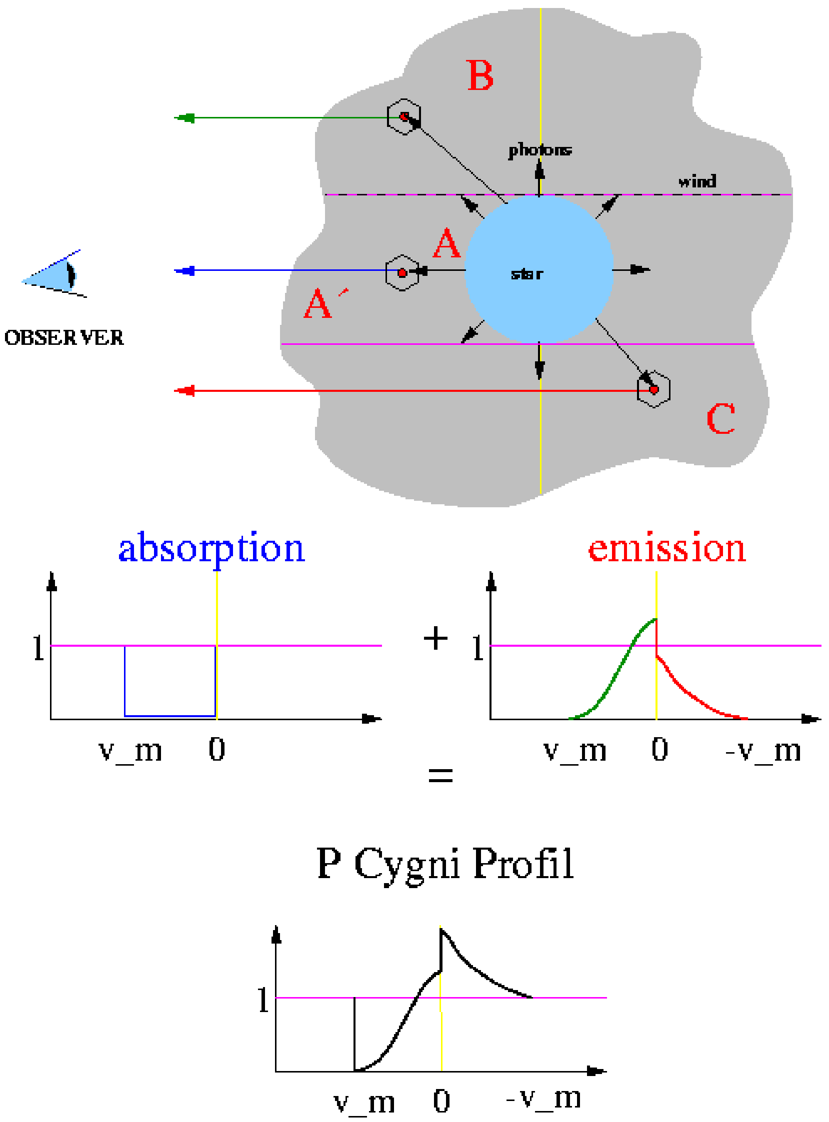
Winds from massive stars

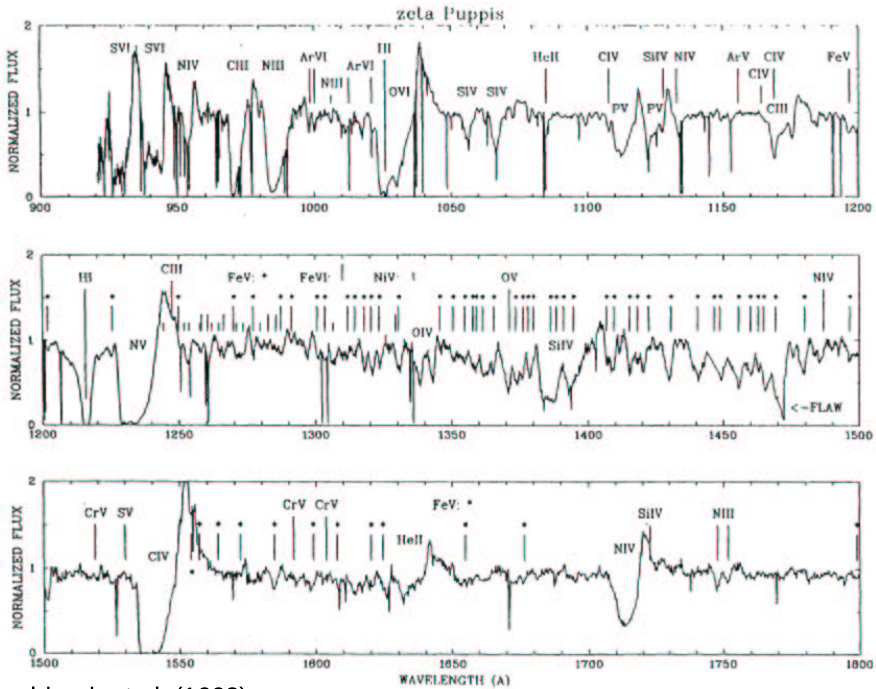
- **Wind properties from spectral lines**
  - Review article: Kudritzki & Puls 2000,
    Annual Review of Astronomy and Astrophysics, Vol. 38, p. 613
  - P-Cygni profiles:
    blue absorption trough and red emission peak
  - Pure emission profiles
  - UV resonance lines of CIV, NV, SiIV, OVI, ...
  - Hα line
  - IR lines: sample different depths of the wind
    than UV and optical lines

  → Determine wind parameters
    - maximum wind velocity V_*
      typically 2000 km s^{-1}
      cf. solar wind mean velocity $\approx$ 500 km s^{-1},
      low mass stars $\approx$ 10 km s^{-1}
    - shape of velocity law $V(R)$ described by parameter β
    - mass loss rate $\dot{M}_*$
      on the order of $10^{-6} M_\odot$ yr^{-1}
      cf. solar type stars $\approx 10^{-14} M_\odot$ yr^{-1},
      low mass stars $\approx 10^{-7} M_\odot$ yr^{-1}

P Cygni profile formation

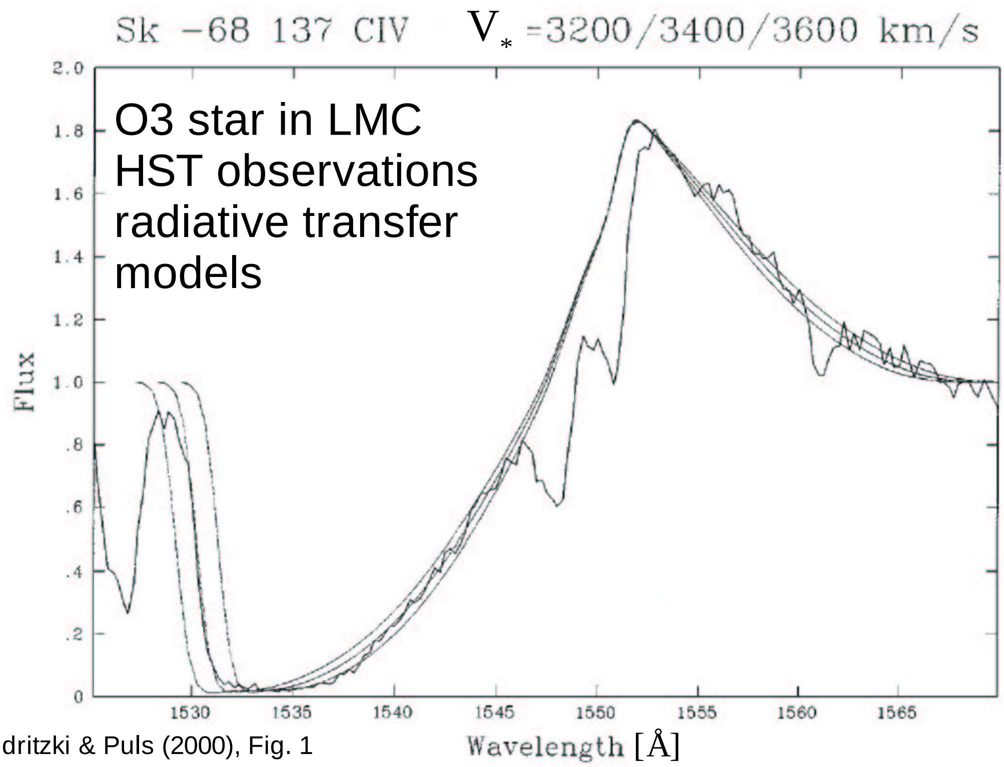


from Joachim Puls
http://www.usm.uni-muenchen.de/people/puls/windsfromhotstars/windframes.html

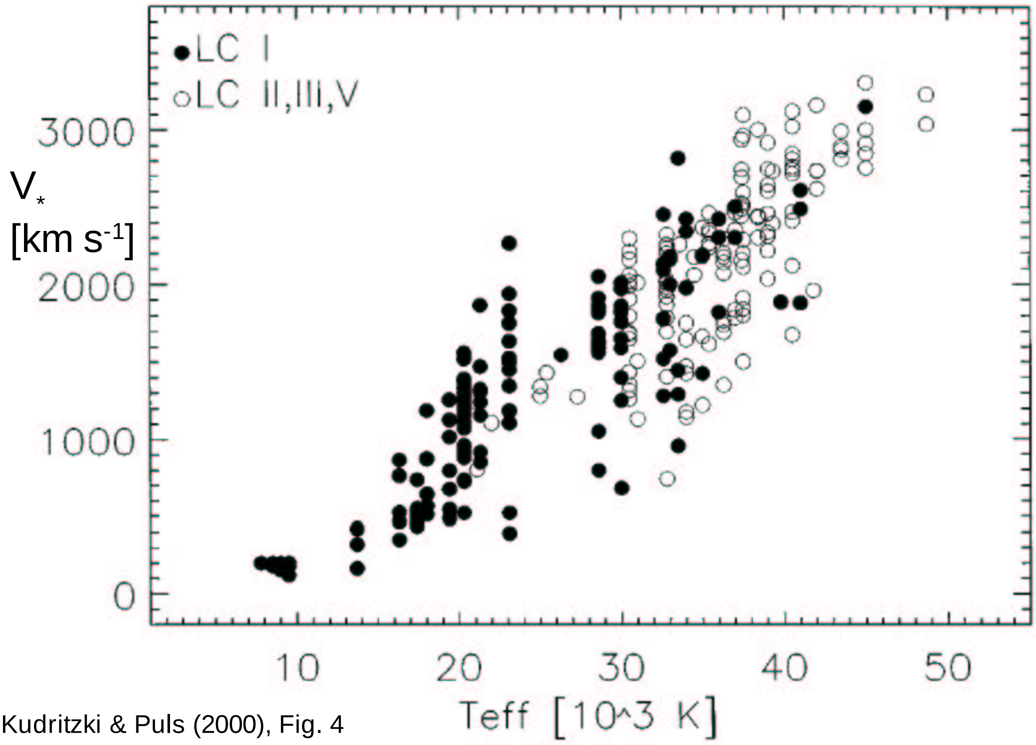


Pauldrach et al. (1993)

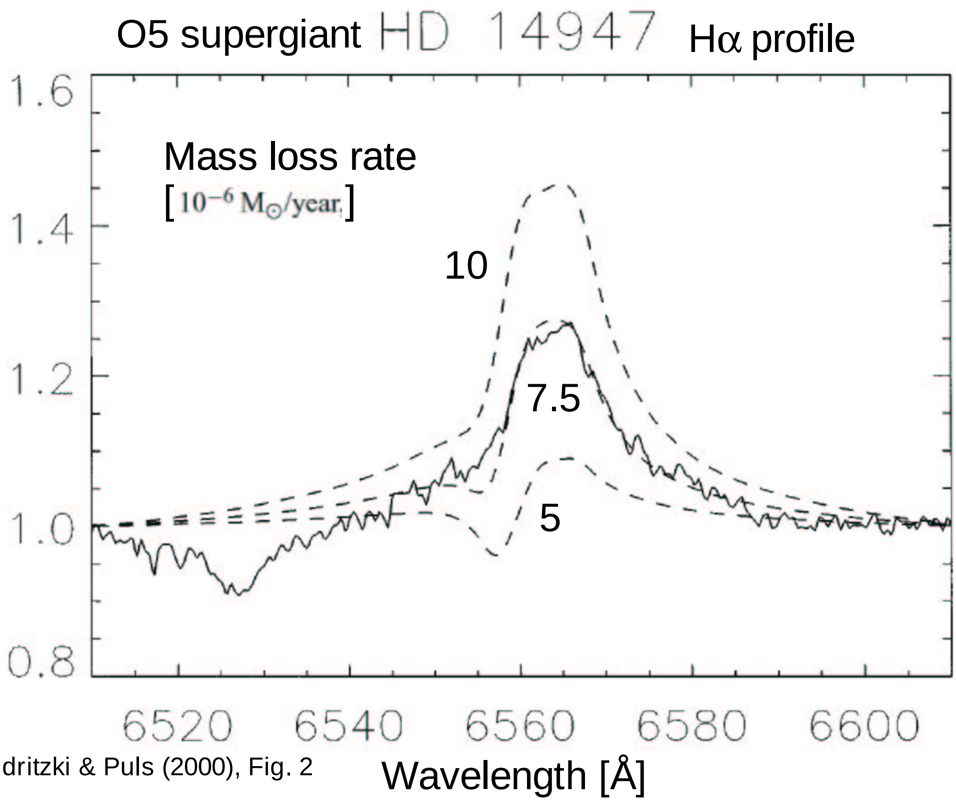
Fig. 1. **Observed Copernicus (900-1500A, Morton and Underhill (1977)) and IUE (1500-1800A, Walborn et al. (1985)) high resolution UV spectrum.**



Kudritzki & Puls (2000), Fig. 1



Kudritzki & Puls (2000), Fig. 4



Kudritzki & Puls (2000), Fig. 2

- **Flow pattern around massive stars**
  - Star surrounded by HII region
  - Wind gas meets ionized IS gas
    with velocity $V_* \approx 2000$ km s^{-1}
  - Sound speed $c_\mathrm{i} \approx 10$ km s^{-1} $\rightarrow$ supersonic flow
    $\rightarrow$ **shock wave S_2 in IS gas**
  - Shocked IS gas acts like an obstacle to wind gas
    $\rightarrow$ **shock wave S_1 in wind gas in opposite direction**

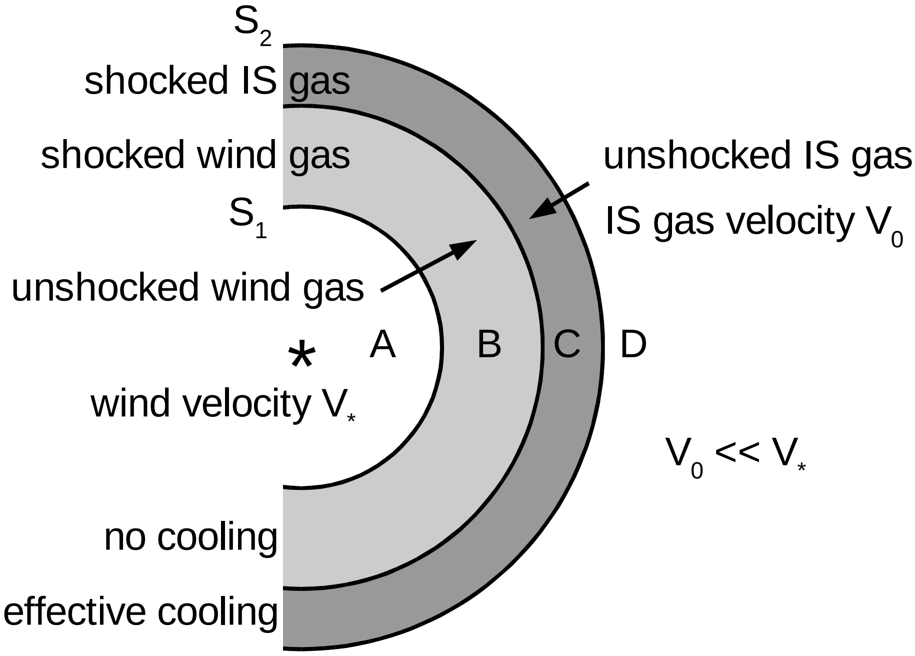
  $\rightarrow$ Flow pattern with 4 main regions (see figure)
  - **Region A**
    - unshocked wind gas with velocity V_*
    - enters shock S_1, where it is slowed down and heated
  - **Region B**
    - shocked wind gas
    - shock velocity $V_\mathrm{S} = V_*$
      highly supersonic $\rightarrow$ strong shock
    - high post-shock temperature:

$$T_\mathrm{S} = \frac{3}{16} \frac{1/2 \cdot m_\mathrm{u} V_*^2}{k} \approx 4.5 \cdot 10^7 \text{ K}$$

    - almost no cooling, because
      low cooling rate at this temperature
      and long cooling time $t_\mathrm{c} \propto V_*^3$
      $\rightarrow$ adiabatic shock
      $\rightarrow$ compression by factor 4 (only)
      $\rightarrow$ finite thickness
    - slowly expanding bubble of hot gas
      with high sound speed $\rightarrow$ short sound crossing time
      $\rightarrow$ no pressure gradient

- **Region C**
  - shocked IS gas
  - shock velocity $V_\mathrm{S} = V_0 \ll V_*$
  - lower post-shock temperature $\rightarrow$ higher cooling rate $\rightarrow$ effective cooling $\rightarrow$ isothermal shock $\rightarrow$ compression by large factor
    $\rightarrow$ very thin shell (mass conservation)
    $\rightarrow$ short sound crossing time
    $\rightarrow$ constant pressure
- **Surface between B and C: "contact discontinuity"**
  - separates shocked wind gas and shocked IS gas
  - temperature + density change discontinuously, pressure $\mathcal{P}$ does not change
- **Region D**
  - surrounding unshocked interstellar gas with density ρ_0
  - assumed to be at rest with respect to shock fronts

Flow pattern around massive stars



- **Simple model for the evolution of the flow pattern**
  - Region C is described by a single radius R
    $\rightarrow$ represents the outer boundary of the hot expanding bubble (region B)
  - Conservation of momentum in region B

$$\frac{\mathrm{d}}{\mathrm{d}t}(M(R)\dot{R}) = 4\pi R^2 \mathcal{P}$$

  - Conservation of energy in region B

$$\frac{\mathrm{d}}{\mathrm{d}t}(E_{\mathrm{th}}(R)) = \frac{1}{2}\dot{M}_* V_*^2 - \mathcal{P}\frac{\mathrm{d}}{\mathrm{d}t}(\mathrm{Volume}(R))$$

- Combination of the two equations
  gives equation of motion
  $\rightarrow$ 3$^{\mathrm{rd}}$ order differential equation for size of bubble R
  as a function of time
- Choose a solution in form of power law

$$R = A \cdot t^{\alpha}$$

$$\alpha = \frac{3}{5} \qquad A \propto \left(\frac{1}{2} \frac{\dot{M}_* V_*^2}{\rho_0} \right)^{\frac{1}{5}}$$

$\rightarrow$ With this model:
calculate the fraction of energy in the wind
converted to kinetic energy of the IS gas
$\rightarrow \approx 20\% \rightarrow$ much higher conversion efficiency
than for converting stellar UV energy to gas energy

- Using ionization balance in the shell
  and the isothermal jump condition for shock S_2: $\frac{\rho_C}{\rho_0} = \frac{\dot{R}^2}{c_i^2}$
  calculate maximum radius at which hot wind bubble
  stays within HII region
  $\rightarrow$ for typical values of star, wind and cloud parameters
  $R_{\max} \approx 2$ pc

- **Departures from spherical symmetry**
  - Usual case
  - Simple model cannot be used
  - Need numerical simulations