MACROCLUMPING RESOLVES DISCREPANCY BETWEEN Hα AND P v MASS-LOSS DIAGNOSTICS

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Motivation

- $\tau_{\mathrm{rad}} \propto \dot{M}\, q_i\, A_E$
- P is not a cosmically abundant element (P v never saturates) $\Longrightarrow \dot{M}\, q_i$
- P v is the dominant ion in the winds of mid- to late- O-type stars ($q_i \sim 1$)
- $\dot{M}_{P_{\mathrm{v}}}$ should agree with $\dot{M}$ from ρ^2 diagnostic

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ρ^2 diagnostics gives higher $\dot{M}$ by a factor of at least 10

(e.g. Crowther et al. 2002, Massa et al. 2003, Hillier et al. 2003, Bouret et al. 2003, 2005, Fullerton, Massa, & Prinja 2006)

P v ($\lambda\lambda$ 1118, 1128 Å) PROBLEM – discrepancy between Hα and P v $\dot{M}$ diagnostics

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WIND CLUMPING – universal property of O-star winds

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- optically thin clumps – MICROCLUMPING ($\dot{M}$ needs to be scaled down by $\sqrt{D}$)

  see e.g., Hamann et al. 2008
- clumping factor D (f=1/D)
- void inter-clump medium (ICM)
- smooth (monotonic) velocity field

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Reduction of P abundance compared to solar value

High clumping factor

(see e.g., Bouret et al. 2003, 2005, 2012)

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MACROCLUMPING – clumps of correct optical depth (Oskinova et al. 2007)

Research goals

- 3-D description of wind clumping – application to O-type stars

- clumps may be either optically thin or thick
- clumping separation parameter (number of clumps)
- onset of clumping (radius at which clumping sets up)
- clumping factor (density inside clumps)
- inter-clump medium density
- velocity deviation parameter (velocity inside clumps)

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- To fit P v line profiles using the same $\dot{M}$ rates derived from Hα diagnostic (solar abundances of P v and less extreme D)
- To derive some global properties of O-star wind clumping

Stellar sample and 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.

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Stellar sample and observation

- 5 O-type Galactic supergiants
- OPTICAL SPECTRA
  - CCD SITe ST-005 800×2000 pix camera (Ondřejov observatory)
  - 6254 – 6764 Å - Hα region (R = 13 600)
  - 4656 – 4908 Å - Hβ + He II 4686 Å (R = 19 400)
  - 4754 – 5005 Å - Hβ region (R = 20 000)
  - 4269 – 4522 Å - Hγ region (R = 17 600)

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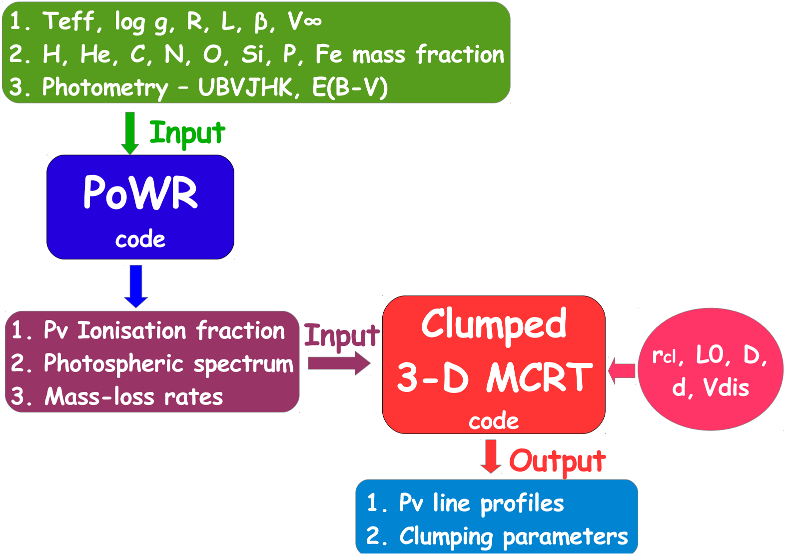
- ULTRAVIOLET SPECTRA
  - High-resolution FUV spectra (960 to 1190 Å) - Far Ultraviolet Spectroscopic Explorer (FUSE) taken from `MAST`
  - Low-resolution NUV spectra (1200 to 2000 Å) - International Ultraviolet Explorer (IUE) taken from `INES Archive Data Server`

Calculation scheme



PoWR – 1-D spherically symmetric wind models

- INPUT
  - STELLAR AND WIND PARAMETERS

Star	$T_{\rm eff}$ [kK]	$\log g$	R_* [$R_\odot$]	$\log \frac{L}{L_\odot}$	β_1	v_∞ [km/s]
HD 66811[2]	39.0	3.55	19.6	5.90	0.90	2250
HD 15570[3]	38.0	3.28	21.6	5.94	1.10	2200
HD 14947[1]	37.5	3.45	26.6	6.09	0.95	2350
HD 210839[1]	36.0	3.55	23.3	5.91	1.00	2250
HD 192639[1]	35.0	3.45	18.5	5.66	0.90	2150

Table: Data taken from 1 – Puls et al. 2006; 2 – Oskinova et al. 2007; 3 – Bouret et al. 2012.

PoWR – 1-D spherically symmetric wind models

- INPUT PARAMETERS
  - STELLAR AND WIND PARAMETERS
  - ABUNDANCES

Star	H	He	C	N	O
HD 66811	0.61	0.37	2.86E-03	1.05E-02	1.30E-03
HD 15570	0.71	0.28	3.27E-03	4.79E-03	2.63E-03
HD 14947	0.68	0.31	1.66E-03	5.00E-03	1.44E-03
HD 210839	0.68	0.31	1.32E-03	4.67E-03	3.23E-03
HD 192639	0.62	0.37	1.09E-03	5.01E-03	4.01E-03

Table: Stellar sample's mass fractions of H, He, C, O, N taken from Bouret et al. 2012.

Si $=6.649 \times 10^{-4}$, Fe-group elements $= 1.292 \times 10^{-3}$

P $= 5.825 \times 10^{-6}$

(solar abundances by Asplund et al. 2009)

PoWR – 1-D spherically symmetric wind models

- INPUT PARAMETERS
  - STELLAR AND WIND PARAMETERS
  - ABUNDANCES
  - PHOTOMETRY AND REDDENING

Star	U	B	V	J	H	K	E(B-V)
HD 66811	0.890	1.941	2.210	2.790	2.955	2.968	0.040
HD 15570	8.391	8.796	8.110	6.477	6.310	6.158	0.966
HD 14947	7.850	8.452	7.998	7.037	6.945	6.861	0.730
HD 210839	4.620	5.242	5.050	5.053	4.618	4.500	0.513
HD 192639	6.830	7.455	7.116	6.300	6.271	6.217	0.620

Table: The photometry – GOC catalog (Maíz-Apellániz et al. 2004), reddening – Bouret et al. 2012.

PoWR – 1-D spherically symmetric wind model

- INPUT PARAMETERS
  - STELLAR AND WIND PARAMETERS
  - ABUNDANCES
  - PHOTOMETRY AND REDDENING
- OTHER PARAMETERS
  - VELOCITY FIELD - DOUBLE-BETA LAW

$$v(r) = p_1 \left(1 - \frac{1}{r + p_2}\right)^{\beta_1} + p_{1-2} \left(1 - \frac{1}{r + p_{2-2}}\right)^{\beta_2}$$

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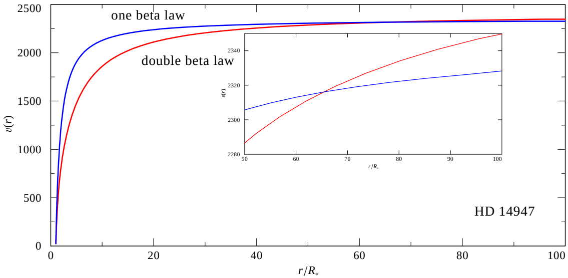


PoWR – 1-D spherically symmetric wind model

- INPUT PARAMETERS
  - STELLAR AND WIND PARAMETERS
  - ABUNDANCES
  - PHOTOMETRY AND REDDENING
- OTHER PARAMETERS
  - VELOCITY FIELD - double-beta law
  - CLUMPING FACTOR - depth dependent D
  - MICROTURBULENCE - $v_{\text{mt}} = 20\,\text{km/s}$
  - INTERSTELLAR AND DUST EXTINCTION - the reddening law of Cardeli et al. 1989

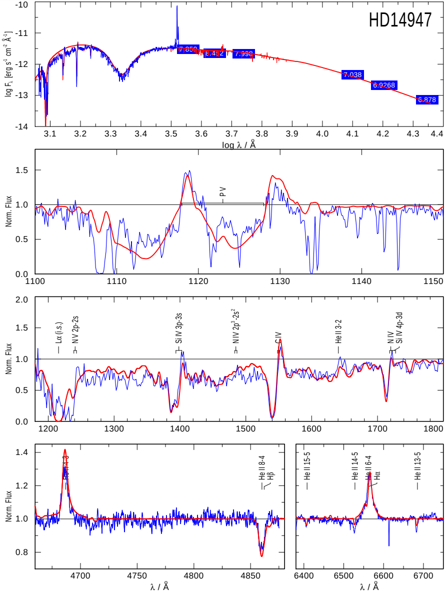
Extinction parameter

Distance

$\dot{M}$

(to best fit strength of the Hα line profiles)

Results of 1-D wind modeling



$T_{\rm eff}$	$\log g$	R_*	$\log \frac{L}{L_\odot}$	β	v_∞
37.5 kK	3.45	26.6 $R_\odot$	6.09	0.95	2350 km/s

d	R_V	M_V	$\log \dot{M}$
3.00 kpc	2.80	−6.90 mag	-4.77

FUSE

IUE

Ondřejov

3-D Monte Carlo Radiative Transfer clumped wind model

- INPUT FROM 1-D MODELING
  - Photospheric spectrum – without contribution of P and Si
  - Ionization fraction of P v (depth dependent)
  - Mass-loss rate (opacity parameter)

3-D Monte Carlo Radiative Transfer clumped wind model

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- 3-D MC wind solution
  (Šurlan, Hamann, Kubát, Oskinova, Feldmeier, 2012, A&A 541, A37)
  - to study effects of clumping on resonance line formation (both singlets and doublets)
  - dimensionless solution of radiative transfer
  - gridless code, no symmetry required
  - only line opacity (parametric description)
  - parametric description of clumps

3-D Monte Carlo Radiative Transfer clumped wind model

- INPUT FROM 1-D MODELING
  - Photospheric spectrum – without contribution of P and Si
  - Ionization fraction of P v (depth dependent)
  - Mass-loss rate (opacity parameter)
- CLUMPING PARAMETERS

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

Opacity parameter

$$\chi_L = \frac{\chi_0}{r^2 \frac{v(r)}{v_\infty}} q_{i,E}(r)\phi_x; \quad \phi_x = \frac{1}{\sqrt{\pi}} e^{-x^2}$$ (Hamann 1980)

- Parametric line opacity for a given $\dot{M}$

$$\chi_0 = \frac{\pi e^2}{m_e} f_{l,u} \frac{\lambda}{v_D v_\infty} \frac{\dot{M}}{4\pi R_*} \frac{1}{A_k m_H}$$

Constant	Value
Cross-section of the classical oscillator	$\pi e^2 (m_e c)^{-1} = 0.0265\,[\mathrm{cm}^2\ s^{-1}]$
Oscillator strength for components of P v	$f_{l,u,\mathrm{blue}} = 2\ f_{l,u,\mathrm{red}} = 0.473$
Wavelength	$\lambda_{P_v} = 1117.979 \cdot 10^{-8}$ [cm]
Mass fraction	$X_{P_v} = 5.825 \cdot 10^{-6}$
Atomic weight	$A_{P_v} = 31$
Atomic mass of hydrogen	$m_\mathrm{H} = 1.67 \cdot 10^{-24}\ [g]$

Number of clumps

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

Model parameters	Value
Inner boundary of the wind	$r_{\mathrm{min}} = 1\,R_*$
Outer boundary of the wind	$r_{\mathrm{max}} = 100\,R_*$
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	$r_{\mathrm{cl}} = 1\,R_*$
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$$f_V = \frac{1}{D}$$

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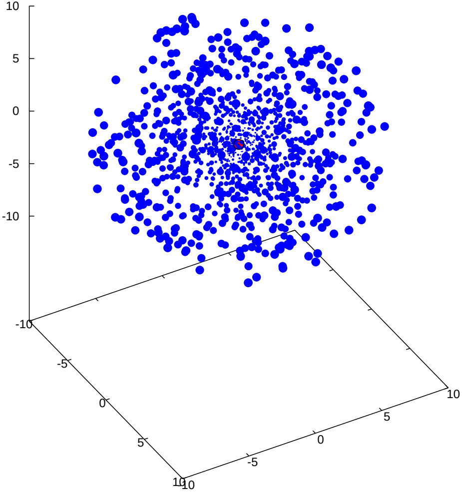
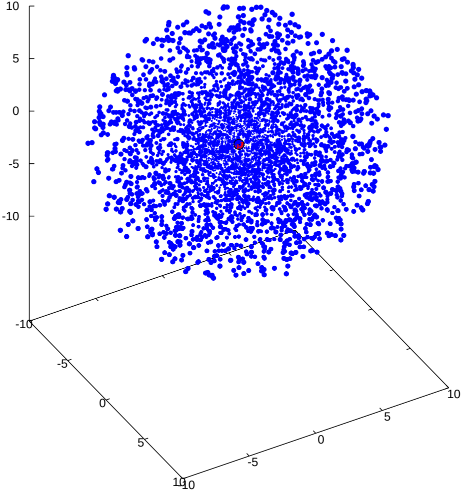
Clumps' distribution

$L_0 = 0.5\,(N_{\mathrm{cl}} = 1.13 \cdot 10^4); D = 10; d = 0$



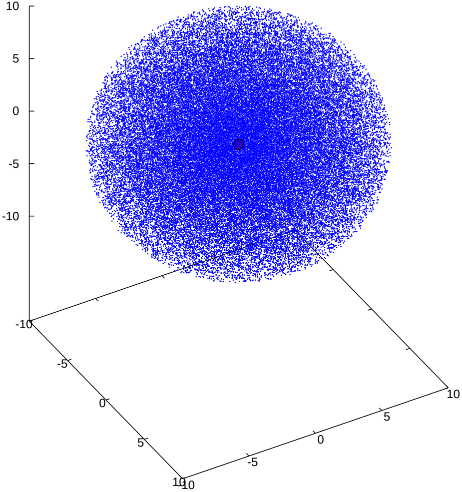
Clumps' distribution

$L_0 = 0.3\,(N_{\rm cl} = 5.17 \cdot 10^4); D = 10; d = 0$

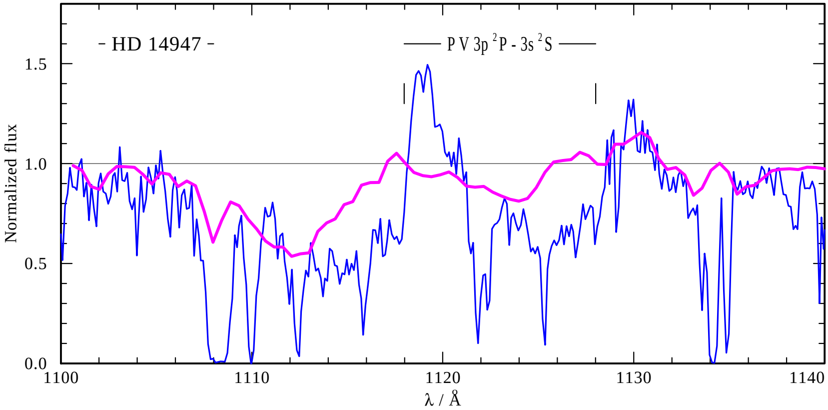


Clumps' distribution

$L_0 = 0.1\,(N_{\rm cl} = 1.40 \cdot 10^6); D = 10; d = 0$

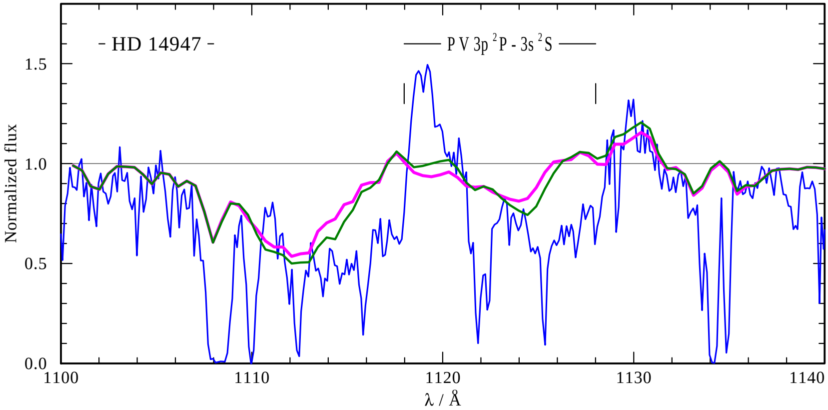


Number of clumps



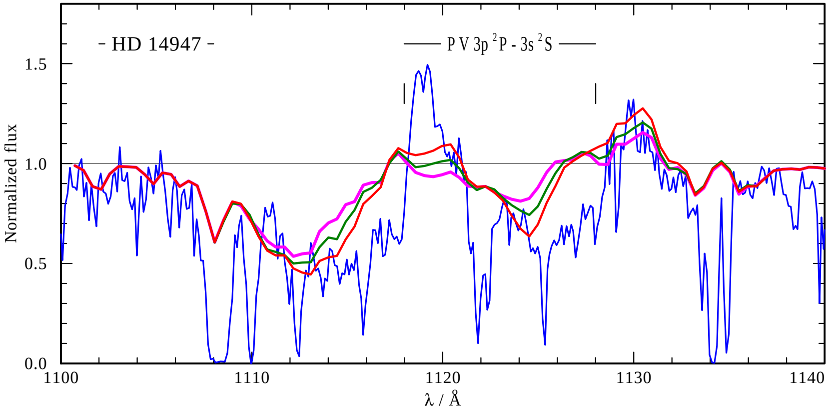
$$L_0 = 0.5\,(N_{\text{cl}} = 1.13 \cdot 10^4)$$

Number of clumps



$L_0 = 0.5\,(N_{\mathrm{cl}} = 1.13 \cdot 10^4)$ $L_0 = 0.3\,(N_{\mathrm{cl}} = 5.17 \cdot 10^4)$

Number of clumps



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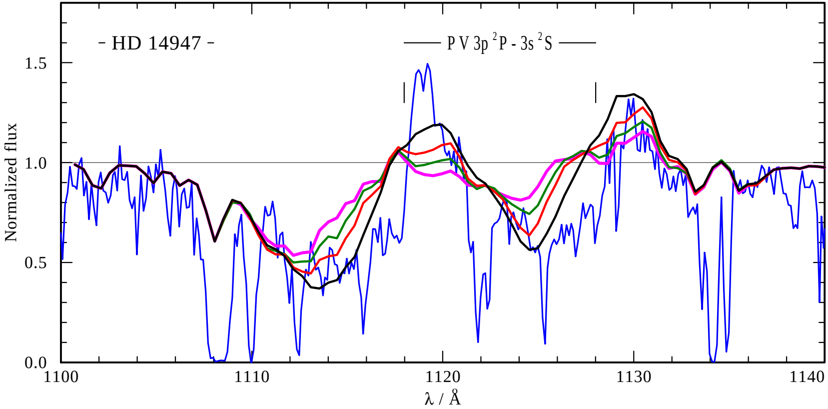
Number of clumps



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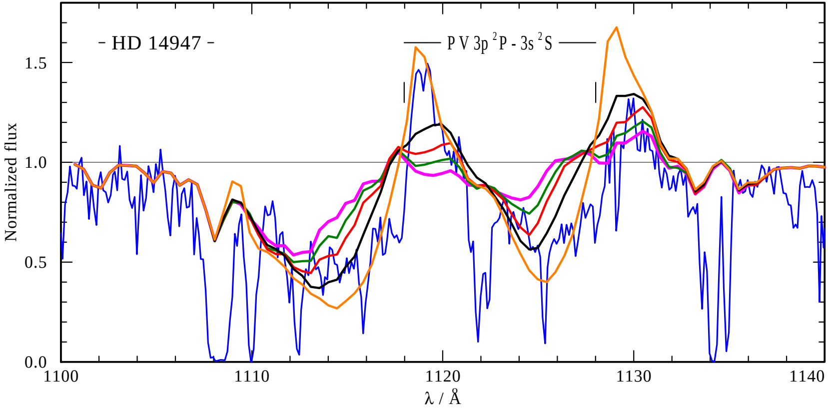

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$L_0 = 0.1\,(N_{\text{cl}} = 1.40 \cdot 10^6)$

smooth wind

Number of clumps

One-component wind (void inter-clump medium)

- even 10^6 clumps can not reproduce observed P v line profile
- Additional absorbing matter is needed
  can be put to the space between clumps (inter-clump medium)

Inter-clump medium

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

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

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

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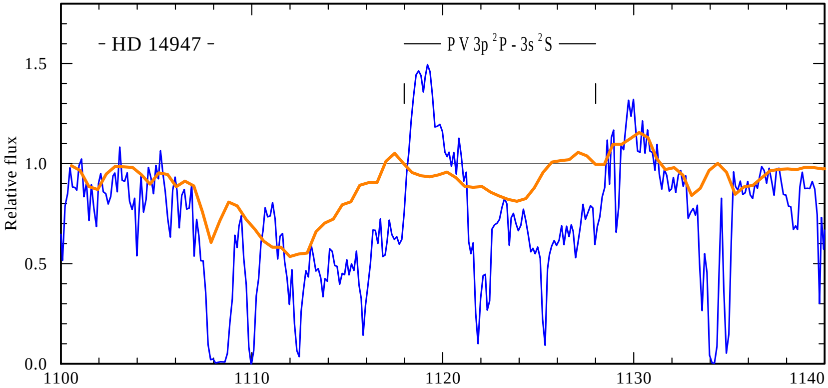
$$f_V = \frac{1-d}{D-d}$$

Inter-clump medium

$$L_0 = 0.5\,(N_{\mathrm{cl}} = 1.13 \cdot 10^4),\ r_{\mathrm{cl}} = 1$$



$d = 0$

Inter-clump medium

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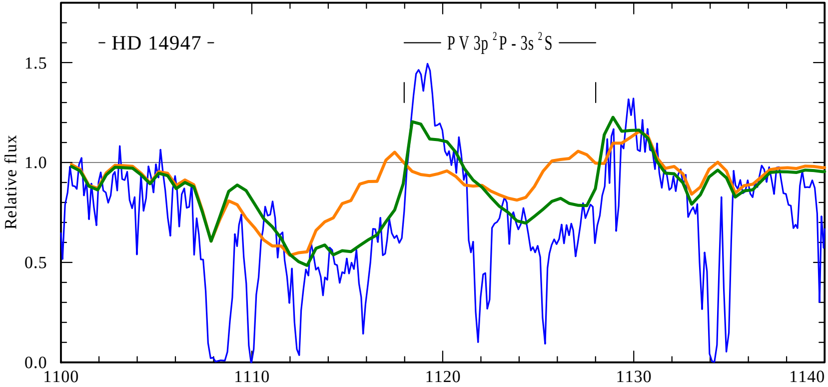

$d = 0$, $d = 0.1$

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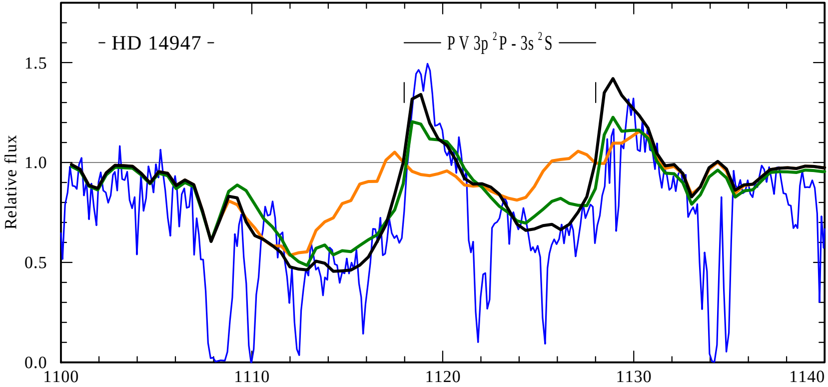

$d = 0$, $d = 0.1$, $d = 0.25$

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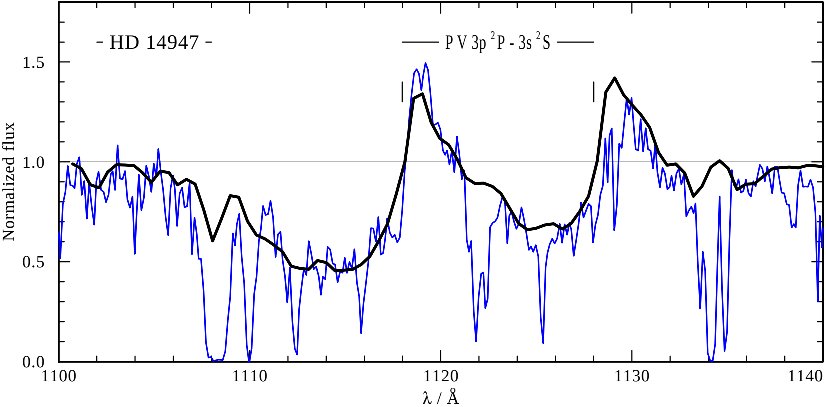

$$d = 0.25$$

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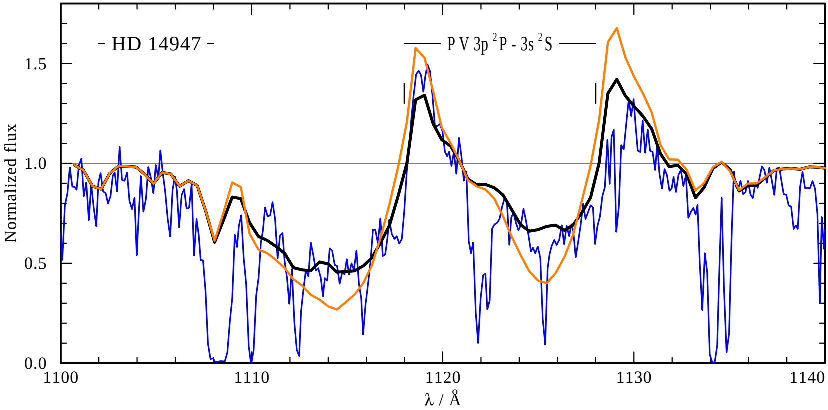


$d = 0.25$

smooth wind

Inter-clump medium

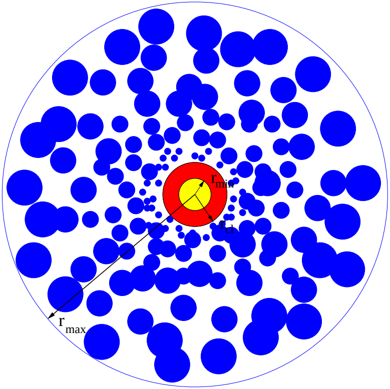
Two-component wind (non-void inter-clump medium)

- Two-component wind is more realistic
- Different combinations of L_0 and d may give equally good agreement with observation
- **Inter-clump medium can not be void!!!**

Onset of clumping

- HD simulations ⇒ clumping starts above photosphere

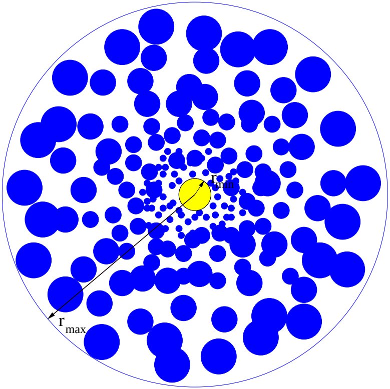
$$L_0 = 0.5\ (N_{\text{cl}} = 1.13 \cdot 10^4),\ r_{\text{cl}} = 1.1$$



- SMOOTH region
  ($r_{\text{min}} < r < r_{\text{cl}}$; $r_{\text{min}} = R_*$)
- CLUMPED region
  ($r_{\text{cl}} < r < r_{\text{max}}$)
  Two density components:
  ICM and CLUMPS

Onset of clumping

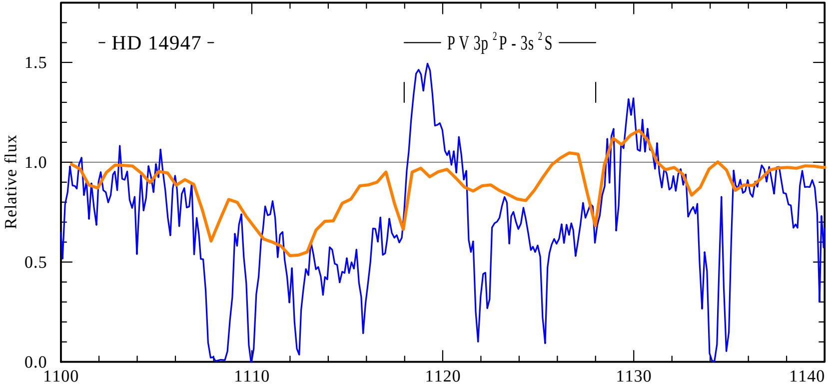
$$L_0 = 0.5\ (N_{\rm cl} = 1.13 \cdot 10^4),\ r_{\rm cl} = 1$$



- 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

Onset of clumping

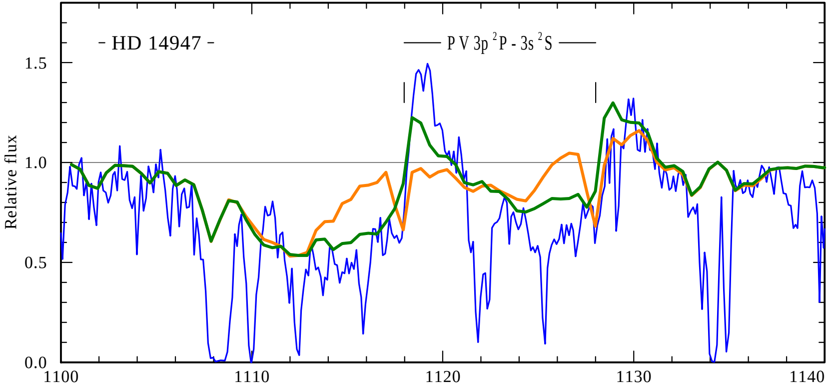
$$L_0 = 0.5\ (N_{\mathrm{cl}} = 1.13 \cdot 10^4),\ r_{\mathrm{cl}} = 1.1$$



$d = 0$

Onset of clumping

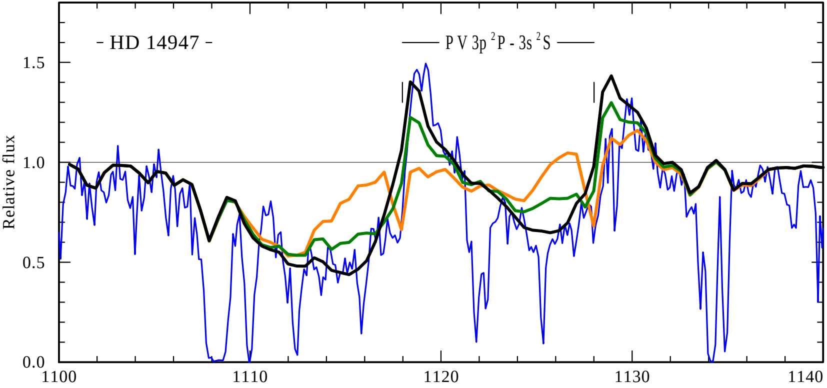
$$L_0 = 0.5 \ (N_{\text{cl}} = 1.13 \cdot 10^4), \ r_{\text{cl}} = 1.1$$



$d = 0$, $d = 0.1$

Onset of clumping

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

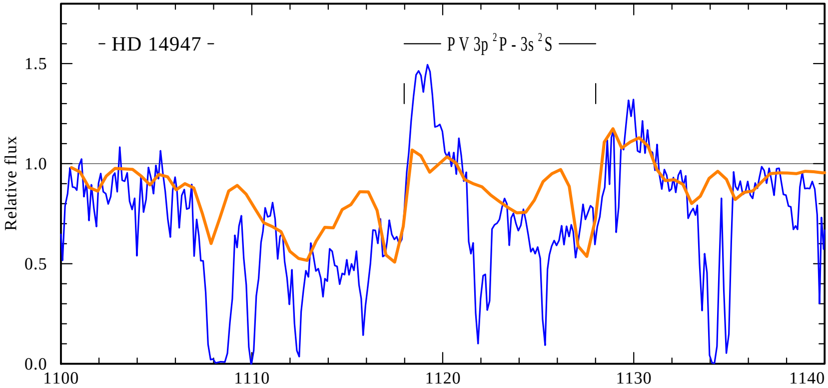


$d = 0$, $d = 0.1$

$d = 0.25$

Onset of clumping

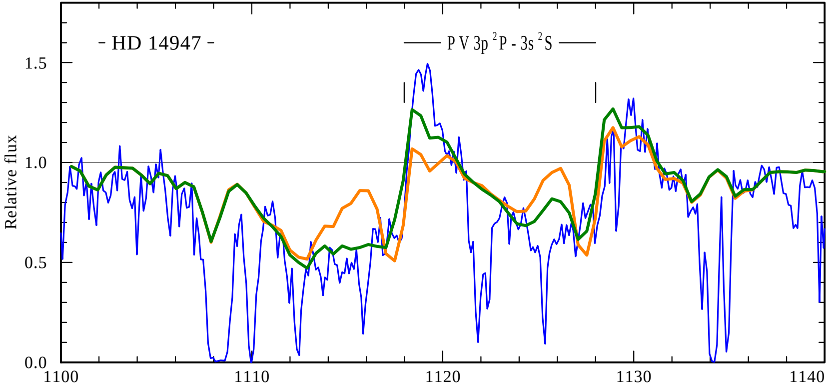
$$L_0 = 0.5\ (N_{\mathrm{cl}} = 1.13 \cdot 10^4),\ r_{\mathrm{cl}} = 1.3$$



$d = 0$

Onset of clumping

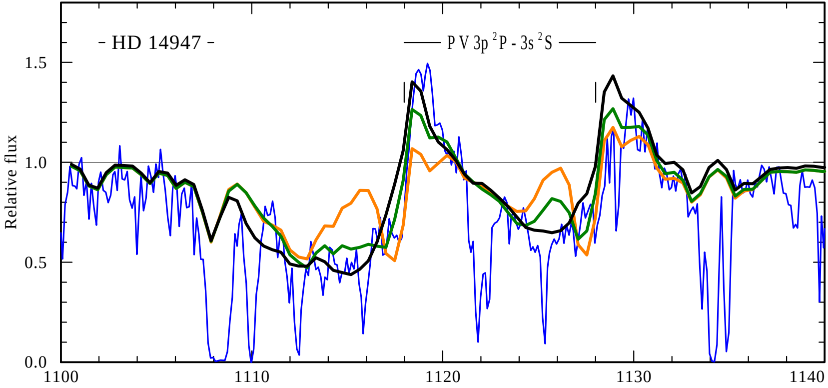
$$L_0 = 0.5\ (N_{\mathrm{cl}} = 1.13 \cdot 10^4),\ r_{\mathrm{cl}} = 1.3$$



$d = 0$, $d = 0.1$

Onset of clumping

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

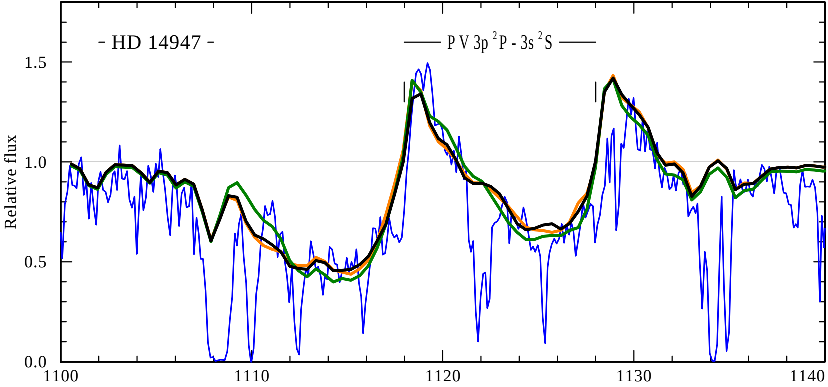


$d = 0$, $d = 0.1$

$d = 0.25$

Onset of clumping

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



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

Onset of clumping

One-component wind

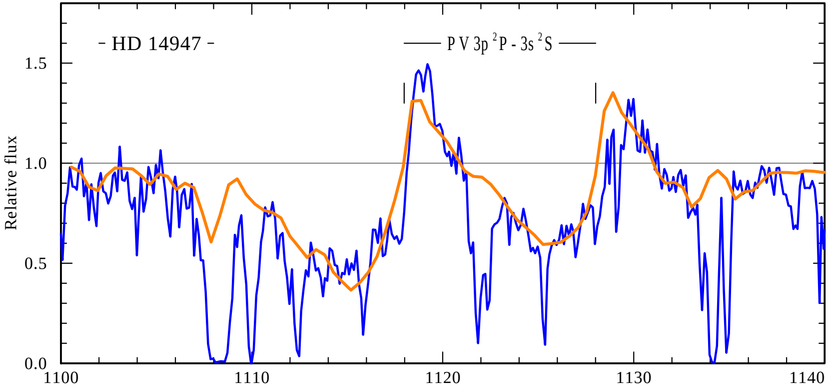
- wind clumping has to start at the surface of the star
  otherwise absorption dip appears

Two-component wind

- inter-clump medium hides spectral signature of onset of clumping
- different combination of r_{cl} and d may give very similar agreement with observations

Velocity dispersion – “vorosity”

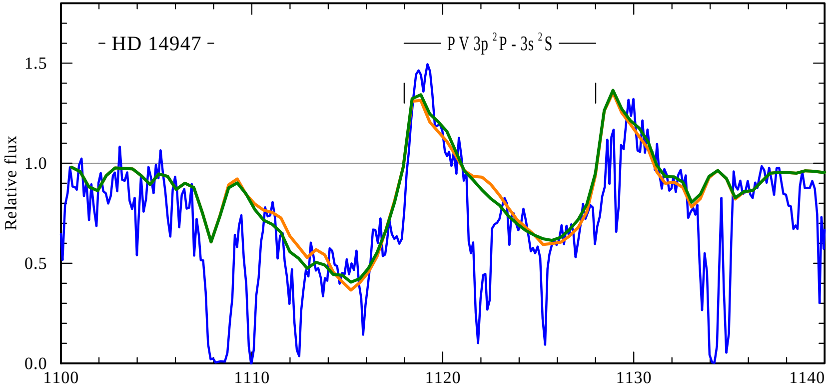
$$L_0 = 0.5\ (N_{\text{cl}} = 1.13 \cdot 10^4),\ r_{\text{cl}} = 1,\ d = 0.25$$



$v_{\text{dis}} / v_\beta = 0.01$

Velocity dispersion – “vorosity”

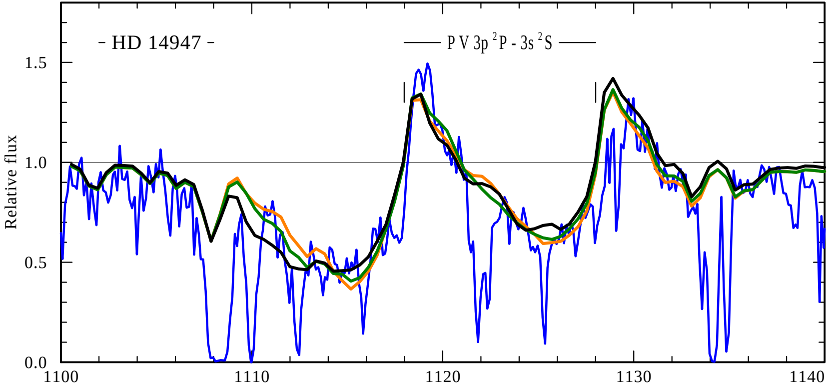
$$L_0 = 0.5\ (N_{\rm cl} = 1.13 \cdot 10^4),\ r_{\rm cl} = 1,\ d = 0.25$$



$v_{\rm dis}/v_\beta = \mathbf{0.01}$, $v_{\rm dis}/v_\beta = \mathbf{0.1}$

Velocity dispersion – "vorosity"

$$L_0 = 0.5\ (N_{\text{cl}} = 1.13 \cdot 10^4),\ r_{\text{cl}} = 1,\ d = 0.25$$



$v_{\text{dis}}/v_\beta = 0.01$, $v_{\text{dis}}/v_\beta = 0.1$

$v_{\text{dis}}/v_\beta = 0.2$

Velocity dispersion – “vorosity”

“Vorosity’

- mainly affects outer part of the wind (extending absorption beyond v_∞)
- insignificant reduction of line strength

Global clumping properties

Fixed clumped model parameters used in our 3-D MC code to fit the observed P v lines

Model parameters	Value
Inner boundary of the wind	$r_{\rm min} = 1\,R_*$
Outer boundary of the wind	$r_{\rm max} = 100\,R_*$
Clump separation parameter	$L_0 = 0.5$
Clumping factor	$D = 10$
Set-up of clumping	$r_{\rm cl} = 1\,R_*$
Velocity at the photosphere	$v_{\rm min} = 10$ [km/s]
Doppler velocity	$v_{\rm D} = 20$ [km/s]

Derived clumping parameters

Star	Interclump medium density factor d	Velocity deviation $v_{\rm dis}$	$\dot{M}$ $[10^{-6}]$ $M_\odot$/yr
HD 66811	0.15	0.25	2.51
HD 15570	0.40	0.20	2.75
HD 14947	0.25	0.20	2.82
HD 210839	0.25	0.10	1.62
HD 192639	0.10	0.01	1.26

Summary

- 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., in preparation

THANK YOU FOR YOUR ATTENTION!