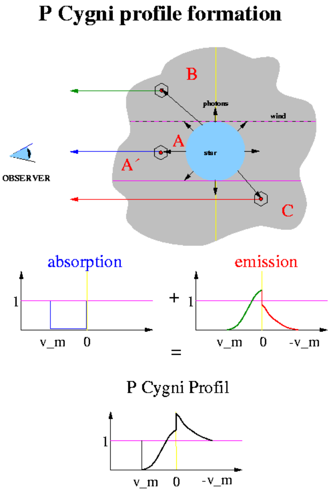
- "Resonance line scattering" - line transition from the ground state of the atom



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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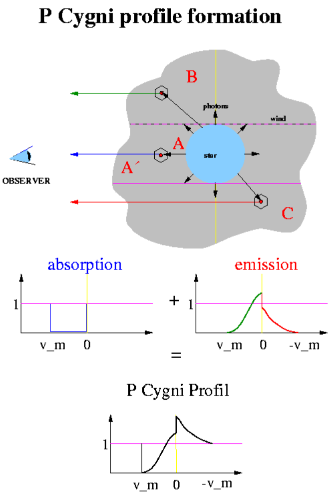
- The key effect is the Doppler-effect



Formation of P-Cygni line profile

- P CYGNI PROFILE - signature of an expanding stellar atmosphere

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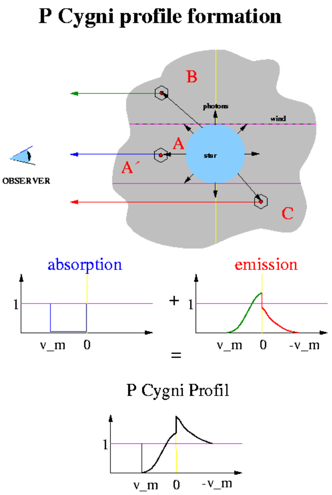
- The key effect is the Doppler-effect
- What can be investigate from P Cygni profiles?
  - Determination of the terminal velocity
  - Determination of the ion densities
  - Determination of the shape of the velocity field



Spectral diagnostics of stellar winds

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

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

$$\bar{\rho} = \frac{\dot{M}}{4\pi\, \mathrm{R}_*^2} v_\infty$$

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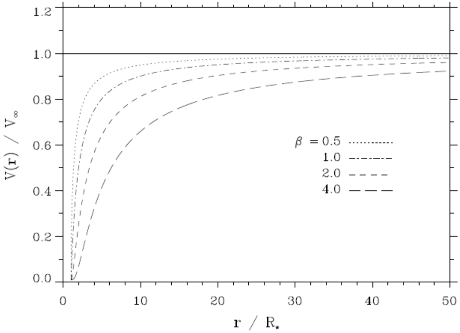
$$v(r) = v_\infty \left(1 - \frac{b}{r}\right)^\beta$$

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

- $v(\mathrm{R}_*)$ is of the order of the isothermal sound speed



Spectral diagnostics of stellar winds

- “Standard model”

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

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

  - 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

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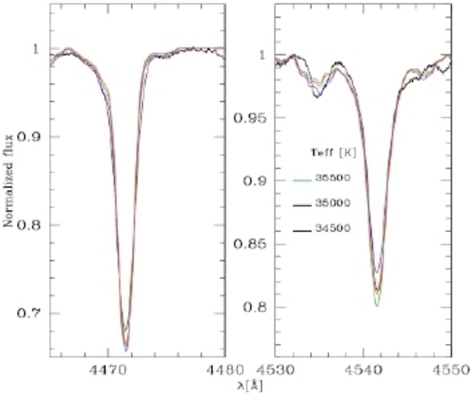
- In the late 1980s and 1990s - the models were improved to include metal opacities and line blanketing (e.g., Werner 1988, 1989; Anderson 1989, Hubeny & Lanz 1995)
  - metal line blanketing - effect caused by the presence of numerous metal lines in the UV region

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)
  - He I λ 4471 and He II λ 4542 lines - the most reliable indicators for O and WR stars (e.g., Martins et al. 2002)



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- Optical determination - uncertainties of 500 to 2000 $\rm K$ depending on the quality of the observational data and on the temperature itself
- For mid- and late-B stars ($T_{\rm eff}$< 2 700 $\rm K$, 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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- 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

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

  - M_V - the absolute magnitude, BC($T_{\rm eff}$) - the bolometric correction at temperature $T_{\rm eff}$, $\mathrm{M}_{\odot}^{bol}$ - the sun bolometric magnitude
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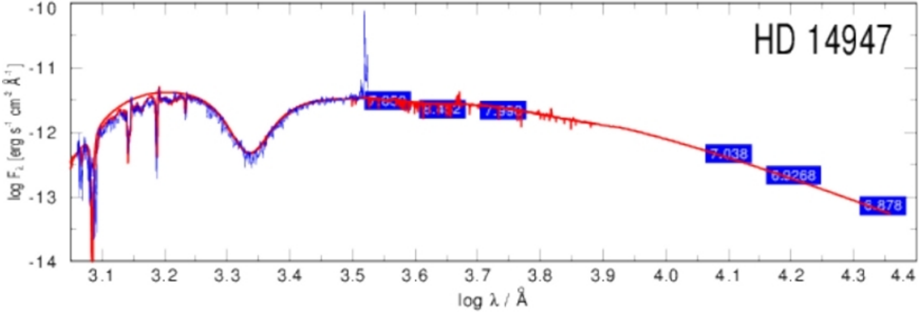
  - this method requires the use of calibrations of bolometric corrections
- Comparing directly absolute magnitudes (usually in the V band) to theoretical fluxes in the appropriate band convolved with the filter's response
- SED fitting - spectrophotometry ranging from the (far)UV to the infrared is used 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 by `PoWR` code (from Šurlan et al., 2013)



Best fit from PoWR modeling (red line) to the observed HD 14947 fluxes (blue line). Blue labels with numbers are UBVJHK magnitudes.

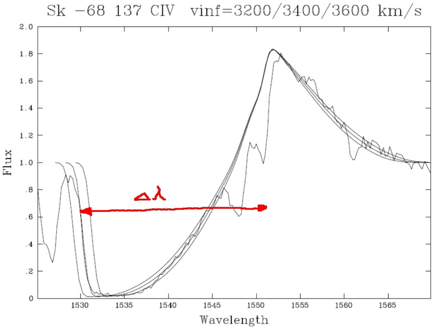
Photospheric parameters determination

- Determination of the surface abundances
  - 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

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



HST FOS spectrum of the LMC O3-star Sk - 68° 137 (from Kudritzki, 1998)

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

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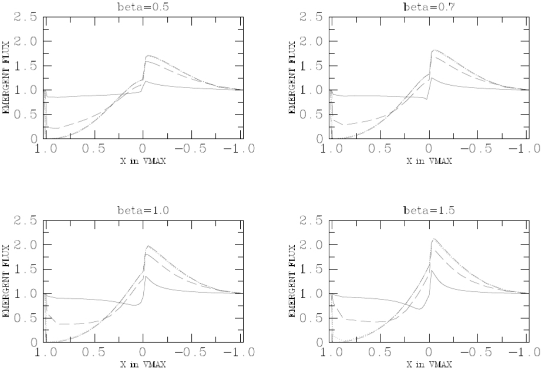
- Optical region - Balmer lines (Hα, Hβ, Hγ, Hδ) and He I
- For pure emission lines - the line width is related to the wind velocities

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



From Astrophysics Lab "A". Winds from Hot Stars: Diagnostics and Wind-Momentum Luminosity Relation, by J. Puls

Terminal velocity determination

- Determination of the ion densities and the shape of the velocity field
  - 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
- 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 wind hydrodynamical models
  - Input:
    - T_{eff} (effective temperature)
    - R_* (stellar radius)
    - M_* (stellar mass)
    - L_* (stellar luminosity)
    - $F(\nu)$ (radiation at the lower boundary of the wind)
    - chemical composition
  - Output:
    - $\rho(r)$ (density $\rightarrow dM/dt = \dot{M}$)
    - $v(r)$ (velocity $\rightarrow v_\infty$)
    - T(r) (temperature)

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- Determination of mass-loss rates
  - For given $v(r)$ and $\rho(r)$ (consequently dM/dt and v_∞) determine the emergent radiation
  - Compare with observations
  - Common assumption - β-velocity law

Mass-loss rates determination

- "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)

Mass-loss rates determination

- The strengths of UV P-Cygni profiles
  - resonance lines from dominant ions; saturated (e.g., C IV, N V) and unsaturated (e.g., Si IV, P V)
  - the most sensitive mass-loss rate diagnostics
  - originates in the intermediate region of the wind (10 - 100 $R_\odot$)
  - 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 $\dot{M}$
  - the product $\dot{M}\, q_i$ can be inferred (q_i - ionization fraction)

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

$q_i \sim 1$ - only for dominant ion

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

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

Mass-loss rates determination

- Hα emission
  - Hα emission originates in inner regions of the wind ($\lesssim 2\mathrm{R}_\odot$)
  - Hα - recombination lines (scale with density square)
  - comparison of observed Hα line profiles with theoretical profiles calculated using the β-velocity law
  - mass-loss rate corresponding to the model with the best fitis then called observed mass loss rate
  - calculations often based on non-LTE model atmospheres with a given velocity field
  - core-halo approach
  - sensitive to clumping
  - overestimate the mass-loss rate of a clumped wind
  - model atmosphere codes
    - CMFGEN (Hillier & Miller 1998, Hillier at al. 2003)
    - WM-basic (Pauldrach et al. 2001)
    - FASTWIND (Santolaya-Rey et al. 1997, Puls et al. 2005)

Mass-loss rates determination

- Thermal radio and FIR continuum emission
  - radio emission originates in the outermost region of the wind (above 100 $R_\odot$)
  - FIR emission originates in the intermediate region of the wind (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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  - FIR emission originates in the intermediate region of the wind (10-100 $R_\odot$)
  - free-free and bound-free transitions (scale with density square)
  - extremely sensitive to clumping in the wind
- Radio measurements (Panagia & Felli 1975; Wright & Barlow 1975)
  - simplified conditions (completely ionized gas, LTE, spherical symmetry, $dv/dr = 0$, $n_e \propto r^{-2}$, only free-free opacity)
  - known F_{radio}, distance to the star, $v_\infty \Rightarrow \dot{M}$
  - (+) most reliable values of mass-loss rates
  - (+) relatively free of uncertain assumptions
  - (-) low flux at radio wavelengths
  - (-) unknown influence of non-thermal radiation

Mass-loss rates determination

PROBLEM!

- 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)

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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

Influence of clumping on mass-loss rates determination

AT THE NEXT LECTURE