

Clumped Winds of Massive Hot Stars

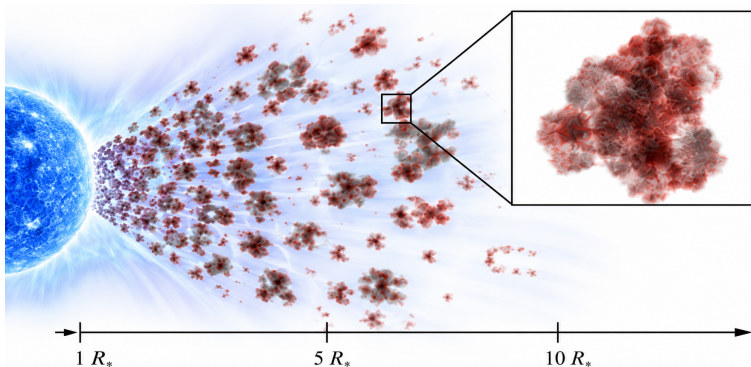
and Their Impact on Mass-Loss Determinations

Brankica Kubátová

brankica.kubatova@asu.cas.cz

Stellar Physics Department
Astronomical Institute of the CAS

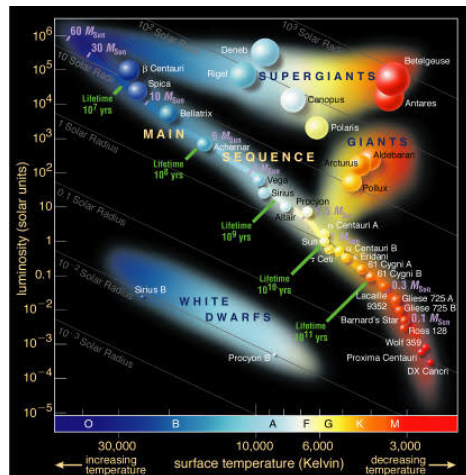
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Basic properties of massive hot stars

- **MASSIVE** – $M \gtrsim 8 [M_{\odot}]$
- **EXTREMELY LUMINOUS** – $L \gtrsim 10^3 [L_{\odot}]$
- **HOT** – $T_{\text{eff}} \gtrsim 20\,000 \text{ [K]}$
- **SPECTRAL TYPE** – **OB-type**
Massive stars in short-lived transition phase (WR, LBVs, BSGs, and B[e]SGs)
- **SHORT LIFETIMES** – $\sim 10^6 \text{ yr}$
- **STRONG WIND (MASS LOSS)**
Mass-loss rate – $\dot{M} \sim 10^{-6} [M_{\odot}/\text{yr}]$
Terminal velocity – $v_{\infty} \sim 10^2 - 10^3 \text{ km/s}$
- **SPECTACULAR DEATH VIA SUPERNOVA EXPLOSION OR GAMMA-RAY BURST**

Remnant: neutron star or black hole



Credit: ESO.

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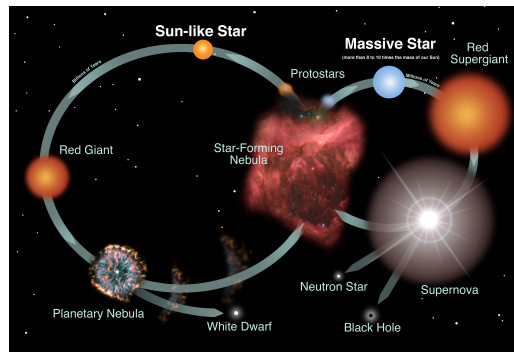


The nebula M1-67 around Wolf-Rayet star WR 124

Credit: ESA/Hubble & NASA.

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Credit: NASA, Night Sky Network.

- Understanding of the **evolution and fate of massive stars** in the universe.
 - **reliable mass-loss recipes** for stellar evolution - $\dot{M} = f(Z)$
- Understanding the nature of different types of **supernovae, neutron stars and black holes**
- A better understanding of the progenitors of **gravitational waves - the masses of BH mergers** (LIGO/Virgo: Abbott et al. 2016; Abbott et al. 2020).

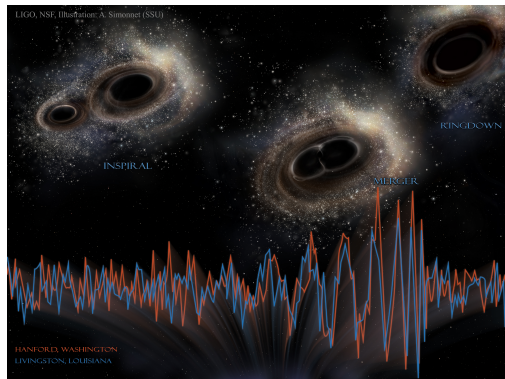


Illustration Credit: LIGO, NSF, Aurore Simonnet.

The basic principle of wind driving

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**

- **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

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

- for stationary and spherically symmetric wind $\Rightarrow$

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

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

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

“OBSERVED” wind parameters - the result of diagnostic techniques based on theoretical modelling (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

- **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** (Krtićka & Kubát, 2017)
- **Unified non-LTE model atmosphere** - stellar and wind parameters are derived simultaneously and consistently

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

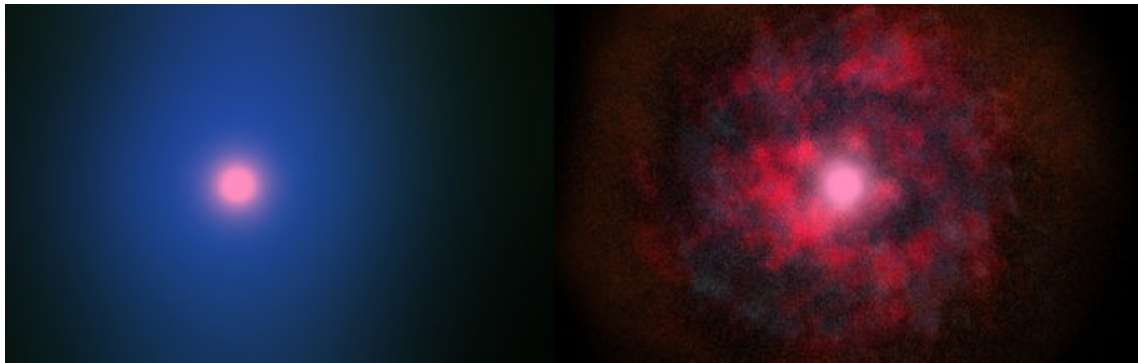
- **THEORETICAL wind parameters** - from the hydrodynamical calculations
- **“OBSERVED” wind parameters** - from the observations

PROBLEM!

- Discrepancy between theoretical (predicted) and “observed” mass-loss rates
(e.g., Bouret et al., 2003, Martins et al., 2005, Puls et 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 - evidences

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

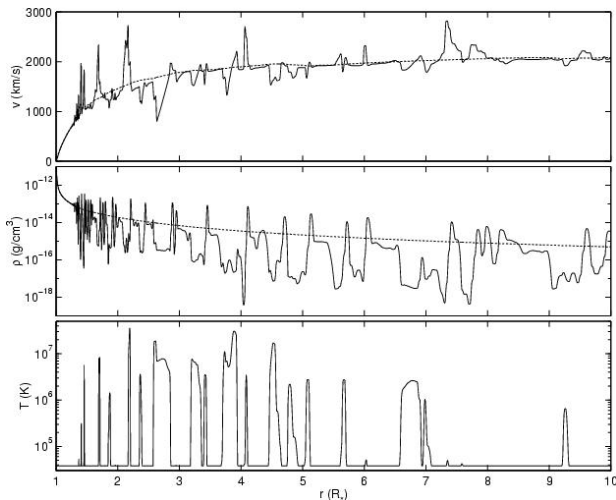
Theoretical evidence

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

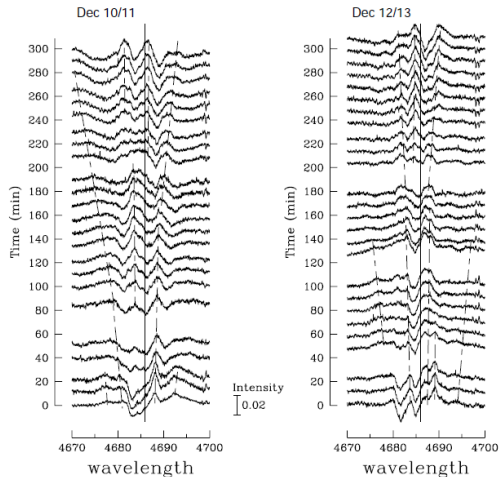


Runacres & Owocki (2002)

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

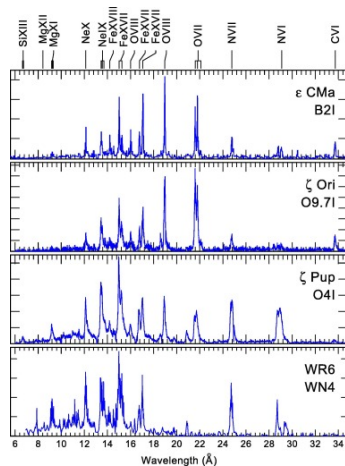


He II $\lambda 4481$ from ζ Pup (Eversberg et al. 1998)

Diagnostic evidence

QUANTITATIVE SPECTROSCOPY

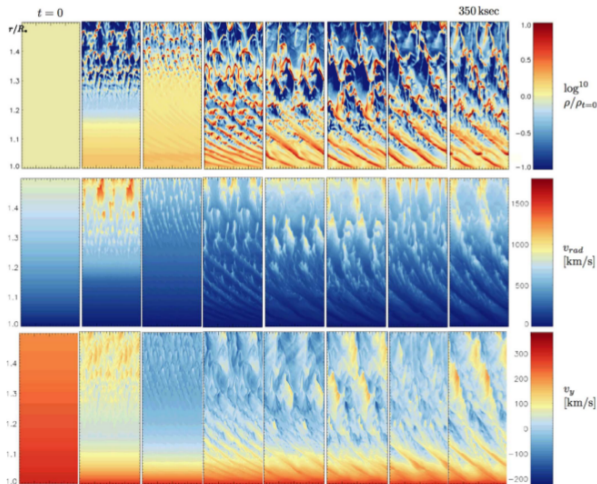
- Electron scattering wings
- Shapes of saturated P Cygni profiles
- Presence of X-ray emission
- UV resonance doublet ratios
- Different diagnostics result in different $\dot{M}$
- Disagreement in the theoretical and “observed” $\dot{M}$



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

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

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}

$$D = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}, \quad f_v = \frac{1}{D}, \quad \rho_{cl} = D \langle \rho \rangle$$

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**

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

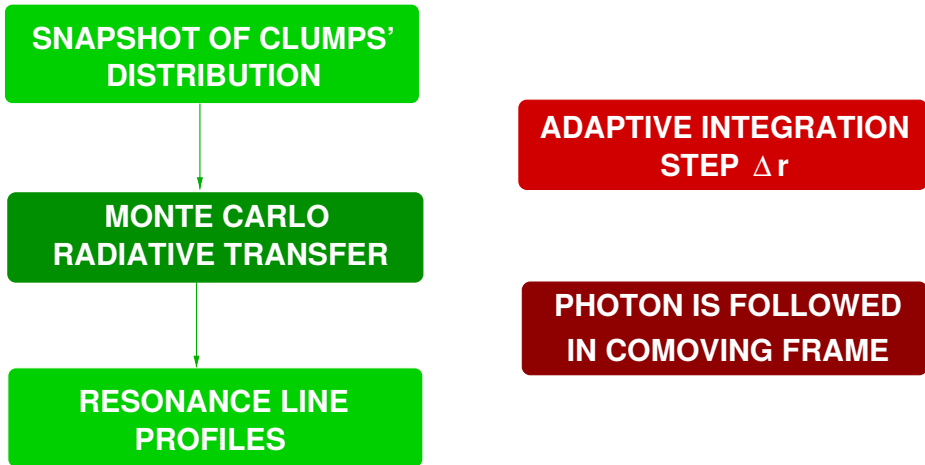
Resolve discrepancies in different mass-loss rates diagnostics and better constrain clumping properties

More realistic properties of clumps

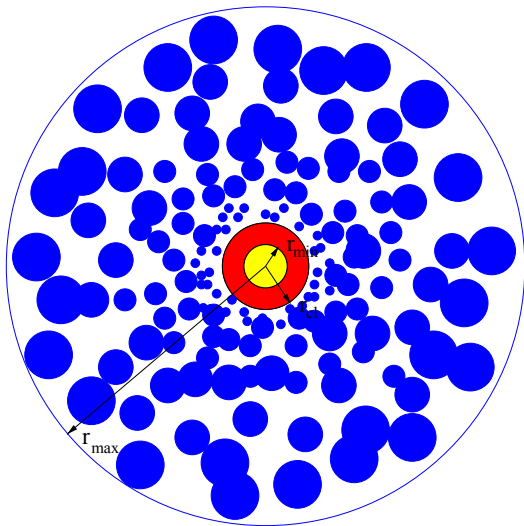
- Depth dependent clumping factor (Puls et al. 2006)
- Onset of clumping (Bouret et al. 2003, Sundqvist et al. 2010)
- Interclump medium density (Zsargó et al. 2008)
- Shape of clumps

Clumping introduces additional complexities into the RT

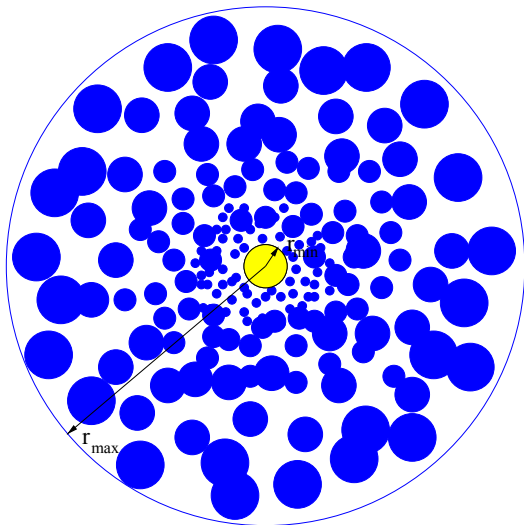
- Due to Doppler shift, opacity and emissivity are **not isotropic**
- Clumping **requires 3D** radiative transfer (RT)
- The real size, shape, and distribution of clumps are unknown → we have to use **approximations**
- Clumps can be optically thick (own ionization structure)
- Clumps can shield other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



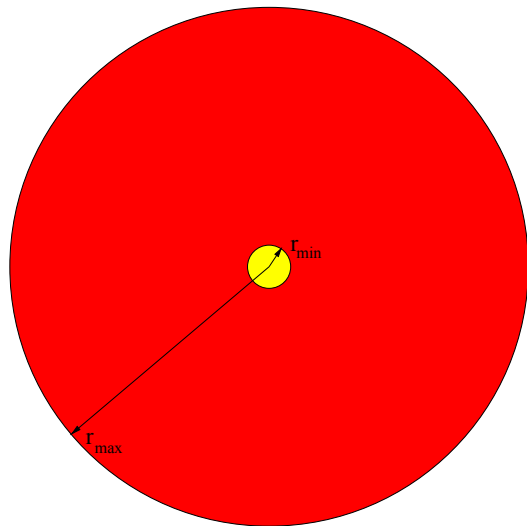
Monte Carlo Radiative Transfer (MCRT) Code – basic concept (Šurlan et al. 2012)



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



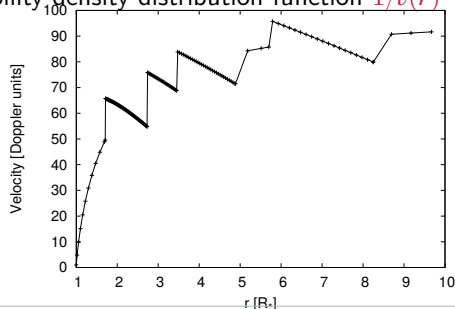
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- **Macroclumping** - clumps can be optically thin or thick
- Clumps are statistically distributed with average separation $L = L(r) - \boxed{L_0}$
- Clumps are spherical with the radius $l = l(r)$
- $\rho_{cl}(r) = D \rho_{sw}(r)$ and $\boxed{D} \geq 1$
- $\rho_{ic} = d \rho_{sw}$; $0 \leq \boxed{d} < 1$
- Onset of clumping $\boxed{r_{cl}}$
- Probability density distribution function $1/v(r)$

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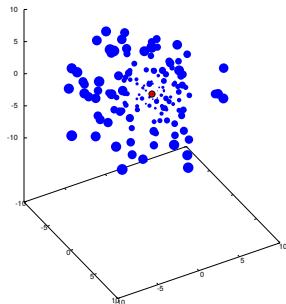
Velocity structure of the wind model along the considered photon path

$$v(r) = v_{\beta}(r) + \boxed{v_{dis}} (r - r_i^c + l_i)$$

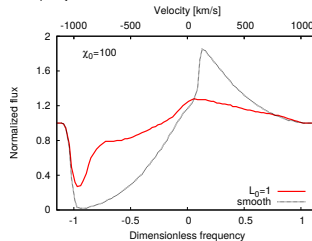
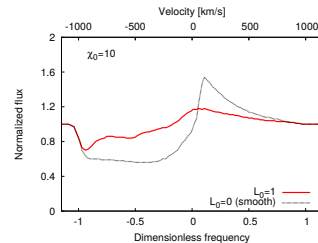
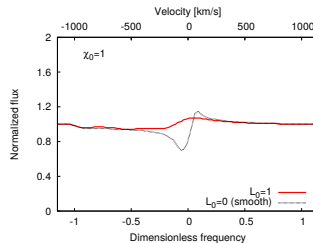
Clump's distribution

different number of clumps

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

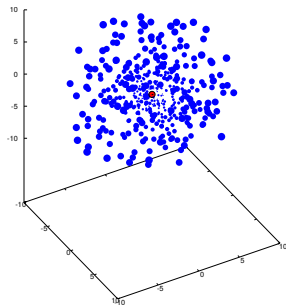


Šurlan et al. 2012

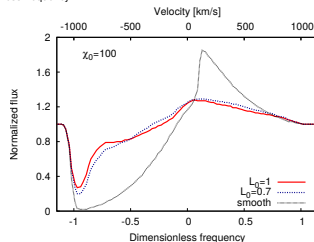
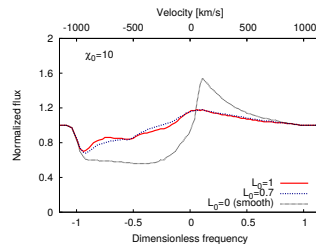
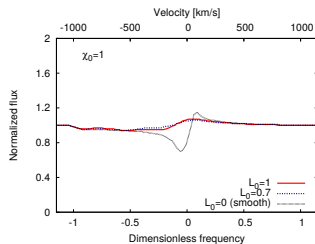


Clump's distribution

$$L_0=0.7 \quad D=10 \quad d=0$$

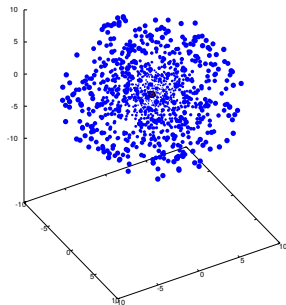


Šurlan et al. 2012

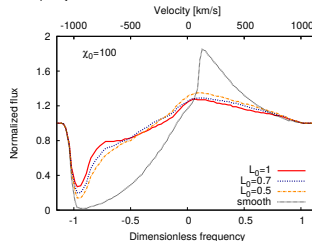
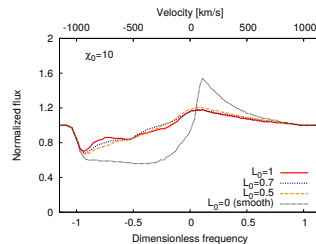
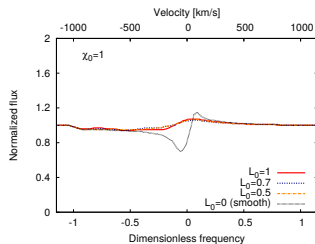


Clump's distribution

$$L_0=0.5 \quad D=10 \quad d=0$$

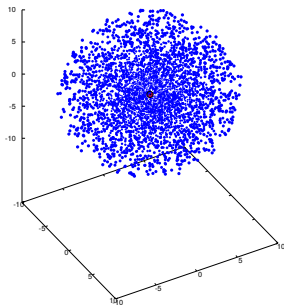


Šurlan et al. 2012

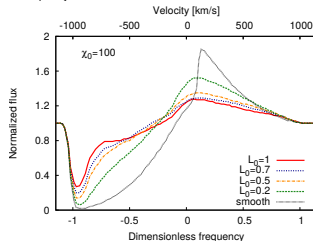
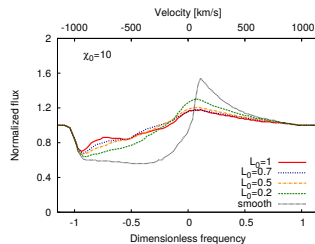
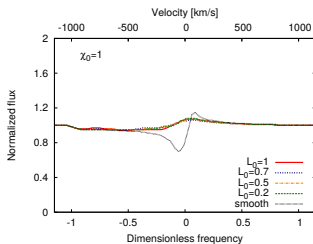


Clump's distribution

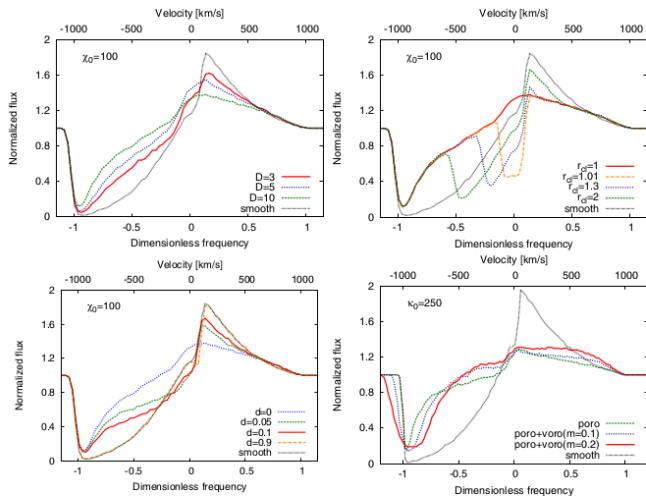
$$L_0=0.3 \quad D=10 \quad d=0$$



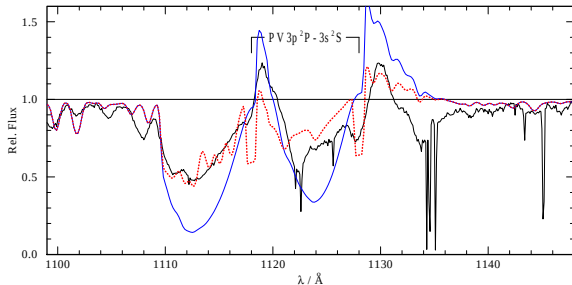
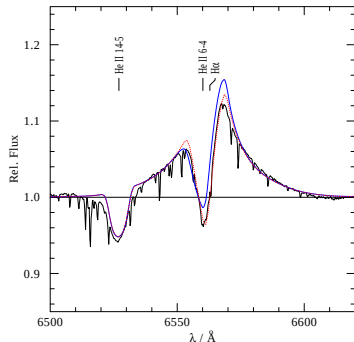
Šurlan et al. 2012



Šurlan et al. 2012



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



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

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

- 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 - H α 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

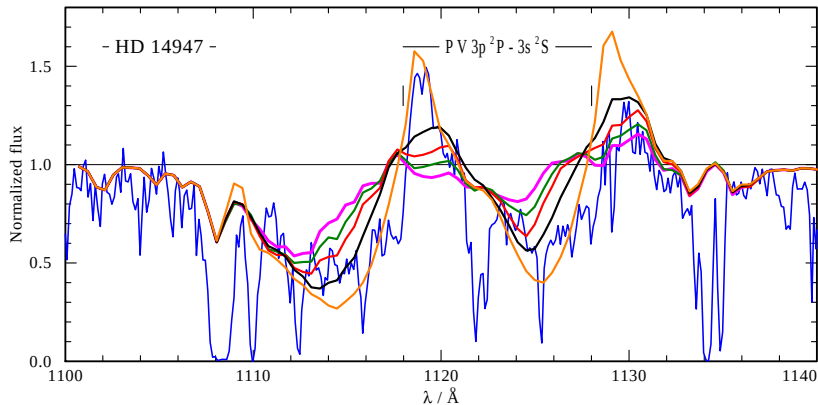


Number of clumps

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

Model parameters	Value
Inner boundary of the wind	$r_{\min} = 1$
Outer boundary of the wind	$r_{\max} = 100$
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	$r_{\text{cl}} = 1$
Velocity deviation	$v_{\text{dis}}/v_{\beta} = 0.2$
Velocity at the photosphere	$v_{\min} = 10 \text{ [km s}^{-1}\text{]}$
Doppler velocity	$v_{\text{D}} = 20 \text{ [km s}^{-1}\text{]}$

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



$$L_0 = 0.5 (n_{cl} = 1.13 \cdot 10^4) \quad L_0 = 0.3 (n_{cl} = 5.17 \cdot 10^4) \quad L_0 = 0.2 (n_{cl} = 1.75 \cdot 10^5) \\ L_0 = 0.1 (n_{cl} = 1.40 \cdot 10^6) \quad \text{smooth wind}$$

Conclusions (one-component wind)

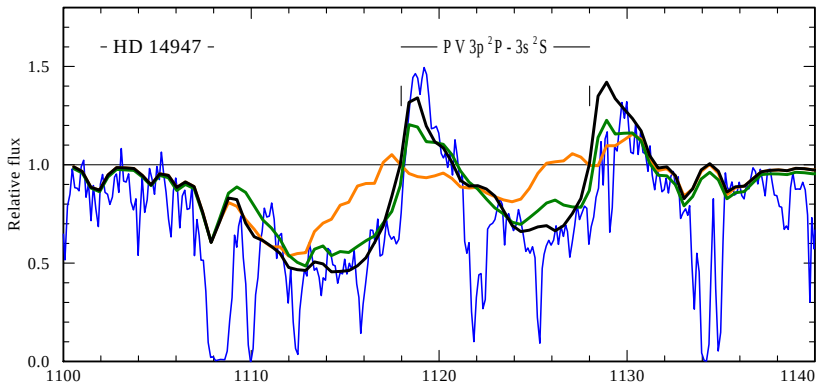
- 10^6 and more clumps
- Even with such large number of clumps neither the strength of the emissions nor depth of absorption cannot be achieved
- Additional matter is needed to be added to satisfactorily reproduce observed line profile

Inter clump medium density

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

Model parameters	Value
Inner boundary of the wind	$r_{\min} = 1$
Outer boundary of the wind	$r_{\max} = 100$
Opacity parameter	$\chi_0 = 257.8$
Clump separation parameter	$L_0 = 0.5$
Clumping factor	$D = 10$
Interclump medium density factor	$d = 0, 0.1, 0.2, 0.25$
Set-up of clumping	$r_{\text{cl}} = 1$
Velocity deviation	$v_{\text{dis}}/v_{\beta} = 0.2$
Velocity at the photosphere	$v_{\min} = 10 \text{ [km s}^{-1}\text{]}$
Doppler velocity	$v_{\text{D}} = 20 \text{ [km s}^{-1}\text{]}$

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



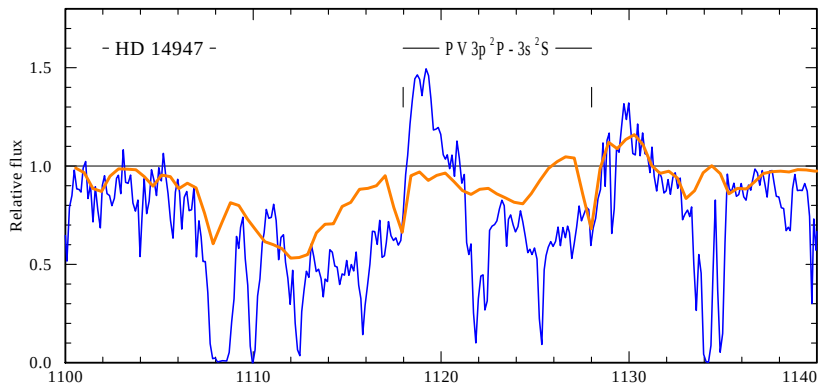
$$d = 0, \quad d = 0.1, \quad d = 0.25$$

Conclusions (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!!!**

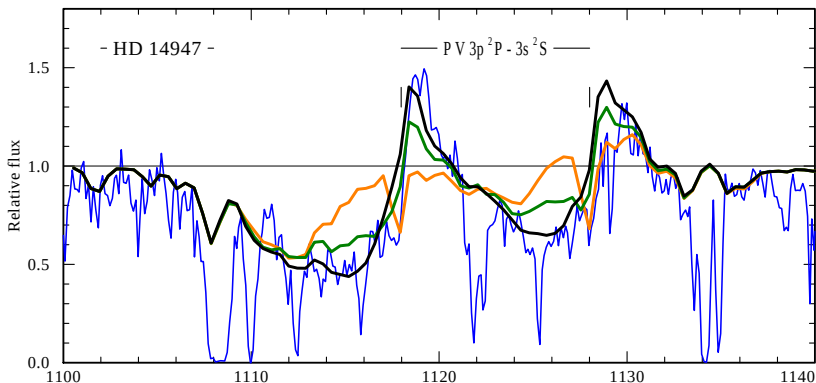
Šurlan et al. 2013

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



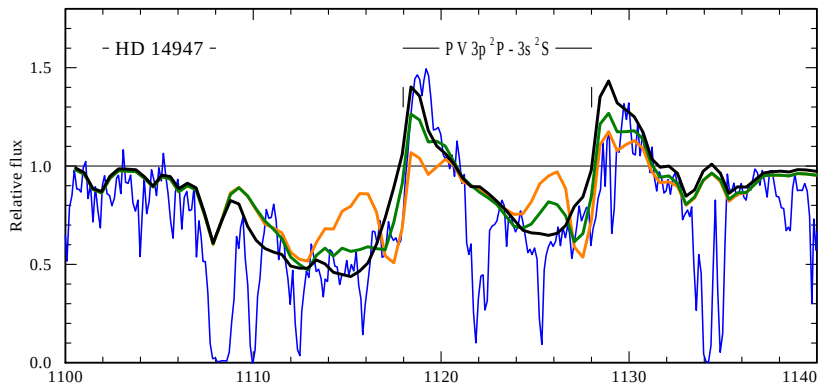
$d = 0$

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



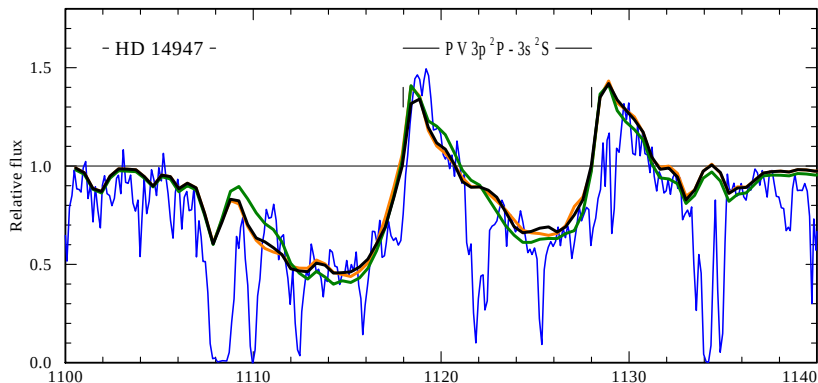
$$d = 0, d = 0.1, d = 0.25$$

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



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

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



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

Conclusions (on-set of clumping)

- 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

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- **Mass loss is a fundamental parameter of massive-star evolution**, with consequences extending from stellar evolution and feedback to supernovae, black holes and gravitational-wave progenitors.
- **Massive-star winds are intrinsically clumped.** A homogeneous wind is an approximation that can strongly bias spectroscopic mass-loss determinations.
- **Microclumping is not sufficient for all diagnostics.** For UV resonance lines we need to account for optically thick clumps, spatial and velocity porosity, and the interclump medium.
- Our 3D modelling shows that the apparent **discrepancy can arise from an inadequate description of wind structure.**
- **We cannot determine the mass-loss rate independently of the structure of the wind.**