# Mass-loss rates of hot stars

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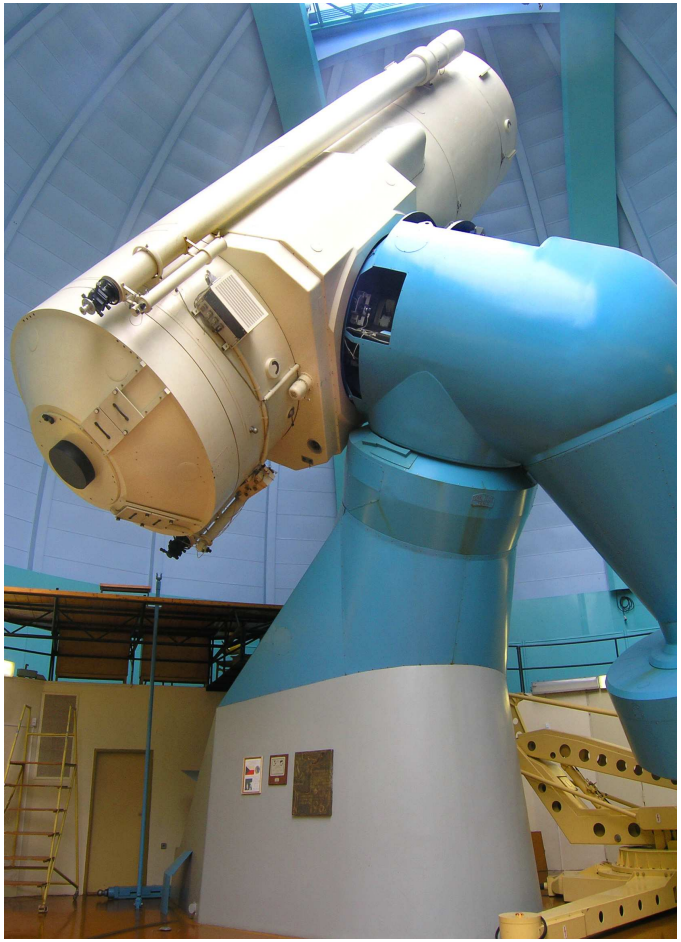
# Outline

# Perek 2-m telescope in Ondřejov

| | | |
|---|---|---|
| Primary mirror: | Diameter: | 2m |
| Focal length: | Primary: | 9m |
| | Cassegrain: | 29.16m |
| | coudé: | 63.5m |

- operating since 1967
- new control system since 2008
- used for coudé spectroscopy
  - medium resolution spectrograph
  - slit echelle spectrograph



dominant research: hot stars

N: 49°54′54.6″
E: 14°46′51.6″

# Hot stars and their winds

## HOT STARS

- O type ($T_{\rm eff} > \gtrsim 30000$ K)
- luminous ($L > 10^6 L_\odot$)
- massive ($M \sim 10 - 50 M_\odot$)
- short lifetimes ($\sim 10^6$ years)
- end as supernova explosion
- very rare
- small fraction of the stellar population

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Importance:

- can be seen at large distances
- heat-up, ionize, or facilitate chemical reactions in ISM
- provide kinetic energy (stellar winds, supernovae)
- enrich ISM with heavier elements (metals)
- trigger, regulate and terminate star formation in stellar clusters

# Hot stars

## Stellar wind

- outflow of material from the stellar surface
- mass-loss rate $\frac{\mathrm{d}M}{\mathrm{d}t}$ up to $10^{-6}\ M_\odot$ year$^{-1}$
- terminal velocity $v_\infty$ up to $\sim 3000\ \mathrm{km\,s^{-1}}$
- outflow driven by radiation
  - continuum (electron scattering + b-f + f-f)
  - line (resonance lines of metals)
  - H, He $\rightarrow$ negligible radiation force
  - momentum transferred by Coulomb collisions

- observations
- theoretical background and modelling

# Wind hydrodynamical models

## standard assumptions

- stationary homogeneous spherically symmetric

## solution of hydrodynamic equations

- continuity equation ($\rho$)
- equation of motion ($v$)
- energy equation ($T$)

## influence of radiation on the wind

- radiation pressure (driving force)
- occupation numbers (NLTE) $\Rightarrow$ opacities

# Radiation force in wind hydrodynamical models

$$g_{\mathrm{rad}} = \frac{\pi}{c\rho} \int_0^\infty \chi(\nu) F(\nu) \mathrm{d}\nu$$

## force multipliers

- $k$, $\alpha$, $\delta$ (Castor, Abbott, Klein 1975)
- free parameters with interpretation ($\delta$ – ionization balance, $\alpha$ – line distribution, $k$ – line strength)

## detailed calculation using occupation numbers

- Monte Carlo calculations (Vink et al. 1999)
- NLTE calculations (Krtička & Kubát 2004)

# Wind hydrodynamical models

## input

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

## output

- $v(r)$ (velocity $\rightarrow v_\infty$) – measured from line profiles
- $\rho(r)$ (density $\rightarrow \frac{\mathrm{d}M}{\mathrm{d}t} = \dot{M}$)
- $T(r)$ (temperature)

# Mass-loss rate determination

using fit of selected observed spectral features with a model prediction (often very simplified wind models)

## Determination of mass-loss rates

- for *given* $v(r)$ and $\rho(r)$ (consequently $\frac{\mathrm{d}M}{\mathrm{d}t}$ and $v_\infty$) determine the emergent radiation
- compare with observations

common assumption – $\beta$-velocity law

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

Milne (1926) and Chandrasekhar (1934): $\beta = 0.5$

# Mass-loss rate determination methods

## radio measurements

(Panagia & Felli 1975; Wright & Barlow 1975)

- outermost wind regions ($\sim 100\,R_*$)
- simplified conditions (completely ionized gas, LTE, spherical symmetry, $\mathrm{d}v/\mathrm{d}r = 0$, $n_\mathrm{e} \sim r^{-2}$, only free-free opacity)
- known $F_\mathrm{radio}$, distance to the star, $v_\infty \quad \Rightarrow \quad \dot{M}$
- (+) 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 rate determination methods

## H$\alpha$ line profiles

- H$\alpha$ emission originates in inner regions of the wind
- comparison of observed H$\alpha$ line profiles with theoretical profiles calculated using the $\beta$-velocity law
- mass-loss rate corresponding to the model with the best fit is then called *observed mass loss rate*
- calculations often based on NLTE model atmospheres with a given velocity field
- core-halo approach
- 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 rate determination methods

## H$\alpha$ line profiles

Markova et al. (2004, 2005), Markova & Puls (2008) – determination of mass-loss rates using H$\alpha$ observations using the Rozhen 2-m telescope

# Mass-loss rate determination methods

## UV (resonance) line profiles

- $\dot{M} q_i$ can be determined ($q_i$ – ionization fraction)
- saturated resonance lines (C IV, N V) indicate lower limit of $\dot{M}$
- unsaturated lines are more sensitive

## P V "problem" 1118, 1128 Å

? P V mass-loss rates are wrong

? ionization fraction of P V is lower than 0.1

- lower ionization fraction does not seem to be the answer, neither additional X-ray nor XUV radiation are able to lower it (Krtička & Kubát 2009, 2012)

# Comparison of measurement methods

- radio measurements
- H$\alpha$ line profiles
- UV (resonance) line profiles

Different mass-loss diagnostics result in different mass-loss rates (e.g. Bouret et al., 2003, 2005; Fullerton et al., 2006)

# Comparison of measurement methods

$\rho^2$ radio measurements

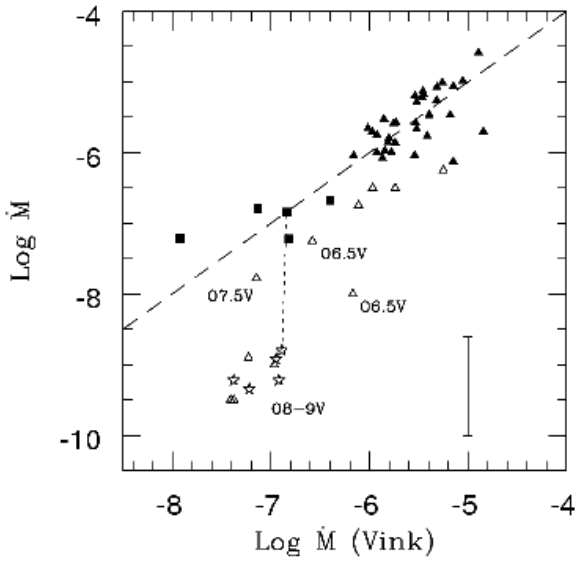
$\rho^2$ H$\alpha$ line profiles

$\rho$ UV (resonance) line profiles

Different mass-loss diagnostics result in different mass-loss rates (e.g. Bouret et al., 2003, 2005; Fullerton et al., 2006)

# Comparison between observations and theory

## Weak wind problem



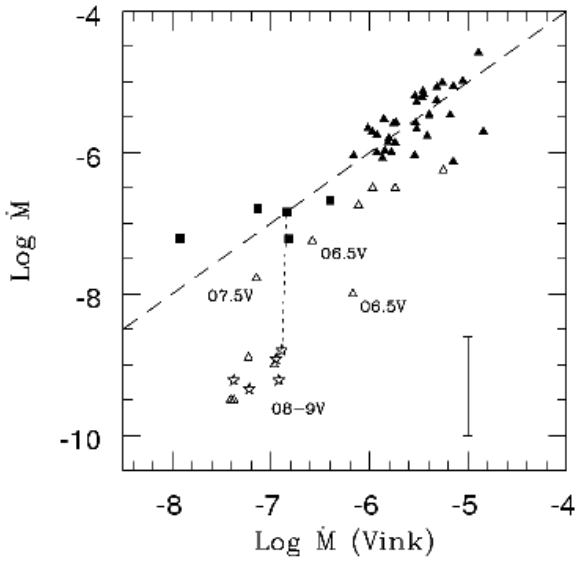

Marcolino et al. 2009, A&A 498, 837

- difference between "observed" and predicted mass-loss rates for some stars

| | theoretical | "observed" |
|---|---|---|
| $\mu$ Col | $7.9 \cdot 10^{-9}$ | $3.2 \cdot 10^{-10}$ |
| | ($M_\odot$ year$^{-1}$) | |

# Comparison between observations and theory

## Weak wind problem

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clumping – possible way to correct the disagreement

# Clumping in stellar winds

## Observational evidence of clumping

Eversberg et al. (1998)

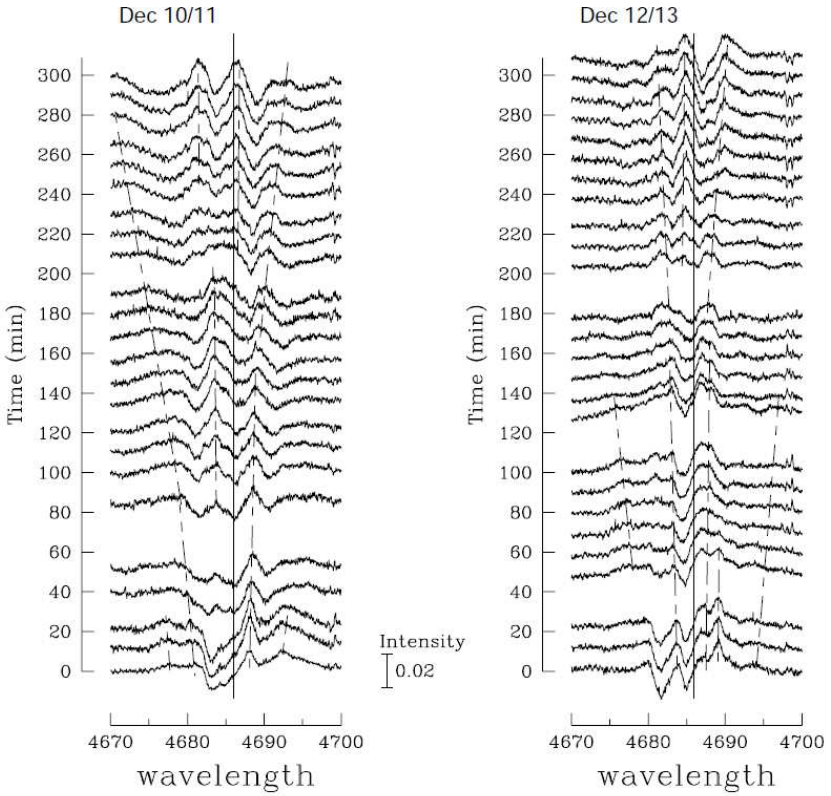


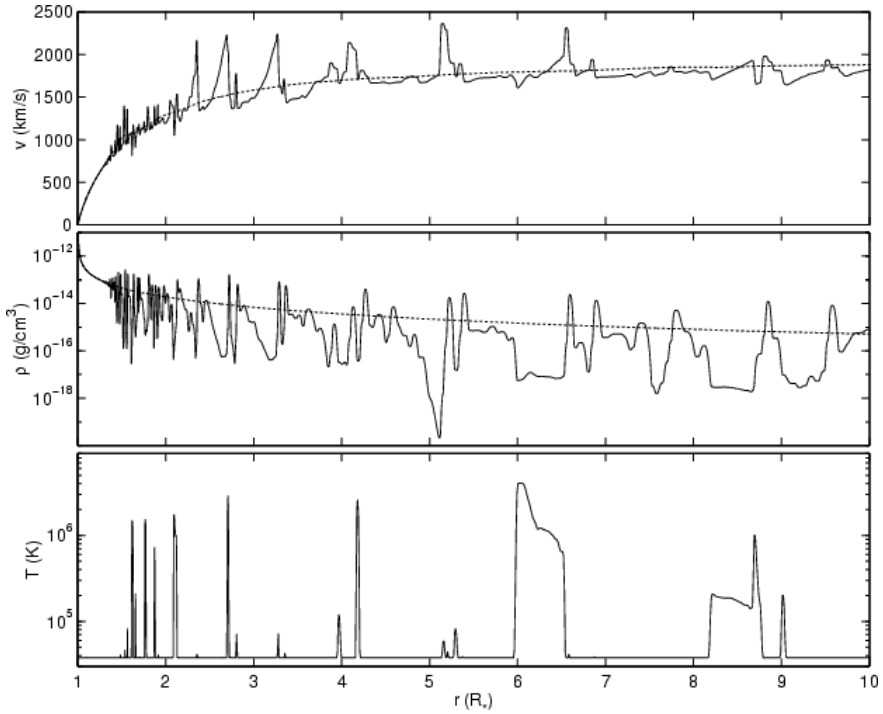

FIG. 1.—Residuals of He II 4686 for ζ Pup on 1995 December 10/11 and 12/13. The vertical axis gives the intensity and the time, respectively. The scale for the residual intensities is indicated. Dashed lines trace detected variations during the night. Vertical solid lines indicate the rest wavelength.

- small scale wind structures in both density and velocity

# Clumping in stellar winds

## Theoretical evidence of clumping

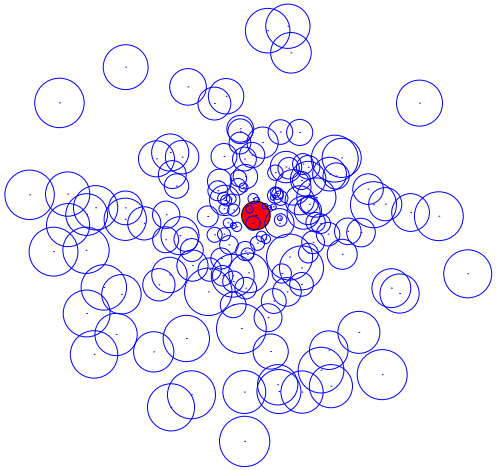
from 1-D radiative hydrodynamic simulations




Runacres & Owocki (2002)

# Modelling of wind clumping

- stellar wind clumping – many unknown details
- simplifying assumptions
- description using adjustable parameters



- all wind matter concentrated to clumps (“clumps in vacuum”)
- optically thin clumps (microclumping)
- (volume) filling factor

$$f = \frac{V_{\text{clumps}}}{V_{\text{wind}}}$$

or clumping factor

$$D = C_{\text{c}} = f_{\text{cl}} = \frac{\rho_{\text{clumps}}}{\langle \rho_{\text{wind}} \rangle} = \frac{1}{f}$$

# Modelling of wind clumping

## microclumping

- all clumps optically thin
- $\rho_{\text{clumps}} = D\langle\rho_{\text{wind}}\rangle \qquad (D > 1)$
- $\chi = (1/D)\chi_{\text{clumps}}(\rho_{\text{clumps}})$
- $\chi \sim \rho$ – same as smooth wind
- $\chi \sim \rho^2$ (recombination, free-free) – opacity is higher

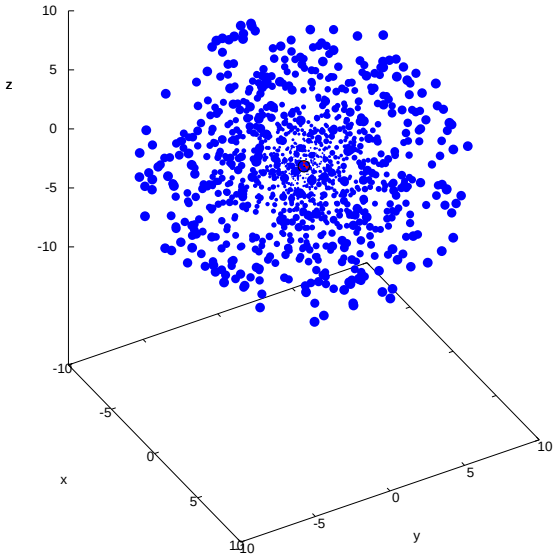
## macroclumping (porosity)

- clumps may be optically thick
- matter is shielded from radiation
- some opacity if effectively “lost”
- $\chi$ dependence more complicated

# Modelling of wind clumping

## modelling of macroclumping

Šurlan et al. 2012, A&A 541, A37; see also poster



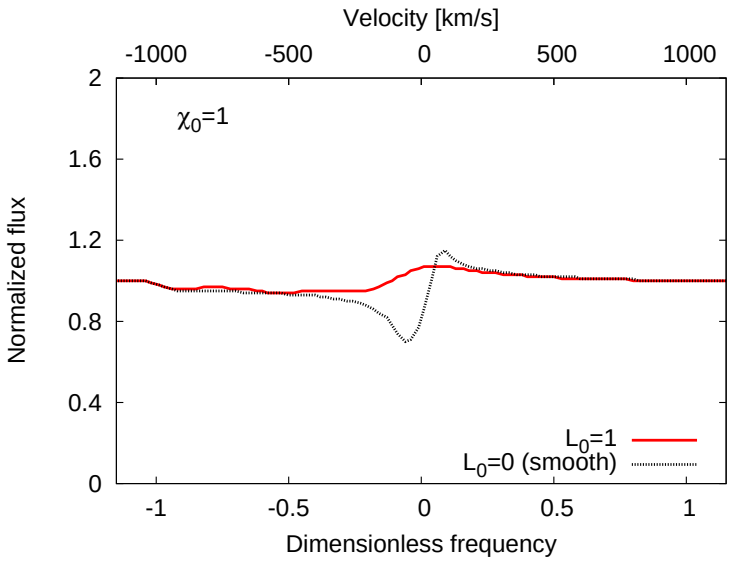

## assumptions

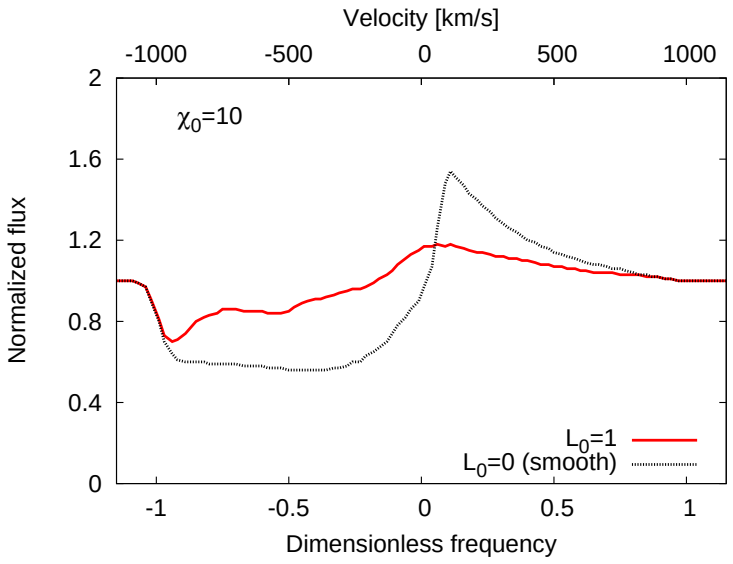
- clumps may be optically thick – macroclumping / porosity
- non-void interclump medium
- spherical clumps
- probability distribution of clumps
- pure scattering

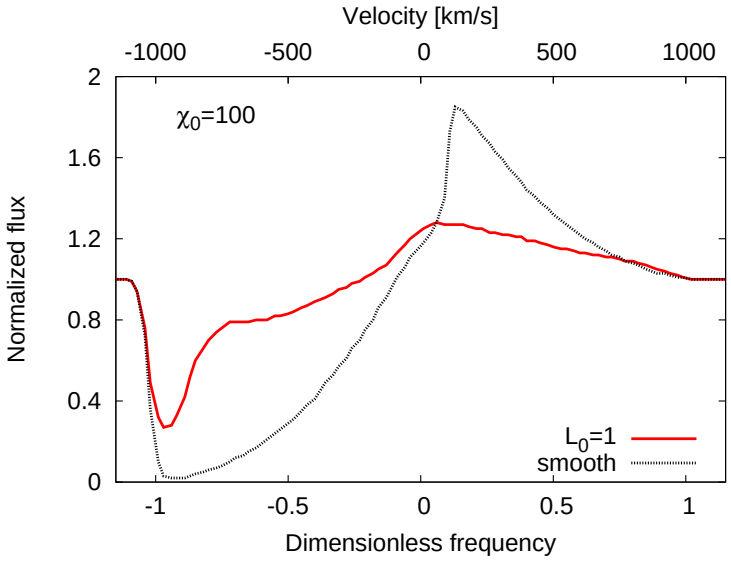
## method of solution

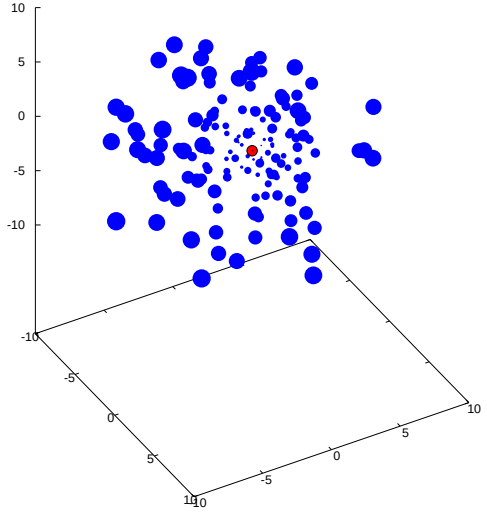
- Monte Carlo radiative transfer

# Effect of the macroclumping on resonance line profiles



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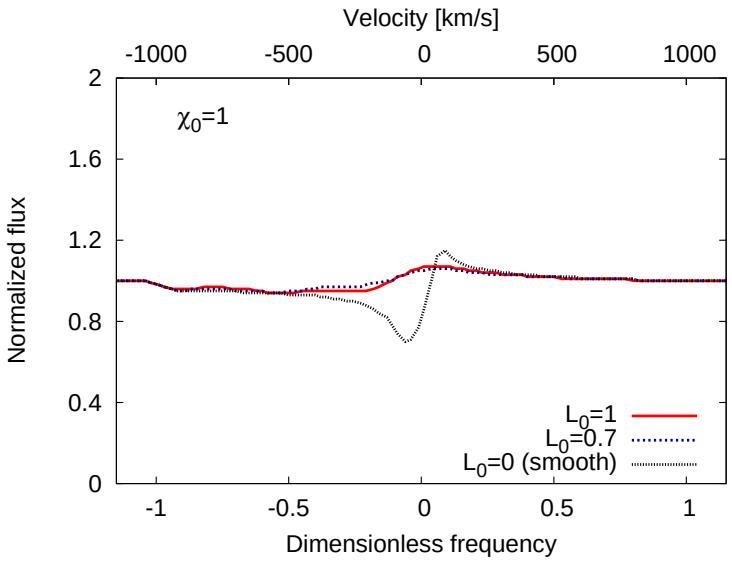


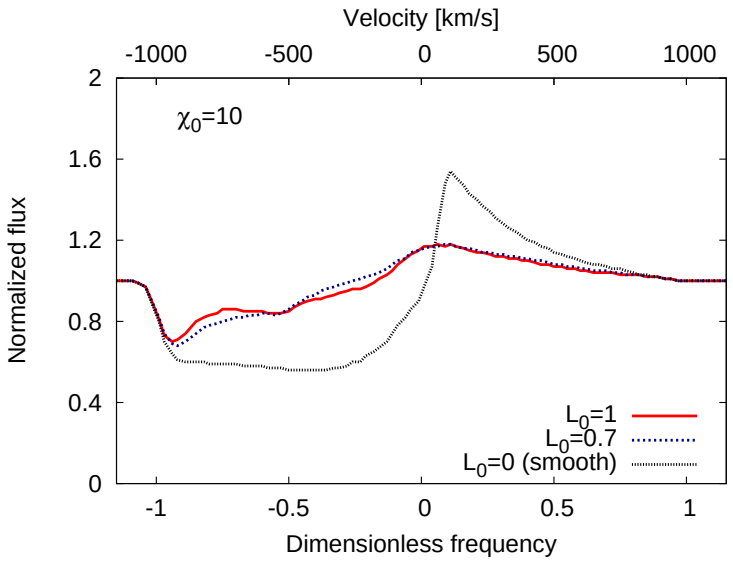


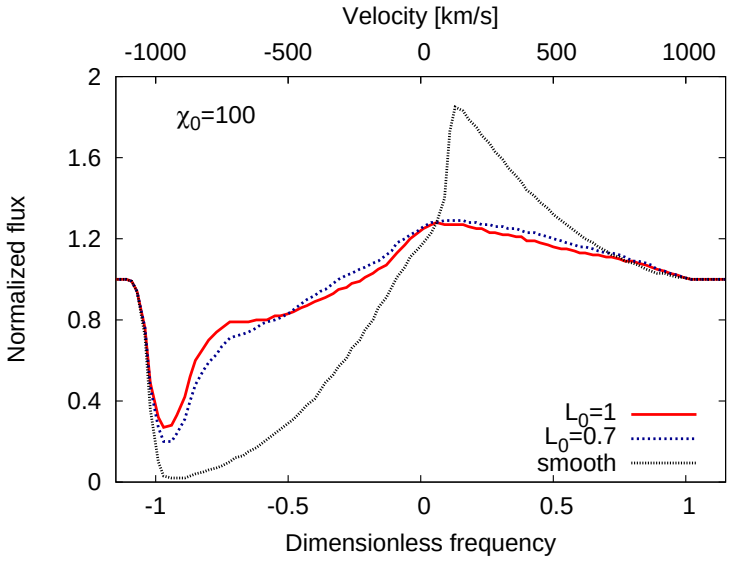


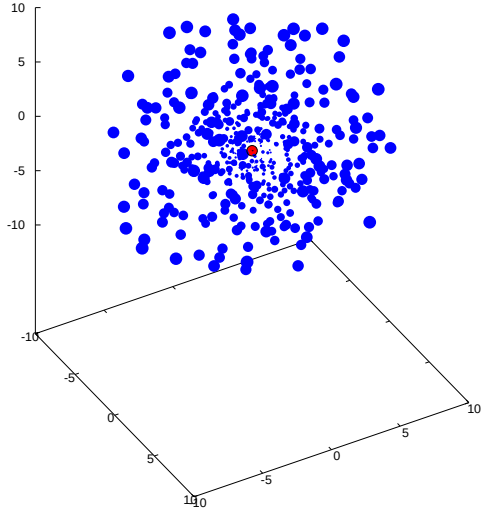

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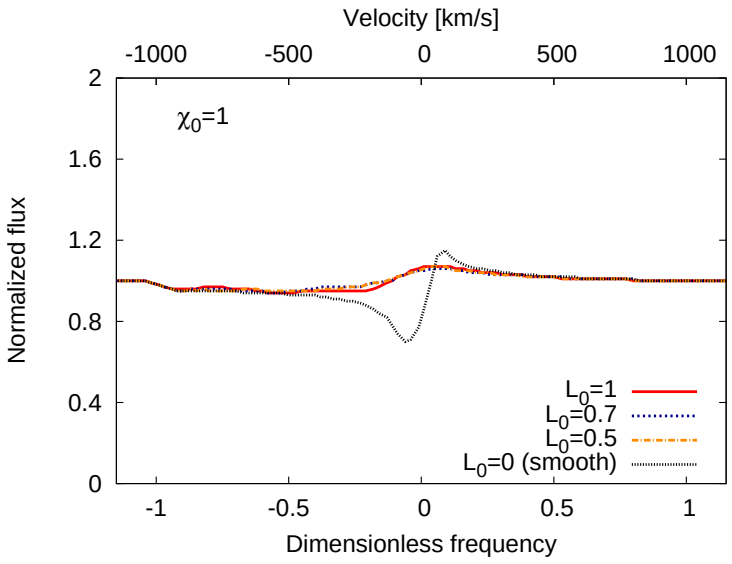


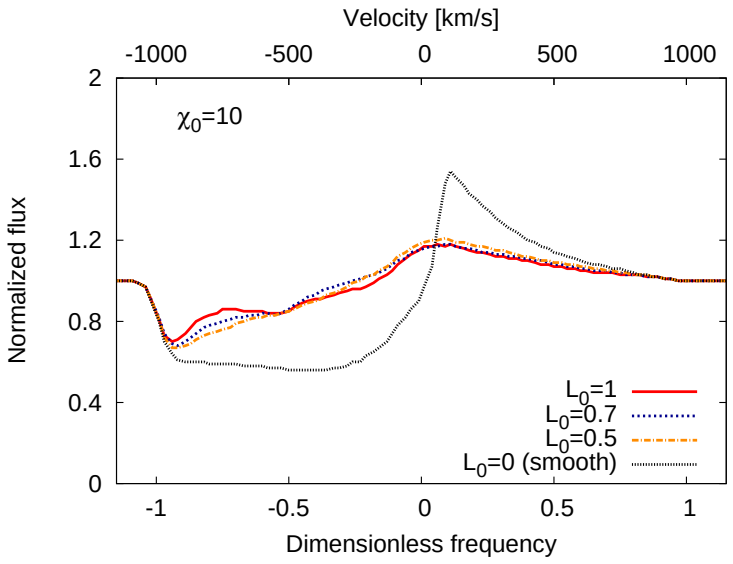


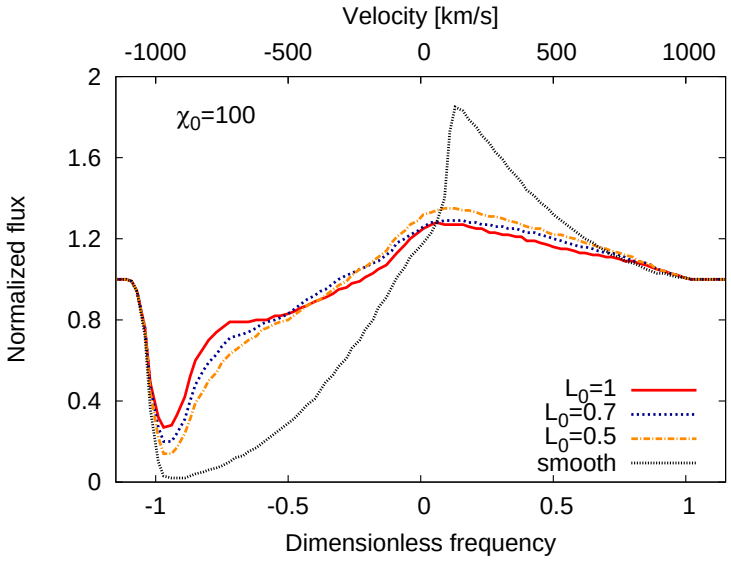


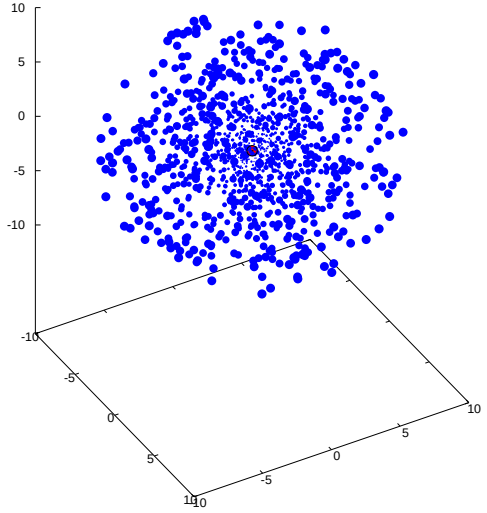

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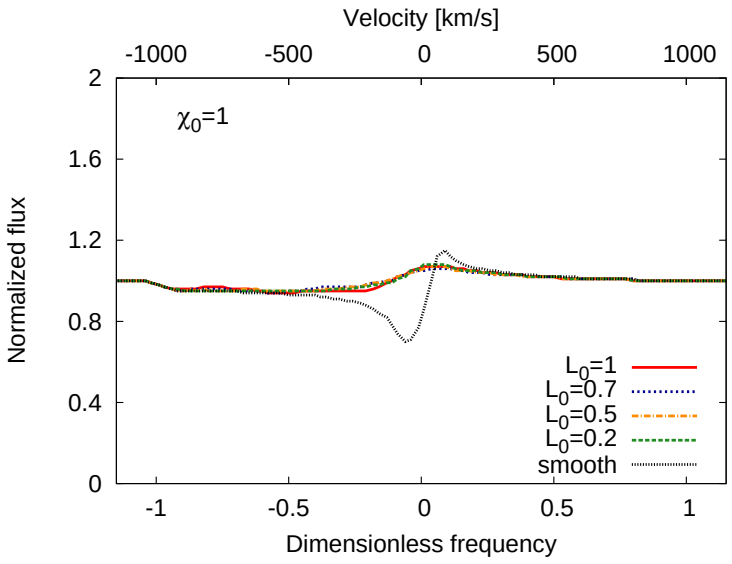
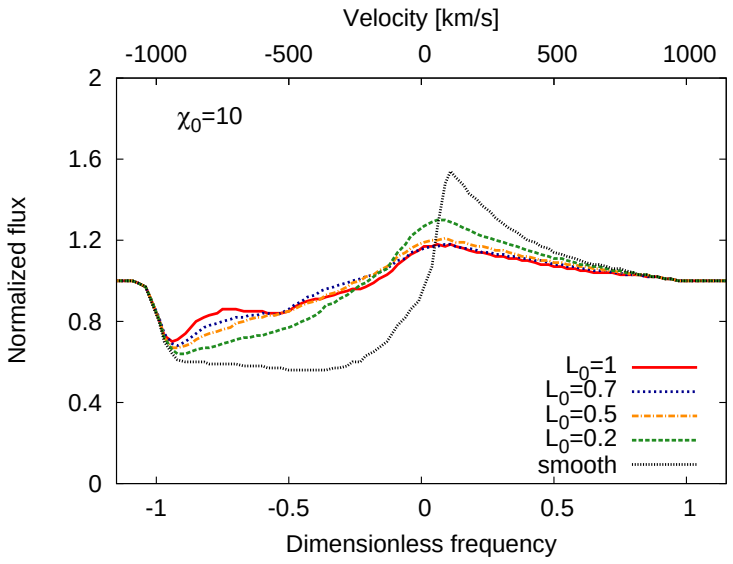
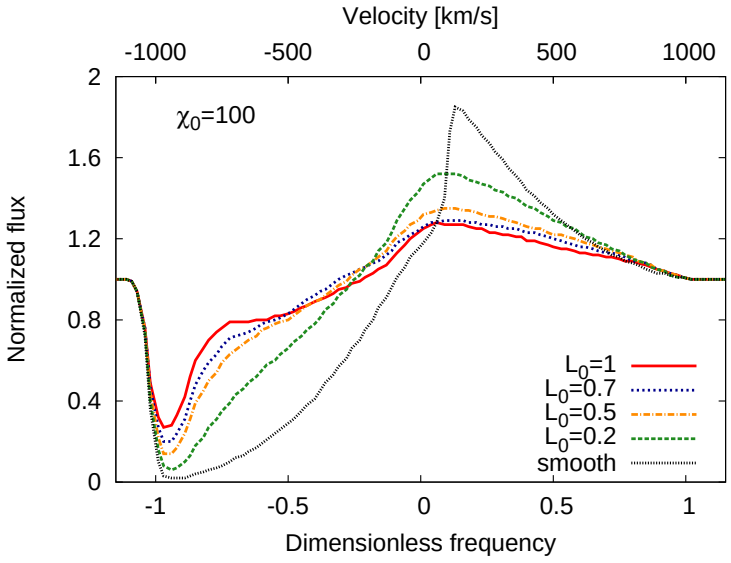
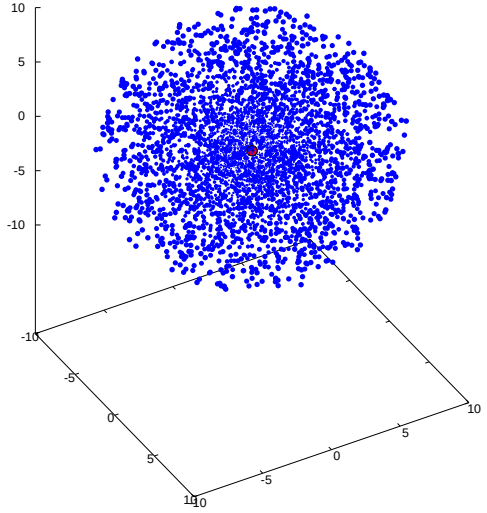


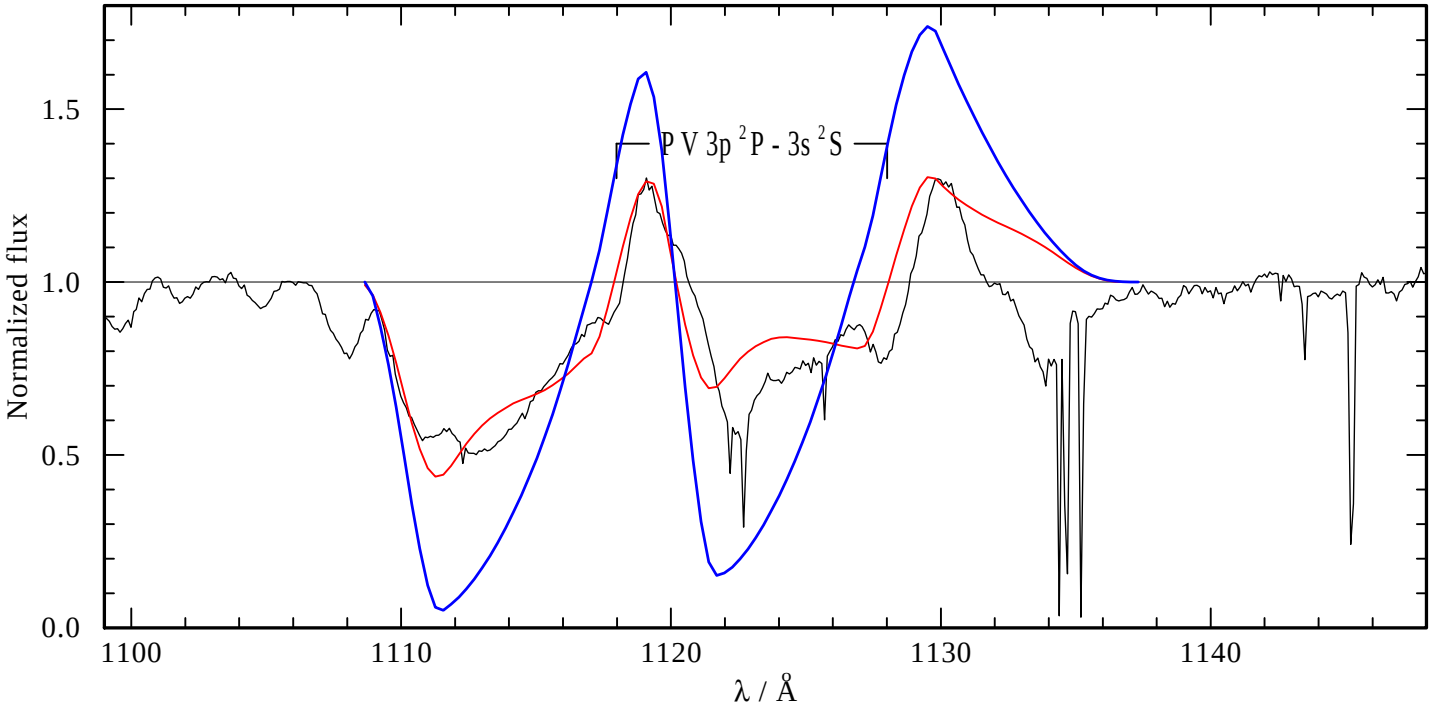



# Other effects of the macroclumping

- velocity clumping (vorosity)
- non-void inter-clump medium
- onset of clumping
- effect on mass-loss rate determination

# Other effects of the macroclumping

## $\zeta$ Pup




COPERNICUS (black line);
the smooth model;
the clumped model

($v_\infty = 2250\,\mathrm{km\,s^{-1}}$, $v_D = 60\,\mathrm{km\,s^{-1}}$, $L_0$=0.5 $R_*$, $D$=10, $d$=0.03, $v_{\mathrm{dis}}/v_\beta$=0.05)

# Summary

- despite sophisticated theory mass-loss rates of hot stars are still not firmly determined
- multiwavelength observations necessary for mass-loss rate determination
- line profiles in clumped wind strongly depend on clump properties
- observational study of clumping in bright stars winds – suitable program for small telescopes