Najveći izazovi u teoriji vetrova vrelih masivnih zvezda

Seminar Katedre za astronomiju

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Basic properties of hot massive stars

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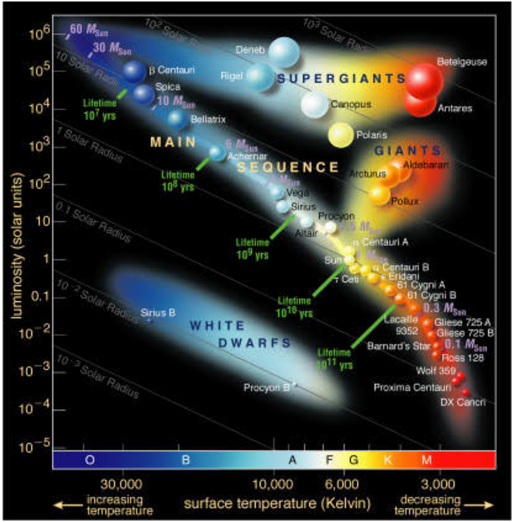
- **SPECTRAL TYPE – OB-type**
  Massive stars in short-lived transition phase (WR, LBVs, BSGs, and B[e]SGs)
- **EXTREMELY LUMINOUS** – $L \gtrsim 10^3$ $[\mathrm{L_\odot}]$
- **HOT** – $T_{\mathrm{eff}} \gtrsim 10\,000$ [K]
- **MASSIVE** – $M \gtrsim 8$ $[\mathrm{M_\odot}]$
- **SHORT LIFETIMES** – $\sim 10^6$ yr
- **END IN SUPERNOVA EXPLOSION**
- **STRONG WIND (MASS LOSS)**
  Mass-loss rate – $\dot{M} \sim 10^{-6}$ $[\mathrm{M_\odot}/\mathrm{yr}]$
  Terminal velocity – $v_\infty \sim 10^2 - 10^3$ km/s



Basic properties of hot massive stars

The nebula M1-67 around Wolf-Rayet star WR 124
Credit: ESA/Hubble & NASA

The Orion's Belt including the Flame Nebula (left) and Horsehead Nebula (lower left)
Credit: Digitized Sky Survey, ESA/ESO/NASA

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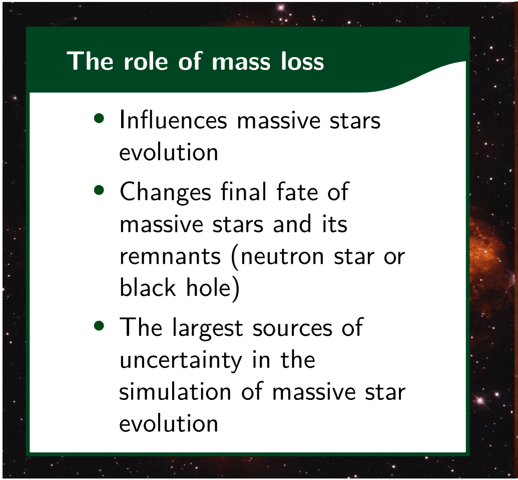
The role of mass loss

- Influences massive stars evolution
- Changes final fate of massive stars and its remnants (neutron star or black hole)
- The largest sources of uncertainty in the simulation of massive star evolution



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The importance of massive stars

- Can be seen at large distances
- Enrich ISM with heavier elements (metals)
- Heat-up, ionize, or facilitate chemical reactions in ISM
- Provide kinetic energy and momentum
- Trigger, regulate and terminate star formation in stellar clusters
- The most likely source for re-ionizing the universe

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Credit: ESA/Hubble & NASA

The Orion's Belt including the Flame Nebula (left) and Horsehead Nebula (lower left)
Credit: Digitized Sky Survey, ESA/ESO/NASA

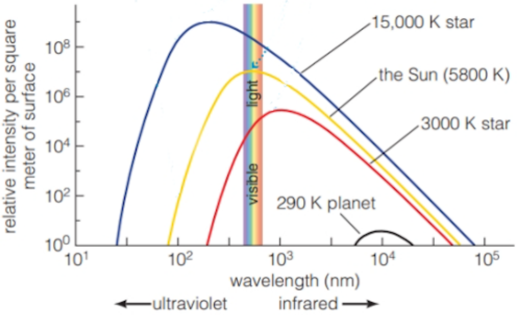
Basic properties of hot massive stars

- Hot massive stars emit their peak radiation in the UV wavelength region
- Wien's displacement law

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

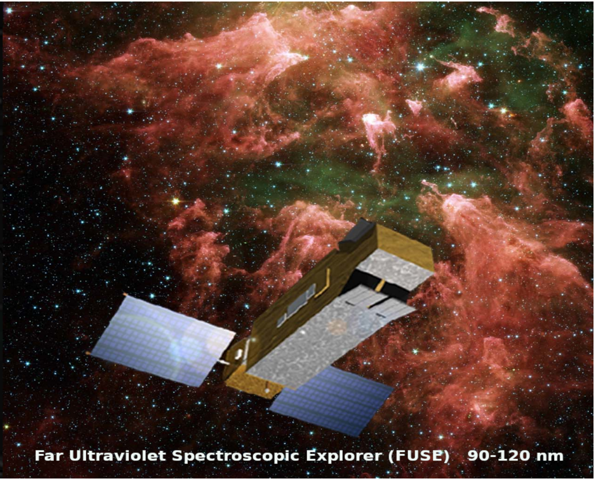
for $b = 0.29\,\text{cm K}; \quad T = 30\,000\,\text{K} \Rightarrow$

$$\lambda_{\text{max}} = 960\,\text{Å}$$



Credit: https://www.chegg.com

Basic properties of hot massive stars



Basic properties of hot massive stars

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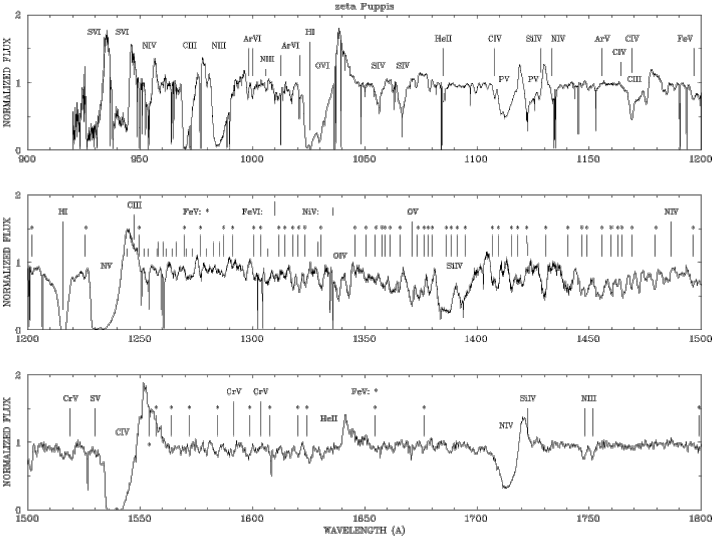
Spectra in UltraViolet (UV) band – Merged spectrum of Copernicus and IUE UV high-resolution observations of the supergiant ζ Puppis (Pauldrach et al., 1994)



Basic properties of hot massive stars

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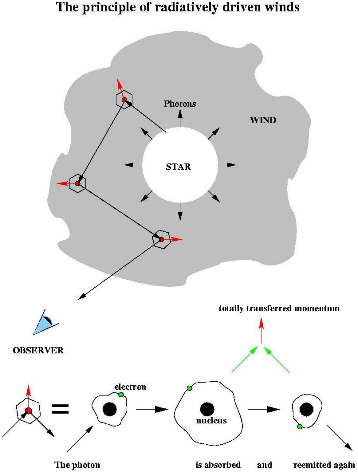
Processes for line formation in winds

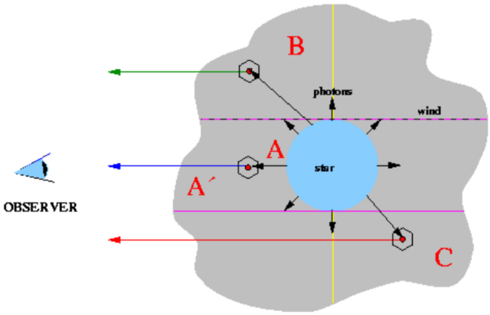
- Line scattering (e.g. P-Cygni UV resonance lines of C IV, N V, Si IV, O VI)
- Line emission by recombination (e.g., H_α)
- Line emission from collisional-excitation or photo-excitation
- Pure absorption
- **Resonance line scattering** – line transition from the ground state of the atom

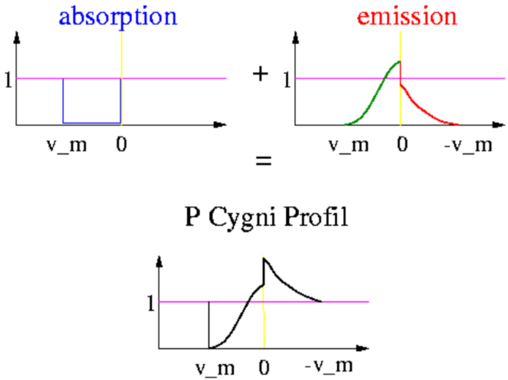


Credit: J. Puls

Basic properties of hot massive stars

- **P-Cygni profile** – signature of an expanding stellar atmosphere
- **Doppler effect!**





Credit: J. Puls

Basic properties of hot massive stars

The principle of radiatively driven winds

Hot star winds are accelerated via a two-step process:

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
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**

Basic properties of hot massive stars

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- **CAK model** - the first hydrodynamical solution of the line driven wind (Castor, Abbott & Klein, 1975)
- **Standard wind model assumptions** - stationary, homogeneous, spherically symmetric with uniform flow, and free of magnetic field

Determination of mass-loss rates

MASS-LOSS RATE

- The key parameter of hot, massive stars (see e..g., Puls et al., 2008)
- Mass loss is inexorably linked to evolution for massive stars
- Stellar evolution calculations must adopt prescriptions for mass-loss rates as input

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GLOBAL WIND PARAMETERS - $\dot{M}$, v_∞ and $\bar{\rho}$ (the average mass density)

- for stationary and spherically symmetric wind $\Longrightarrow$

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

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

LOCAL WIND PARAMETERS - $\rho(r)$, $v(r)$, and $T(r)$

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“OBSERVED“ wind parameters - the result of diagnostic techniques based on theoretical modeling (determination relies on stellar atmosphere models)

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“OBSERVED“ wind parameters - the result of diagnostic techniques based on theoretical modeling (determination relies on stellar atmosphere models)

non-LTE model atmosphere + given $v(r)$ and $\rho(r)$ $\Rightarrow$ Synthetic spectrum

$\Rightarrow$ comparison with observation

$\dot{M}$ and v_∞ are treated as fitted parameters

Determination of mass-loss rates

- **QUANTITATIVE SPECTROSCOPY** - spectroscopic analyses using non-LTE model atmosphere codes - **CMFGEN** (Hillier & Miller, 1998); **PoWR** (Gräfener et al., 2002, Sander et al., 2015, 2017); **FASTWIND** (Puls et al., 2005); **METUJE** (Krtička & Kubát, 2017)
- **Unified non-LTE model atmosphere** - stellar and wind parameters are derived simultaneously and consistently

Determination of mass-loss rates

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- **Unified non-LTE model atmosphere** - stellar and wind parameters are derived simultaneously and consistently
- Current state-of-art wind models are based on:
  - the standard wind model assumptions
  - non-LTE
  - $v(r)$ and $\rho(r)$ are derived from hydrodynamic calculations or using the β velocity law and equation of continuity

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

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

Determination of mass-loss rates

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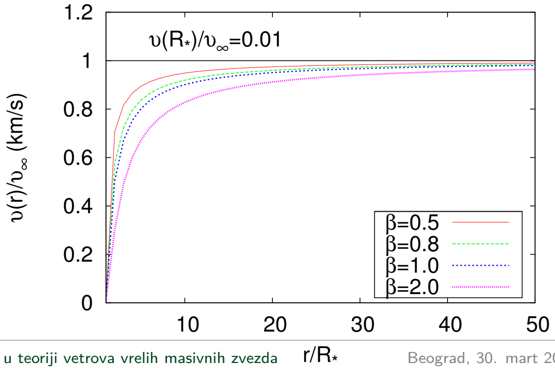
- **Unified non-LTE model atmosphere** - stellar and wind parameters are derived simultaneously and consistently

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

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

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



Determination of mass-loss rates

- **THEORETICAL wind parameters** – from the hydrodynamical calculations

INPUT PARAMETERS

- R_* - stellar radius
- M_* - stellar mass
- L_* - stellar luminosity
- $F(\nu)$ - radiation at the lower boundary of the wind
- chemical composition

OUTPUT PARAMETERS

- $v(r)$ - velocity $\Rightarrow$ v_∞
- $\rho(r)$ - density $\Rightarrow dM/dt = \dot{M}$
- T(r) - temperature

Determination of mass-loss rates

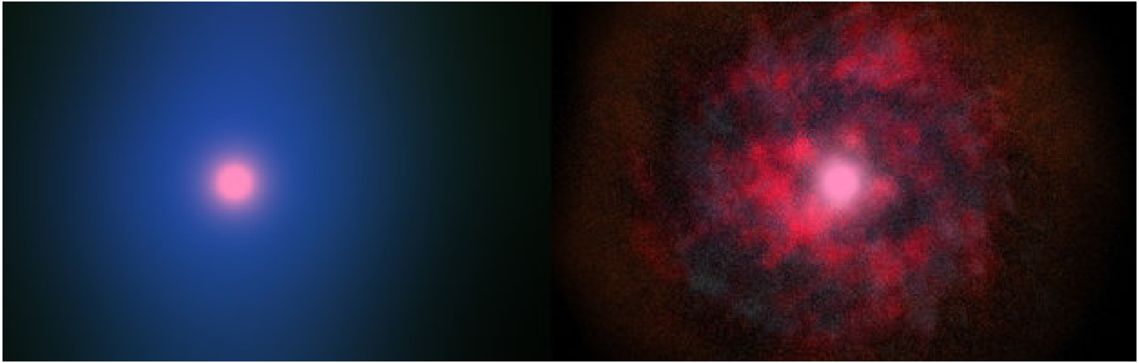
- **THEORETICAL wind parameters** - from the hydrodynamical calculations
- **"OBSERVED" wind parameters** - from the observations

PROBLEM!

- Discrepancy between theoretical (predicted) 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)
  - ρ **dependent $\dot{M}$ diagnostic** (using the UV resonance lines)
  - ρ^2 **dependent $\dot{M}$ diagnostic** (using the recombination H_α, IR emission, or radio emission lines)

Wind clumping

Credit: ESA/XMM-Newton (Carreau/Nezé et al.)



- Stationary
- Homogeneous
- Spherically symmetric

- Time-dependent
- Clumping (clumps+porosity)
  small-scale structure (stochastic)
- Rotation, pulsation, magnetic fields
  large-scale structure

Wind clumping

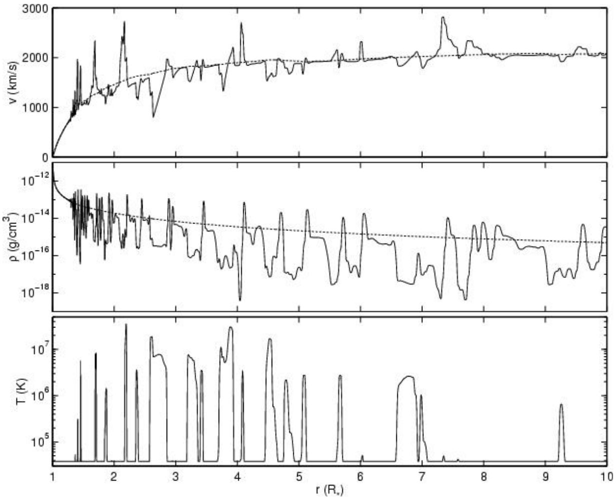
Theoretical evidence

LINE DRIVING INTRINSICALLY UNSTABLE

- Creation of two-component-like structures

WIND CLUMPING

- small-scale wind structures with different density (i.e., **clumps**) and velocity (i.e., **porosity**) than the surrounding wind matter



Runacres & Owocki (2002)

Wind clumping

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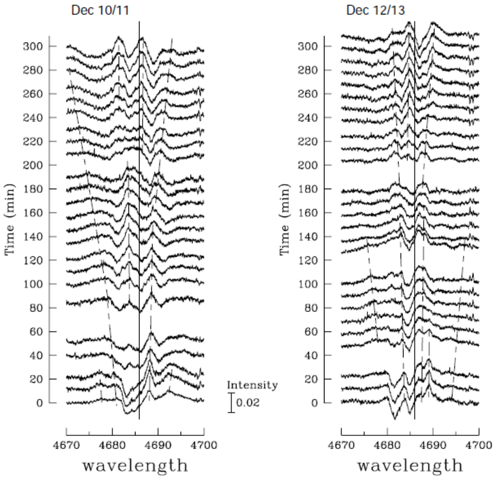
Observational evidence

LINE PROFILE VARIABILITY

- Small-scale stochastic LPVs
  - related to accelerated wind clumping moving outwards
- Cyclical LPVs
  - usually connected with the magnetic field of the star
- Strictly periodic LPVs
  - usually connected with the rotational period of the star



He II $\lambda4686$ from ζ Pup (Eversberg et al. 1998)

Wind clumping

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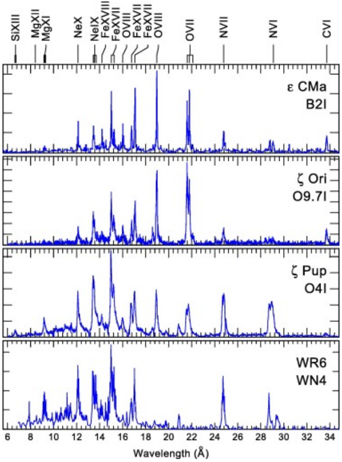
Diagnostic evidence

QUANTITATIVE SPECTROSCOPY

- Electron scattering wings
- Shapes of saturated P Cygni profiles
- Presence of X-ray emission
- UV resonance doublet ratios
- Different diagnostics result in different $\dot{M}$
- Disagreement in the theoretical and "observed" $\dot{M}$

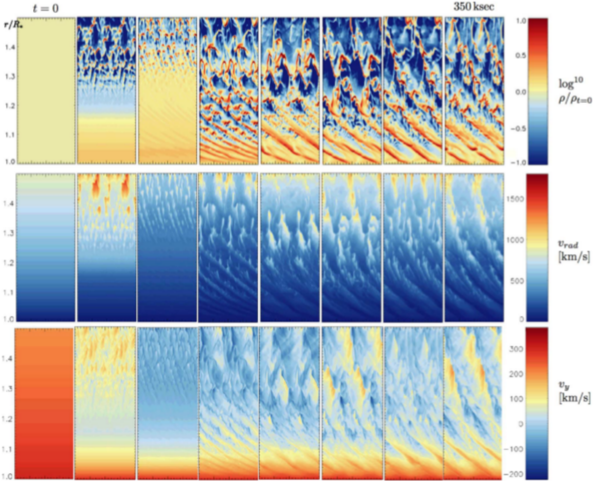


X-ray diagnostics of massive star winds (Oskinova 2016)

Wind clumping

3D PHENOMENON

- **Full 3D time-dependent (M)RHD wind simulation still missing** (account for clumping + spatial and velocity-field porosity)
- Need for developing **simplified assumptions and parameterized methods** which can be implemented into existing global NLTE model atmosphere codes



Sundquist, Owocki & Puls 2018

Wind clumping

Standard assumption

MICROCLUMPING

- Clumps are optically thin at all frequencies
- Void inter-clump medium
- Smooth velocity field
- Implemented in codes: **PoWR, CMFGEN, FASTWIND, and METUJE**

Clumping factor D (or volume filling factor f_V) and over-density of clumps ρ_{cl}

$$D = \frac{<\rho^2>}{<\rho>^2}, \quad f_V = \frac{1}{D}, \quad \rho_{cl} = D <\rho>$$

Linear density $\dot{M}$ diagnostic

- X-ray emission line profiles
- Unsaturated UV resonance lines
- Electron scattering wings of emission lines of WR stars
- **Derived $\dot{M}$ is not affected**

Density square $\dot{M}$ diagnostic

- Thermal radio continuum emission
- Optical (e.g., H_α) and IR (e.g., Br_α) emission lines
- **Derived $\dot{M}$ lowered by a factor of $\sqrt{D}$ relative to smooth-wind model**

Wind clumping

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MACROCLUMPING

- Arbitrary optical thickness of clumps
- Void inter-clump medium
- Non-monotonic velocity field
- Implemented into the PoWR **code**

Oskinova, Hamann & Feldmeier, 2007

"EFFECTIVE OPACITY"

- **Arbitrary optical thickness of clumps + porosity in physical and velocity space**
- Implemented into the FASTWIND **code**

Sundquist & Puls, 2018

3D description of clumping

- **Arbitrary optical thickness of clumps + porosity in physical and velocity space**
- The ionisation structure and underlying photospheric spectrum from PoWR code
- **3D MCRT code** – Calculates only resonance lines

Šurlan, Hamann et al., 2012, 2013

Resolve discrepancies in different mass-loss rates diagnostics and better constrain clumping properties

Wind clumping

More realistic properties of clumps

- Depth dependent clumping factor (Puls et al. 2006)
- Onset of clumping (Bouret et al. 2003, Sundqvist et al. 2010)
- Interclump medium density (Zsargó et al. 2008)
- Shape of clumps

Clumping introduces additional complexities into the RT

- Due to Doppler shift, opacity and emissivity are **not isotropic**
- Clumping **requires 3D** radiative transfer (RT)
- The real size, shape, and distribution of clumps are unknown → we have to use **approximations**
- Clumps can be optically thick (own ionization structure)
- Clumps can shield other clumps
- Clumped wind may be non-spherical

3D description of clumping

SNAPSHOT OF CLUMPS' DISTRIBUTION

↓

MONTE CARLO RADIATIVE TRANSFER

↓

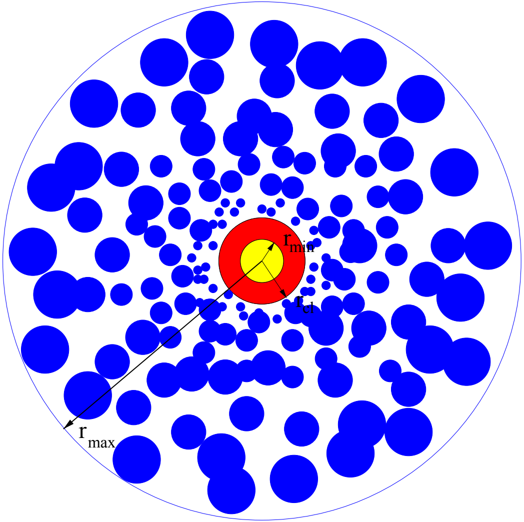
RESONANCE LINE PROFILES

ADAPTIVE INTEGRATION STEP Δr

PHOTON IS FOLLOWED IN COMOVING FRAME

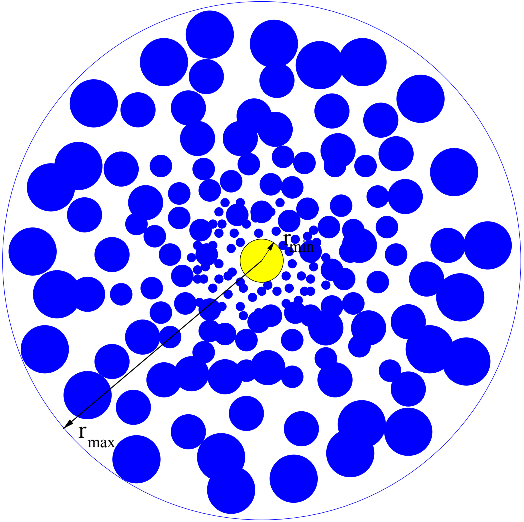
Monte Carlo Radiative Transfer (MCRT) Code – basic concept (Šurlan et al. 2012)

3D description of clumping



- SMOOTH region
  $r_{\rm min} < r < r_{\rm cl}$; $r_{\rm min} = R_*$
- CLUMPED region
  $(r_{\rm cl} < r < r_{\rm max})$
- Two density components:
  ICM and CLUMPS
- Cartesian coordinates
- $r_{\rm min}$ - the lower boundary of the wind
- $r_{\rm cl}$ - the onset of clumping
- $r_{\rm max}$ - the outer boundary of the wind

3D description of clumping



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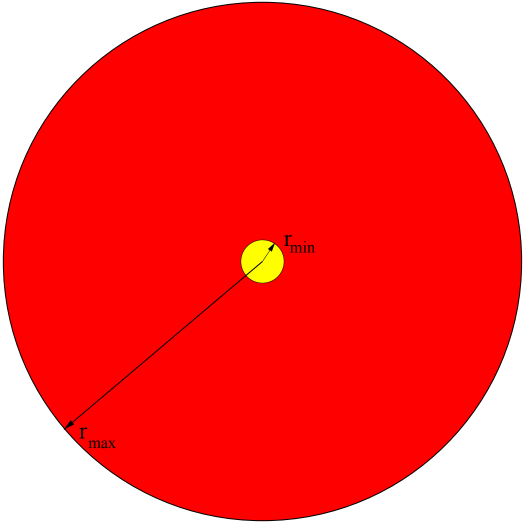

- SMOOTH region
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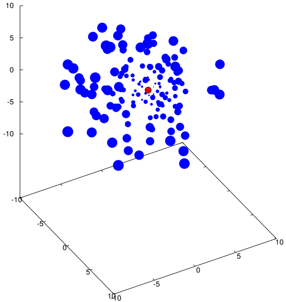
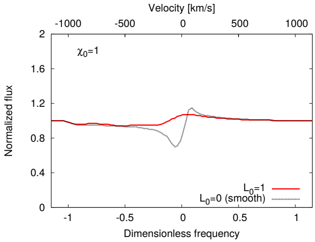
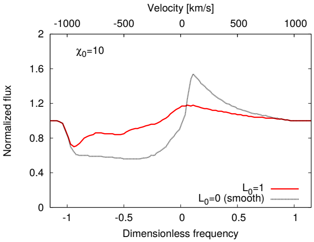
3D description of clumping

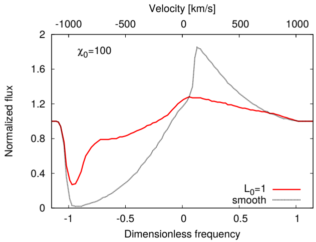
different number of clumps

$L_0=1 \quad D=10 \quad d=0$





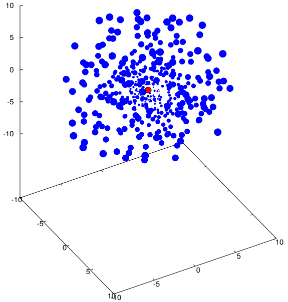


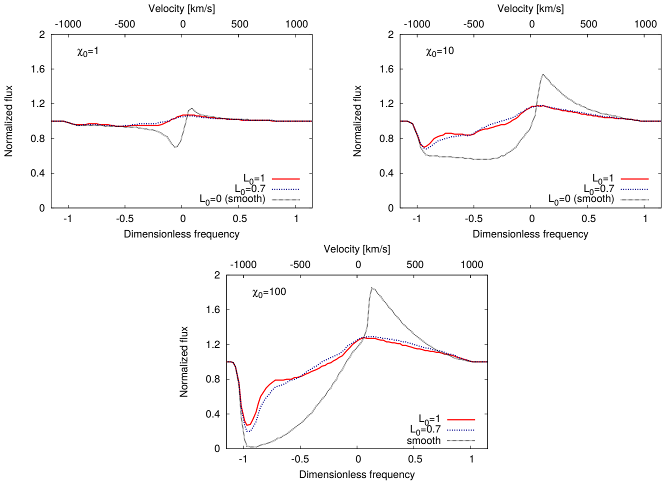


Šurlan et al. 2012

3D description of clumping

L_0=0.7 D=10 d=0

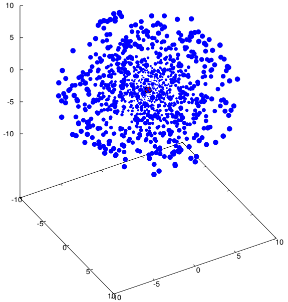


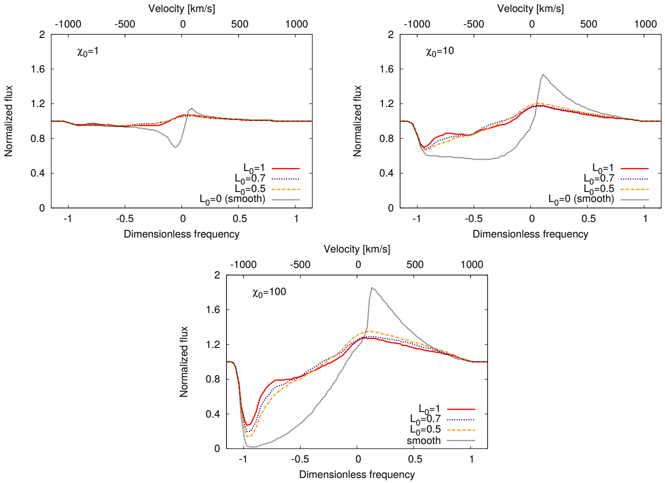


Šurlan et al. 2012

3D description of clumping

L_0=0.5   D=10   d=0





Šurlan et al. 2012

3D description of clumping

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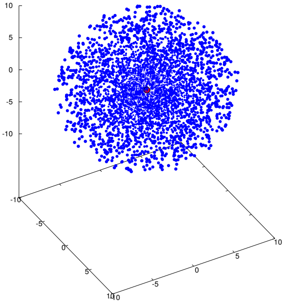
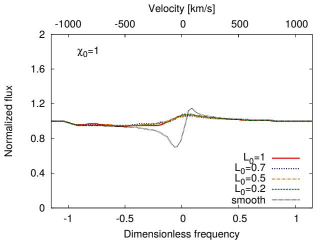
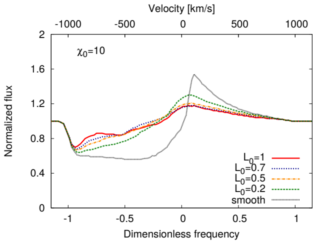
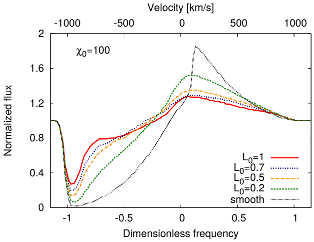
$L_0 = 0.3$ D=10 d=0





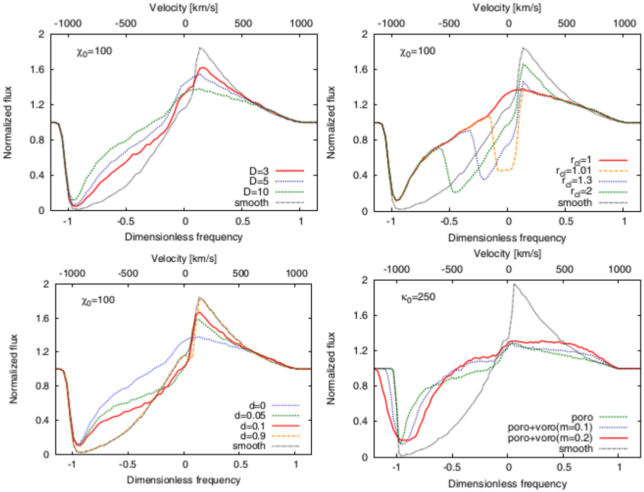




Šurlan et al. 2012

3D description of clumping

Šurlan et al. 2012



Comparison with observation

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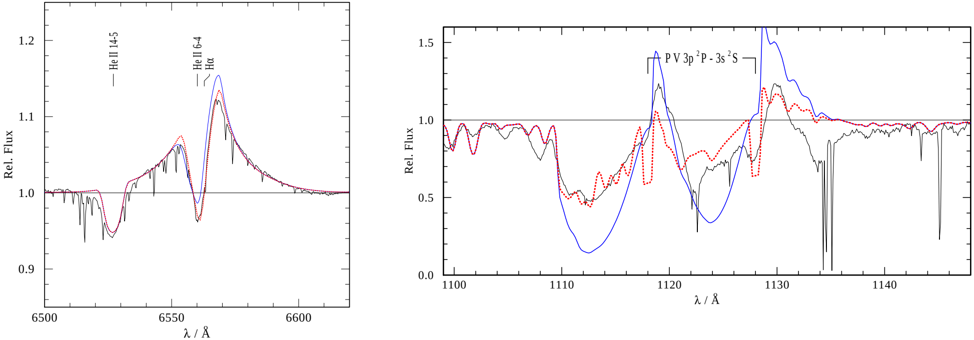
RESEARCH GOALS

- To check whether detailed **3-D description of wind clumping** may resolves discrepancy between Hα and P V mass loss diagnostics



Microclumping vs. **Macroclumping** (Oskinova et al. 2007)

Comparison with observation

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RESEARCH GOALS

- To check whether detailed **3-D description of wind clumping** may resolves discrepancy between Hα and P v mass loss diagnostics

Clumping parameters used in the 3D MCRT code

- Clumps may be either optically thin or thick
- Clumping separation parameter (number of clumps)
- Onset of clumping (radius at which clumping set-up)
- Clumping factor (density inside clumps)
- Inter-clump medium density
- Velocity deviation parameter (velocity inside clumps)

- **Fit P v line profiles using the same $\dot{M}$ rats derived from Hα diagnostic**
- **To derive some global properties of O-star wind clumping**

Comparison with observation

- 5 O-type Galactic supergiants

Star	Other name	Spec.
HD 66811	ζ Pup	O4I(n)fp
HD 15570		O4If+
HD 14947		O5If+
HD 210839	λ Cep	O6If(n)p
HD 192639		O7Ib(f)

Table: Spectral types are taken from Sota et al. (2011), while the photometry is taken from the GOC catalog Maiz et al. (2004), and reddening is taken from Bouret et al. (2012).

- **OPTICAL SPECTRA**
  - CCD SITe ST-005 800×2000 pix camera (Ondřejov observatory)
  - $6254 - 6764$ Å - Hα region ($R = 13\,600$)
  - $4656 - 4908$ Å - + He II 4686 Å ($R = 19\,400$)
  - $4754 - 5005$ Å - region ($R = 20\,000$)
  - $4269 - 4522$ Å - region ($R = 17\,600$)
  - Zeta Pup ...
- **ULTRAVIOLET SPECTRA**
  - High-resolution FUV spectra (960 to 1190 Å) - Far Ultraviolet Spectroscopic Explorer (FUSE) taken from `MAST`
  - Low-resolution NUV spectra (1200 to 2000 Å) - International Ultraviolet Explorer (IUE) taken from `INES Archive Data Server`
  - `COPERNICUS` ... for Zeta Pup

Comparison with observation

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1. Teff, log g, R, L, β, V∞
2. H, He, C, N, O, Si, P, Fe mass fraction
3. Photometry – UBVJHK, E(B-V)

Input

PoWR code

1. Pv Ionisation fraction
2. Photospheric spectrum
3. Mass-loss rates

Input

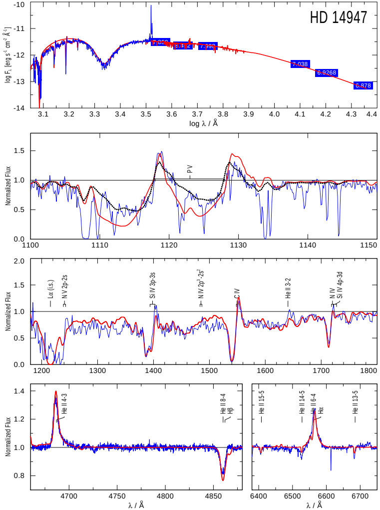
Clumped 3-D MCRT code

rcl, L0, D, d, Vdis

Output

1. Pv line profiles
2. Clumping parameters

Šurlan et al. 2013



Comparison with observation

Number of clumps

One-component wind – dens clumps and void inter-clump medium

Model parameters	Value
Inner boundary of the wind	$r_{\mathrm{min}} = 1$
Outer boundary of the wind	$r_{\mathrm{max}} = 100$
Opacity parameter	$\chi_0 = 257.8$
Clump separation parameter	$L_0 = 0.5, 0.3, 0.2, 0.1$
Clumping factor	$D = 10$
Interclump medium density factor	$d = 0$
Set-up of clumping	$r_{\mathrm{cl}} = 1$
Velocity deviation	$v_{\mathrm{dis}}/v_\beta = 0.2$
Velocity at the photosphere	$v_{\mathrm{min}} = 10\ [\mathrm{km\,s^{-1}}]$
Doppler velocity	$v_{\mathrm{D}} = 20\ [\mathrm{km\,s^{-1}}]$

$$f_v = \frac{1}{D}$$

Comparison with observation

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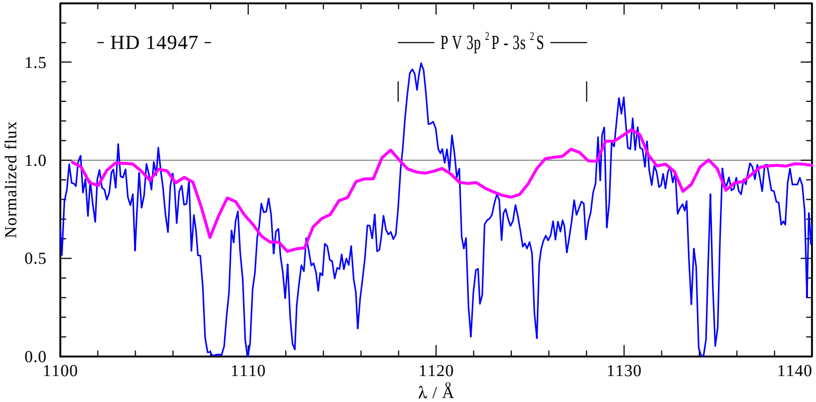
Comparison with observation



$$L_0 = 0.5\ (n_{\mathrm{cl}} = 1.13 \cdot 10^4)$$

Comparison with observation

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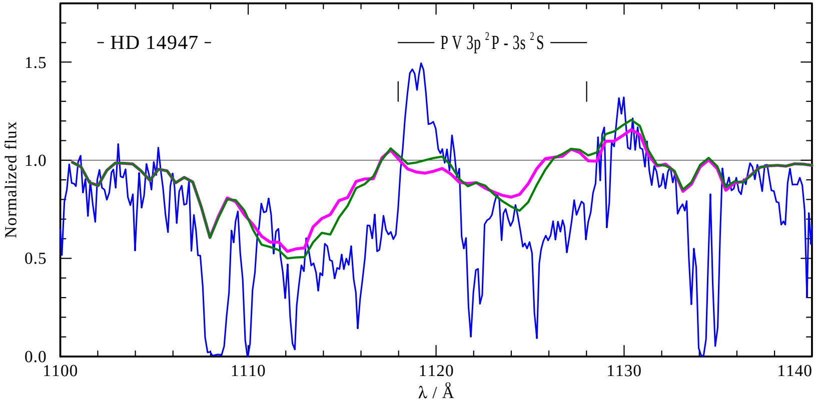

$L_0 = 0.5\ (n_{\mathsf{cl}} = 1.13 \cdot 10^4)$ $L_0 = 0.3\ (n_{\mathsf{cl}} = 5.17 \cdot 10^4)$

Comparison with observation

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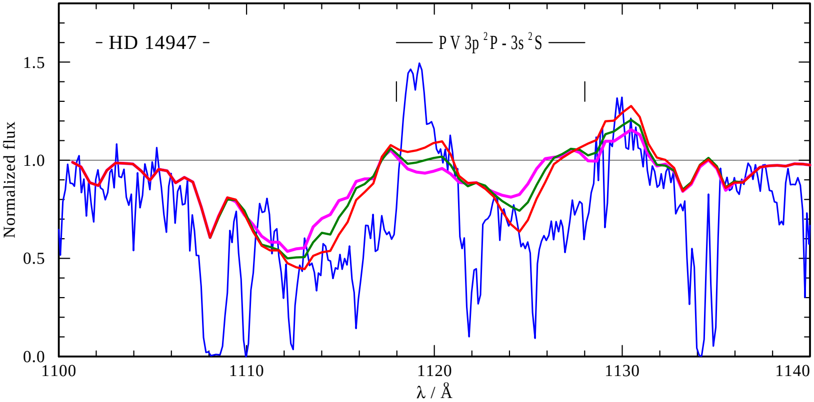
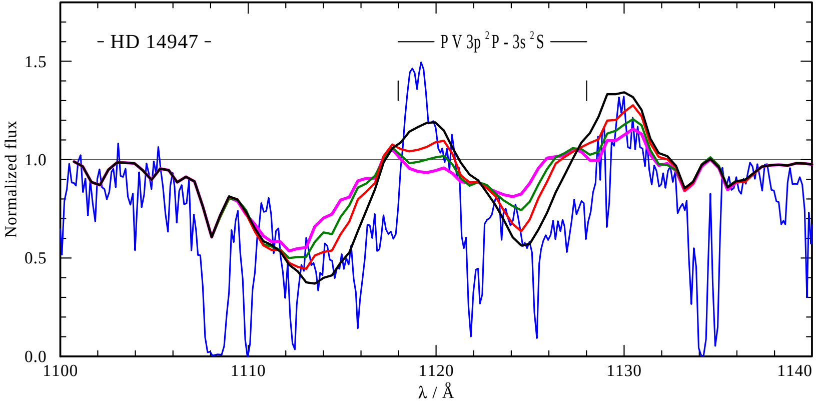
Astronomický ústav AV ČR



$L_0 = 0.5\,(n_{\mathrm{cl}} = 1.13 \cdot 10^4)$ $L_0 = 0.3\,(n_{\mathrm{cl}} = 5.17 \cdot 10^4)$ $L_0 = 0.2\,(n_{\mathrm{cl}} = 1.75 \cdot 10^5)$

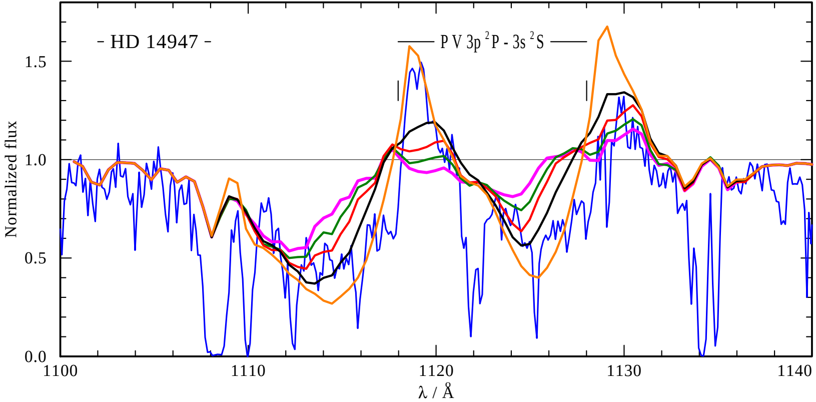
Comparison with observation



$L_0 = 0.5\,(n_{\mathsf{cl}} = 1.13 \cdot 10^4)$ $L_0 = 0.3\,(n_{\mathsf{cl}} = 5.17 \cdot 10^4)$ $L_0 = 0.2\,(n_{\mathsf{cl}} = 1.75 \cdot 10^5)$

$L_0 = 0.1\,(n_{\mathsf{cl}} = 1.40 \cdot 10^6)$

Comparison with observation



$L_0 = 0.5\,(n_{\rm cl} = 1.13 \cdot 10^4)$ $L_0 = 0.3\,(n_{\rm cl} = 5.17 \cdot 10^4)$ $L_0 = 0.2\,(n_{\rm cl} = 1.75 \cdot 10^5)$

$L_0 = 0.1\,(n_{\rm cl} = 1.40 \cdot 10^6)$ smooth wind

Comparison with observation

Conclusion (one-component wind)

- 10^6 and more clumps
- Even with such large number of clumps neither the strength of the emissions nor depth of absorption cannot be achieved
- Additional matter is needed to be add to satisfactorily reproduce observed line profile

Comparison with observation

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Inter clump medium density

One-component wind – dens clumps and non-void inter-clump medium

Model parameters	Value
Inner boundary of the wind	$r_{\mathsf{min}} = 1$
Outer boundary of the wind	$r_{\mathsf{max}} = 100$
Opacity parameter	$\chi_0 = 257.8$
Clump separation parameter	$L_0 = 0.5$
Clumping factor	$D = 10$
Interclump medium density factor	$d = 0$
Set-up of clumping	$r_{\mathsf{cl}} = 1$
Velocity deviation	$v_{\mathsf{dis}}/v_\beta = 0.2$
Velocity at the photosphere	$v_{\mathsf{min}} = 10\ [\mathrm{km\,s^{-1}}]$
Doppler velocity	$v_{\mathsf{D}} = 20\ [\mathrm{km\,s^{-1}}]$

$$f_v = \frac{1-d}{D-d}$$

Comparison with observation

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Model parameters	Value
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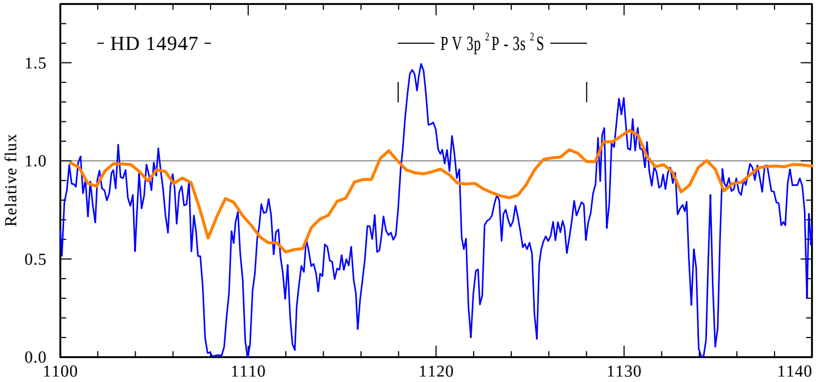
Opacity parameter	$\chi_0 = 257.8$
Clump separation parameter	$L_0 = 0.5$
Clumping factor	$D = 10$
Interclump medium density factor	$d = 0,\ 0.1,\ 0.2,\ 0.25$
Set-up of clumping	$r_{\mathrm{cl}} = 1$
Velocity deviation	$v_{\mathrm{dis}}/v_\beta = 0.2$
Velocity at the photosphere	$v_{\mathrm{min}} = 10\ [\mathrm{km\,s^{-1}}]$
Doppler velocity	$v_{\mathrm{D}} = 20\ [\mathrm{km\,s^{-1}}]$

$$f_v = \frac{1-d}{D-d}$$

Comparison with observation



$d = 0$

Comparison with observation

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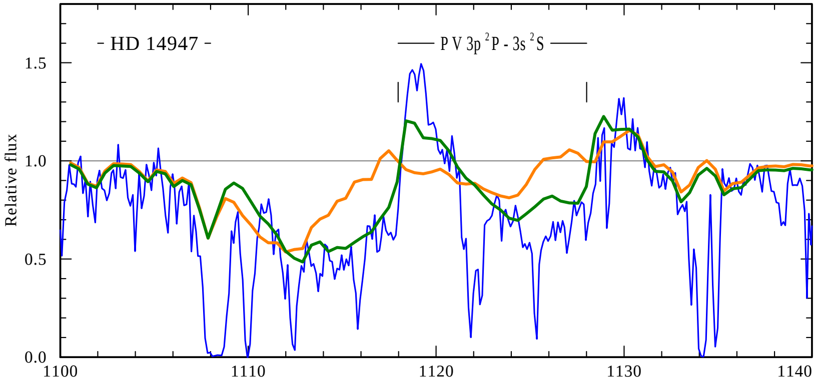
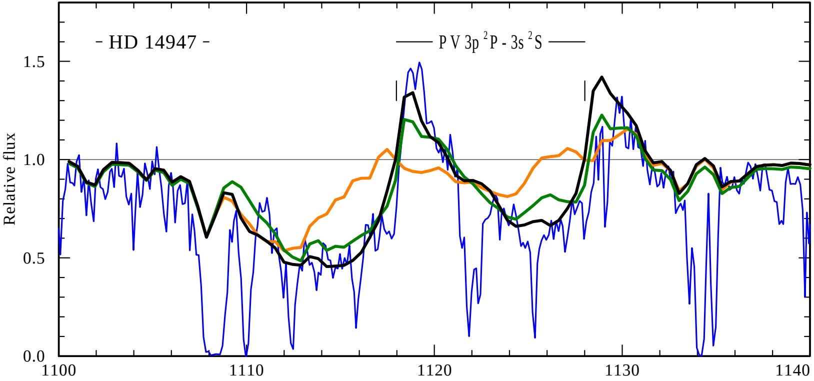


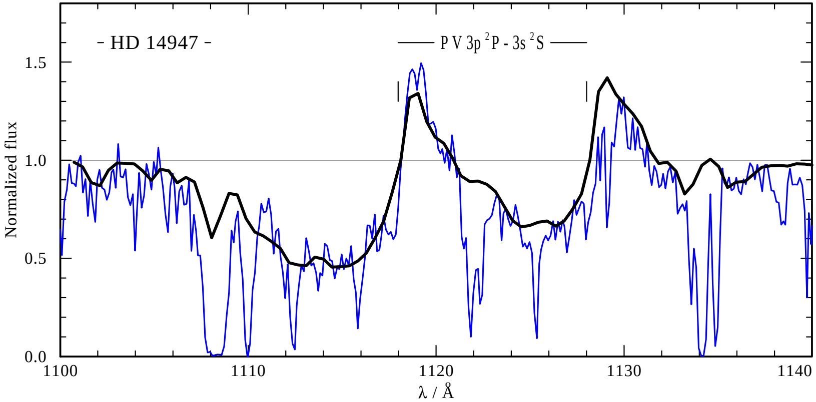
$d = 0$, $d = 0.1$

Comparison with observation



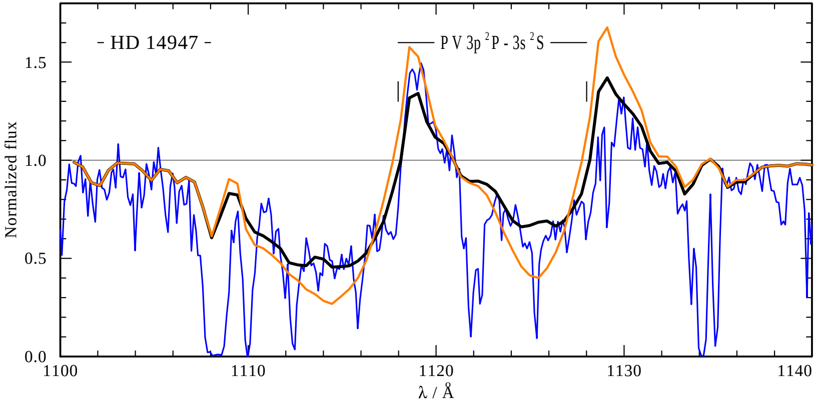
$d = 0$, $d = 0.1$, $d = 0.25$

Comparison with observation



$d = 0.25$

Comparison with observation



$d = 0.25$, smooth wind

Comparison with observation

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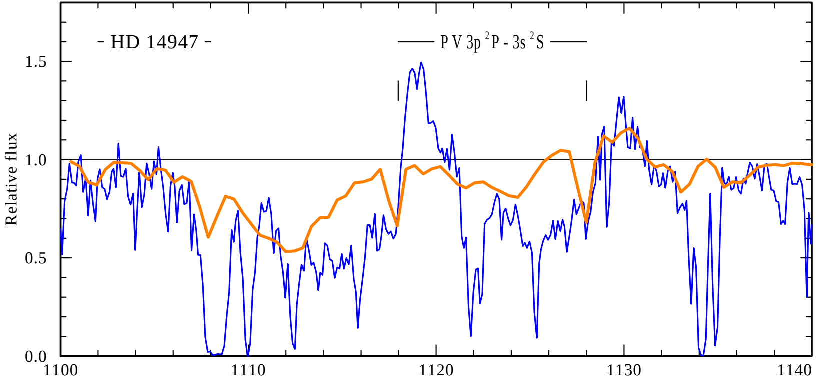
Conclusion (two-component wind)

- Two-component wind is more realistic
- Inter-clump medium density is a necessary ingredient of the wind
- Different combinations of L_0 and d may give equally good agreement with observation
- **Inter-clump medium cannot be void!!!**

Šurlan et al. 2013

Comparison with observation

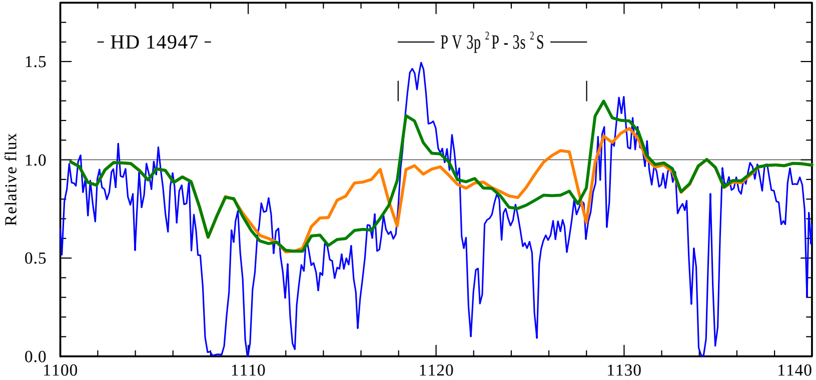
On-set of clumping $L_0 = 0.5$ $(n_{\mathrm{cl}} 1.13 \cdot 10^4)$, $r_{\mathrm{cl}} = 1.1$



$d = 0$

Comparison with observation

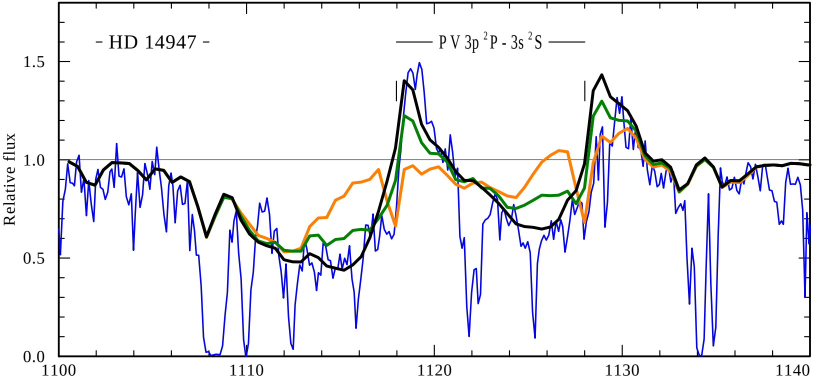
$L_0 = 0.5\ (n_{\mathrm{cl}} 1.13 \cdot 10^4),\ r_{\mathrm{cl}} = 1.1$



$d = 0$, $d = 0.1$

Comparison with observation

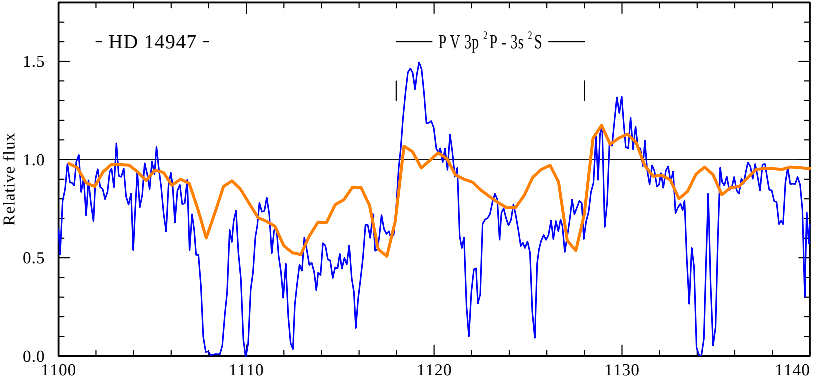
$L_0 = 0.5\ (n_{\mathrm{cl}} 1.13 \cdot 10^4)$, $r_{\mathrm{cl}} = 1.1$



$d = 0$, $d = 0.1$, $d = 0.25$

Comparison with observation

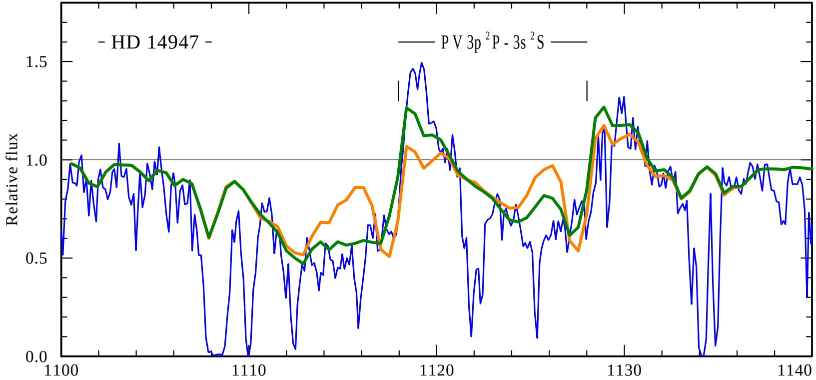
$L_0 = 0.5$ $(n_{\mathrm{cl}} = 1.13 \cdot 10^4)$, $r_{\mathrm{cl}} = 1.3$



$d = 0$

Comparison with observation

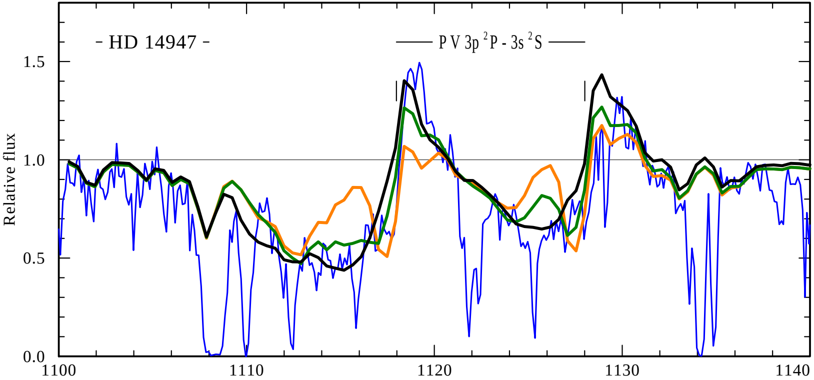
$L_0 = 0.5$ $(n_{\rm cl} = 1.13 \cdot 10^4)$, $r_{\rm cl} = 1.3$



$d = 0$, $d = 0.1$

Comparison with observation

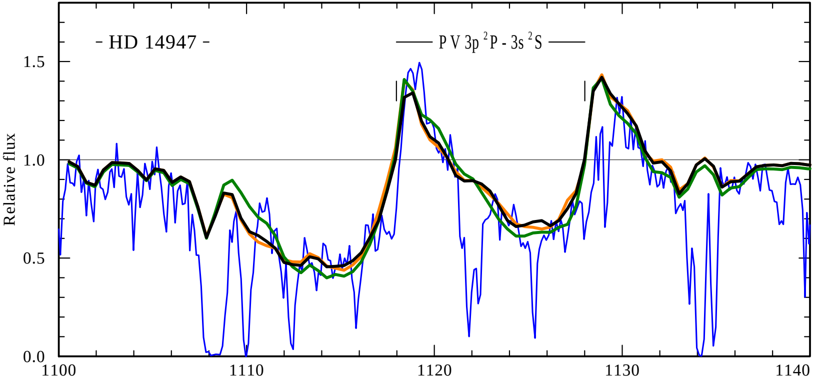
$L_0 = 0.5$ $(n_{\mathrm{cl}} = 1.13 \cdot 10^4)$, $r_{\mathrm{cl}} = 1.3$



$d = 0$, $d = 0.1$, $d = 0.25$

Comparison with observation

$L_0 = 0.5$ ($n_{cl} = 1.13 \cdot 10^4$), $d = 0.25$



$r_{cl} = 1$, $r_{cl} = 1.1$, $r_{cl} = 1.3$

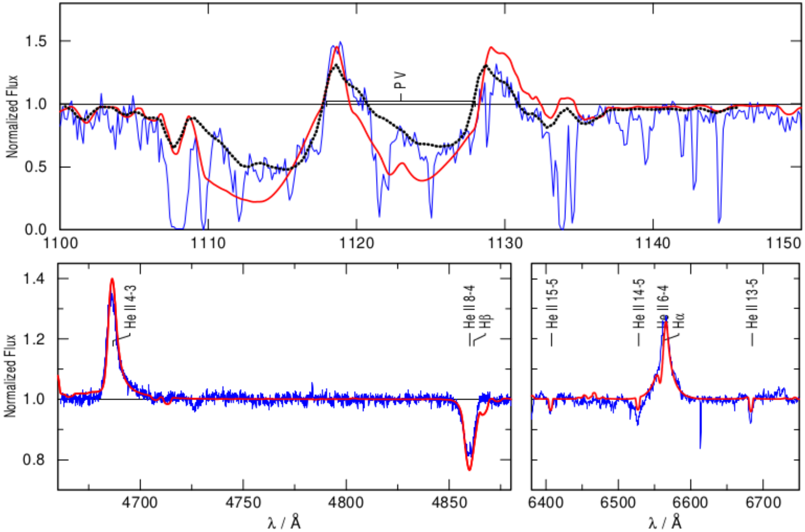
Comparison with observation

Conclusion

- In case of one-component wind clumping has to set-on from the surface of the star
- Wind clumping may start farther from the surface of the star only if inter-clump medium is not void
- Inter-clump medium density is needed in order to fit line profiles
- Different combination of r_{cl} and d may give very similar agreement with observations

Šurlan et al. 2013

Comparison with observation



Comparison with observation

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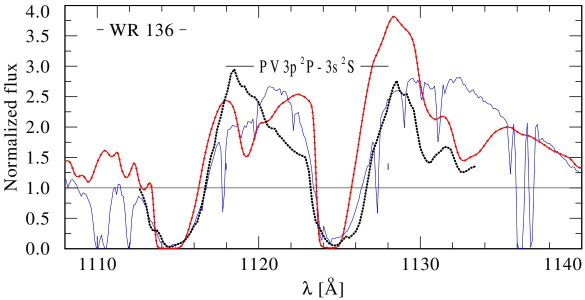
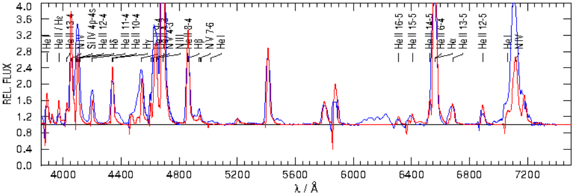
Summary – O-type stars

- Macroclumping (both optically thin and thick clumps exist) resolves discrepancy between Hα and P V $\dot{M}$ rates
- We do not need to lower P V abundance
- We do not need extreme clumping factor D
- Inter-clump medium is needed to achieve satisfactory agreement with observed P V line profiles
  - number of clumps – the higher the inter-clump medium density is, the lower is the number of clumps
  - onset of clumping – clumping may start farther from the surface of the star only if inter-clump medium is not void
- Velocity dispersion inside clumps is important to model outer part of the wind

Šurlan et al., 2013

Comparison with observation





Šurlan et al., 2015

Comparison with observation

Summary - WR 136 star

- Macroclumping has impact on the formation of resonance lines
- A smooth wind cannot reproduce the observed P V line profile, when the mass-loss rate is adopted according to the emission-line spectrum
- The porosity seems to be pronounced (only ≈200 clumps within 100 R_*)
- The interclump density remains unconstrained
- The results are not sensitive to the velocity dispersion within each clump (" vorosity"), except of an additional blue-shift of the P-Cygni absorption edge
- We intend to study a larger sample of WR stars in order to better understand the inhomogeneous structures of their winds Kubátová et al., in preparation

Šurlan et al., 2015

Hubble UV Legacy Library of Young Stars as Essential Standards

https://ullyses.stsci.edu/

B. Kubátová – Point of Contact for WG4 (Wind Structures)

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ULLYSES + XSHOOTER

- Uniformly sample the fundamental astrophysical parameter space for each mass regime - including spectral type, luminosity class, and metallicity for massive OB stars
- Spectral types O2-B1.5, supergiants B2-B9, 11 WR stars (4 close binary systems)
- LMC ($Z=0.2\ Z_\odot$), SMC ($Z=0.5\ Z_\odot$), NGC 3109 ($Z=0.1$-$0.2\ Z_\odot$), and Sextans A ($Z=0.1\ Z_\odot$)
- HST (FUV: 937-1792 Å+ archive data; NUV: 1607-3119 Å; OPT: 2900-5700 Å; NIR: 5240-10270 Å)
- XSHOOTER (UVB: 300-559.5 nm; OPT: 559.5-1024 nm; NIR:1024-2480 nm

HVALA NA PAŽNJI!