WINDS OF HOT MASSIVE STARS

IV Lecture: Wind inhomogeneities

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Selected Topics in Astrophysics
Faculty of Mathematics and Physics
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1. Small and large scale wind structures
2. Observational evidence
3. Theoretical predictions
4. Wind models with clumping
5. Open questions

Observational findings

- Standard wind model - a stationary, spherically symmetric smooth stellar wind in radiative equilibrium
- Observational findings - non-stationarity, clumpiness, shocks and deviation from spherical symmetry and radiative equilibrium

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- more obvious reason - appropriate inclusion of deviation from the standard model requires a significant effort in the diagnostics and a development of new radiative transfer methods

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STANDARD WIND MODEL IS INCAPABLE OF DESCRIBING NUMBER OF OBSERVATIONAL PHENOMENA

Large-scale wind structure

Narrow absorption components (NACs)

- optical depth enhancements in the absorption troughs of P-Cygni profiles
- Howarth & Prinja (1989) - large survey of 203 Galactic O stars observed with IUE; NACs universal phenomena

Large-scale wind structure

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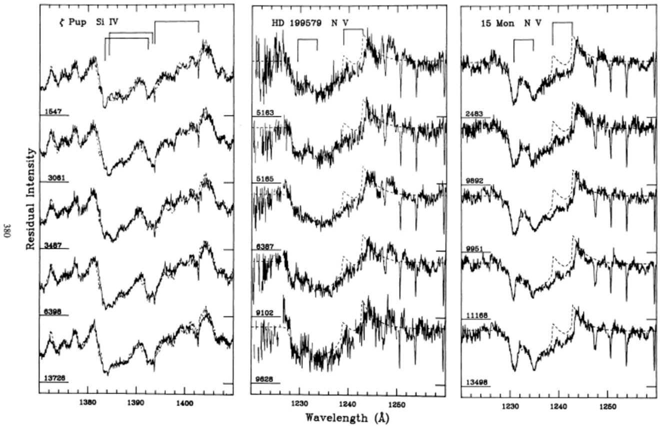

FIG. 1.—Selected N v, C IV, and Si IV spectra for stars showing unsaturated P Cygni profiles and/or narrow absorption components in these doublets. Zero levels and corresponding SWP image numbers are shown for each spectrum, and are separated by 1.2 times the adopted pseudocontinua. Dashed lines are the adopted model fits; the rest wavelengths and mean narrow component positions are also indicated.

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- Lamers at al., (1982) - NACs are interpreted in terms of persistent structures in the wind
- Prinja & Howarth (1986) - NACs vary on time scale of a day or less

Large-scale wind structure

Narrow absorption components (NACs)

From Prinja et al. (1992) - ζ Pup

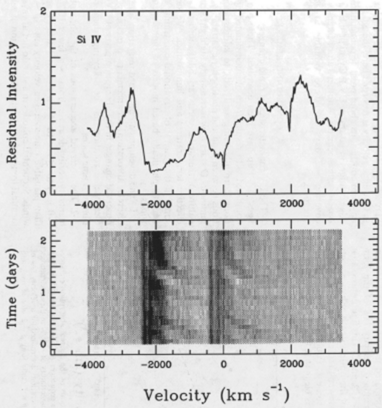

Fig. 2

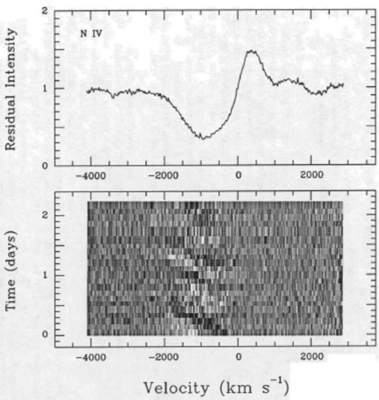

Fig. 3

Fig. 2.—Gray-scale representations of variability in Si IV for the intensive series of observations (SWP 36092–36145). Residual spectra are shown with respect to a fixed underlying P Cygni profile. The mean of the observed Si IV profiles is shown in the upper panel. The formation and progression of four discrete absorption components may be identified, together with two relatively fixed "narrow absorption components" at ~ -2100 and -2300 km s^{-1} (§ 3.1).

Fig. 3.—Same as Fig. 2, except for N IV λ1718.55. The gray-scale image shows residuals from the mean profile.

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Periodic absorption modulations

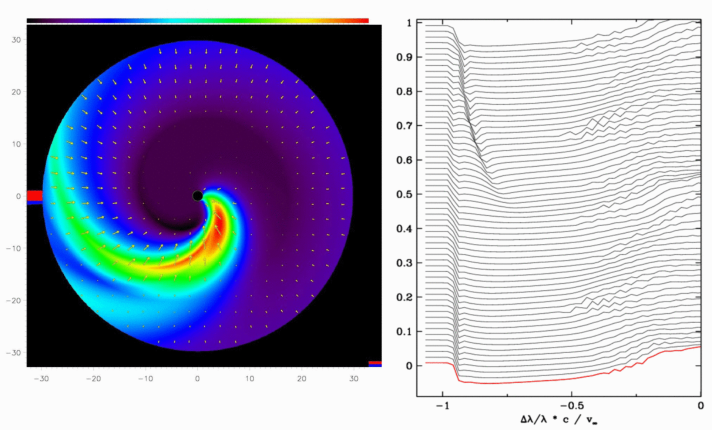
- period of variability different than the stellar rotation period
- variations are due to modulation of the optical depth in the absorption trough
- affect a broad range of velocities nearly simultaneously
- azimuthally extended structure exits the line of sight to a observer - Owocki et al. (1995)
- phase bowing - the presence of longitudinally extended (spiral-shaped) structures in the wind

Co-rotating Interaction Regions

- Mullan (1984) - CIRs are cyclical variability in hot the winds
- interactions between fast and slow streams
- hydrodynamic models of CIRs have been proposed to explain the observed DACs properties qualitatively
- CIRs can be produced by intensity irregularities at the stellar surface, such as dark and bright spots, magnetic loops and fields, or non-radial pulsations
- the surface intensity variations alter the radiative wind acceleration locally, which creates streams of faster and slower wind material
- CIR wind structure produces a DAC in the wind profile that drifts from small to large velocities (Cranmer & Owocki, 1996, Lobel et al., 2008)

Co-rotating Interaction Regions

From Lobel et al. (2008) - Wind model of a hot star with one CIR in the plane of the equator due to a rotating bright spot at the stellar surface. Right-hand panel: The CIR density- and velocity-structure perturbs the smooth accelerating wind and causes a DAC in the absorption portion of P-Cygni line profiles that form in the hot star wind



Small-scale wind structure

- OBSERVATIONAL EVIDENCE
  - Transit emission-line substructures - direct evidence of stochastic small-scale structures (Eversberg et al., 1998; Lépine & Moffat, 2008)
  - Indirect evidence
    - Line profile variations - LPVs (Lépine et al., 1999, 2008; Markova et al., 2004, 2005)
    - Observed X-rays (Feldmeier et al., 1997, 2003; Oskinova et al., 2004; Owocki & Cohen, 2006)
    - Electron scattering wings of emission line profiles (Hillier, 1984; Hillier & Miller, 1998)
    - Extended black troughs of saturated UV resonance lines
    - Soft blue edges of UV resonance lines
    - Discrepant mass-loss estimates
- QUANTITATIVE SPECTROSCOPY - spectroscopic analysis using line-blanketed, non-LTE model atmosphere codes including a treatment of both the photosphere and the wind (CMFGEN (Hillier & Miller, 1998); PoWR (Gräfener et al., 2002); FASTWIND (Puls et al., 2005))

Small-scale wind structure

- Stochastic small-scale structures - Eversberg, Lépine & Moffat (1998), ApJ, 494,805

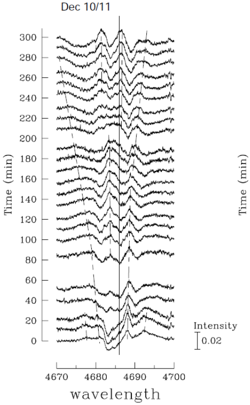


Fig. 1.—Residuals of He II 4686 for ζ Pup on 1995 December 10/11 and 12/13. The vertical axis gives the intensity and the time, respectively. The scale for the residual intensities is indicated. Dashed lines trace detected variations during the night. Vertical solid lines indicate the rest wavelength.

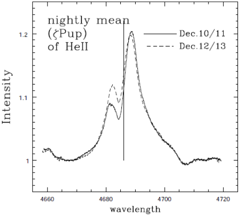
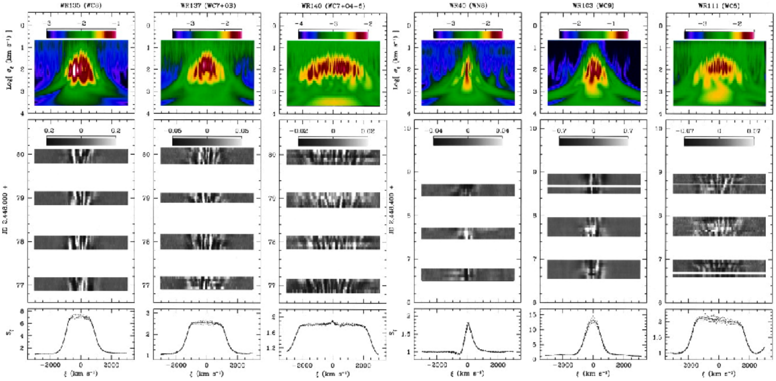


Fig. 9.—Nightly mean of December 10/11 (*solid line*), compared to December 12/13 (*dashed line*).

Small-scale wind structure

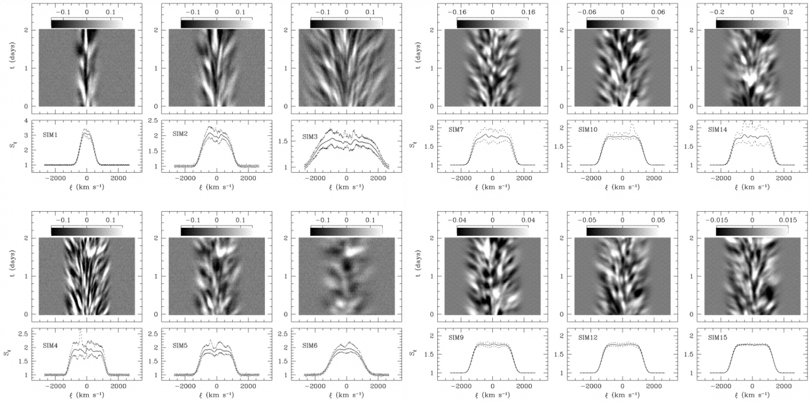
- Line Profile Variability (LPV) - Lépine & Moffat (1999), ApJ, 514, 909L



left the LPVs observed in the C III $\lambda5696$ emission line in HD 192103 (= WR 135), HD 192641 (= WR 137), and HD 193793 (= WR 140). One can see that subpeaks tend to propagate from lower to higher $|\varepsilon|$. Note how the number of apparent subpeaks increases with the emission line width; *right* the LPVs observed in the He II $\lambda5411$ emission line in HD 96548 (= WR 40) and in the C III $\lambda5696$ emission line in HD 164270 (= WR 103) and HD 165763 (= WR 111)

Small-scale wind structure

- Fenomenological model with Discret Wind Emission Elements (DWEE) - Lépine & Moffat (1999)



left simulations of LPVs from our model of radially propagating DWEEs. The LPV pattern from one DWEE distribution is shown to depend (upper panels) on the wind terminal velocity and (lower panels) on the average width of emission sub-peaks; *right* simulations of LPVs, showing the dependence of the LPV patterns on the mean number N_e

Small-scale wind structure

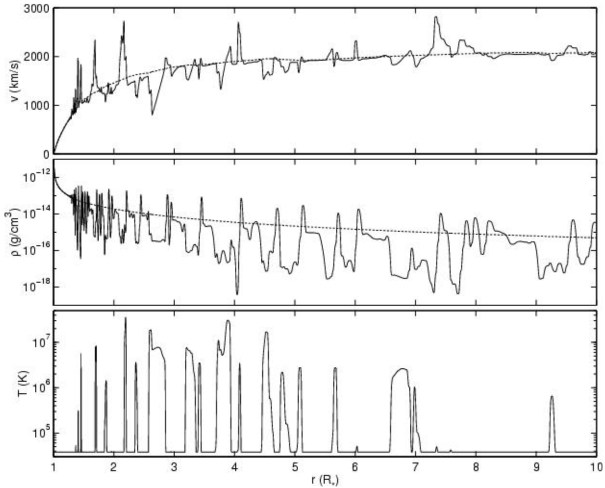
Clumping - theoretical predictions

- STABILITY ANALYSIS OF STELLAR WINDS - Lucy & Solomon 1970; MacGregor et al. 1979; Abbott 1980; Carlberg 1980; Owocki & Rybicki 1984; Owocki & Puls 2002, Krtička & Kubát 2002, and other papers
  - line-deshadowing instability (LDI) is an intrinsic property of the line-driving mechanism
- RADIATION HYDRODYNAMICAL SIMULATIONS of the nonlinear growthof the LDI
  - 1D spherically symmetric wind - Feldmeier (1995), Feldmeier et al. (1997), Owocki et al. (1988), Runacres & Owocki (2002)
  - pseudo 2-D spherically symmetric wind - Dessart & Owocki (2003, 2005)

Theoretical predictions

Small perturbation of driving force tends to grow and steepens into shocks - SHOCK COMPRESSION
CLUMPS - regions with different density than the surrounding wind matter)

Small-scale wind structure



Runacres & Owocki (2002)

Small-scale wind structure

- Indirect evidence of clumps - discrepant mass-loss estimate

Clumping in hot star winds plays important role for:

- determination of mass-loss rates - the key parameter of hot, massive stars (see Puls et al., 2008)
- Clumping has to be take into account for reliable mass-loss rates determination

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$$T_{eff}, L_*, R_* \Rightarrow \dot{M}, v_\infty$$

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PROBLEM!

- 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)

Wind models with clumping

Clumping introduces additional complexities into the RT

- Due to Doppler shift, opacity and emissivity are not isotropic
- Clumping requires 3D radiative transfer (RT)
- Self-consistent 3D RH models not yet available - 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

Wind models with clumping

Treatment of clumping

- The clumping factor D (Hamann & Koesterke, 1998) and the void ICM ($f_V = D^{-1}$)
- Microclumping approach (FASTWIND, Puls; CMFGEN, Hillier; PoWR, Hamann) - clumps are optically thin, a void ICM, and a smooth velocity field
- Macroclumping approach (Owocki et al., 2004; Oskinova et al., 2007; Hamman et al., 2008) - clumps can be nether optically thin or optically thick in the core of some lines, a void ICM, and a smooth velocity field

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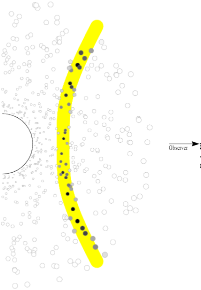

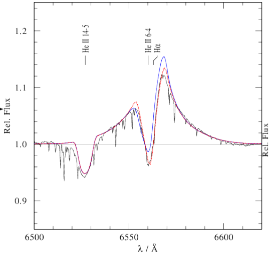

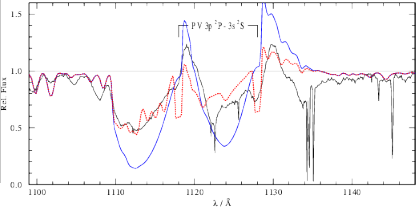

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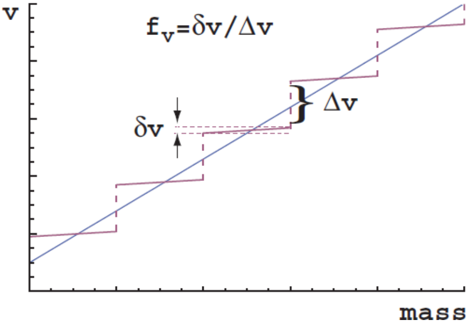

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- Depth dependent clumping factor (Puls et al. 2006); constant D
- Onset of clumping is important (Bouret et al. 2003, Sundqvist et al. 2010); $r_{\mathrm{cl}} = 1.3\,R_*$
- ICM density has to be included (Zsargó et al. 2008); d=0
- Shape of clumps (spheres, shells, pancakes, square)

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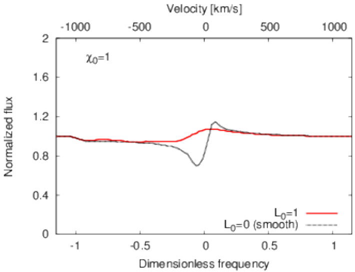
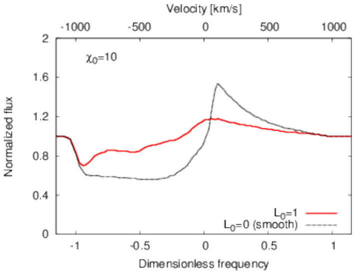
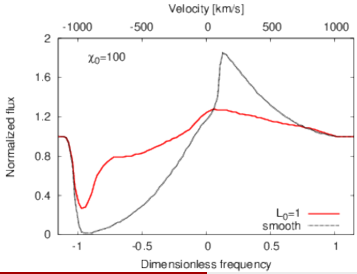
Important!

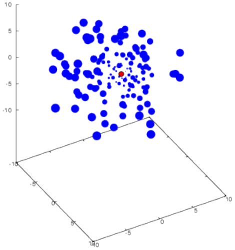
- The detailed density structure, the ICM, and the non-monotonic velocity field are all important for the line formation (Sundqvist et al. 2010, 2011)

Effect of the macroclumping on resonance line profiles









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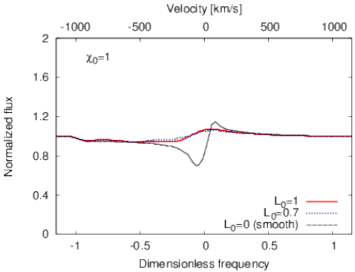

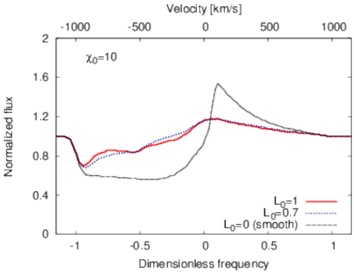

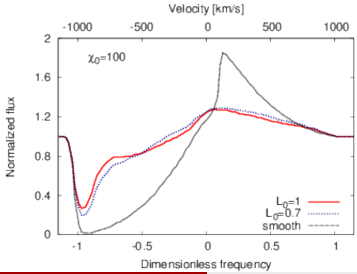

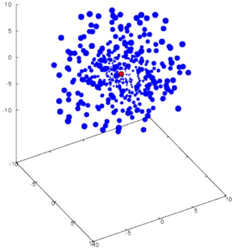

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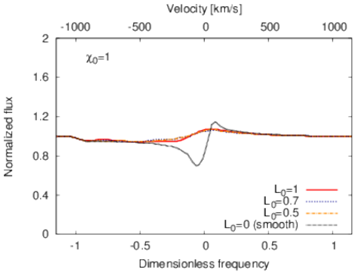

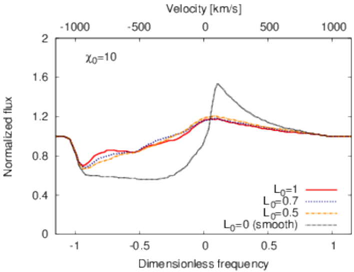

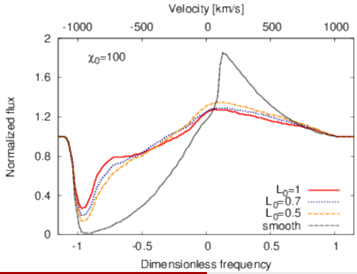

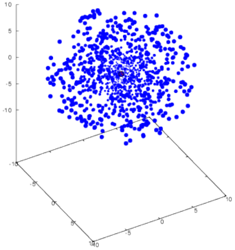

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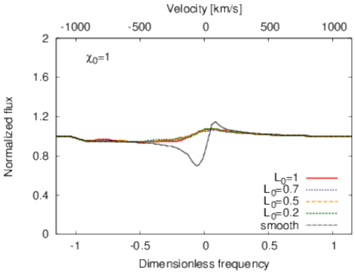
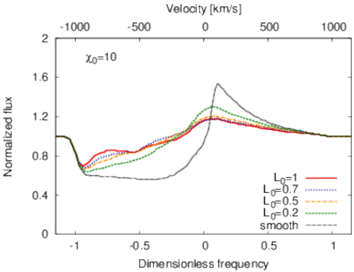
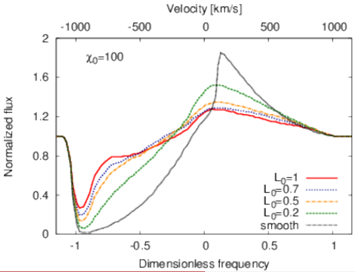
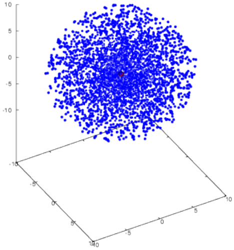
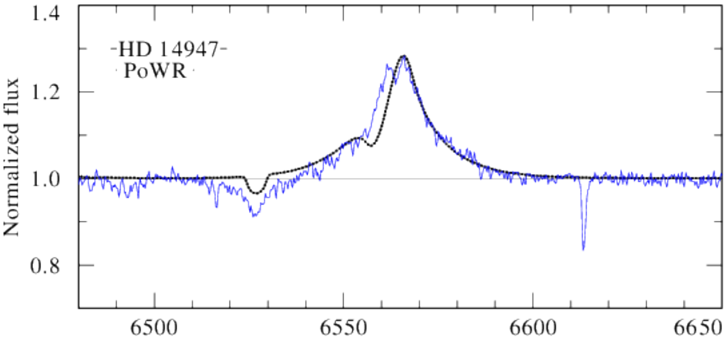








Comparison with observation



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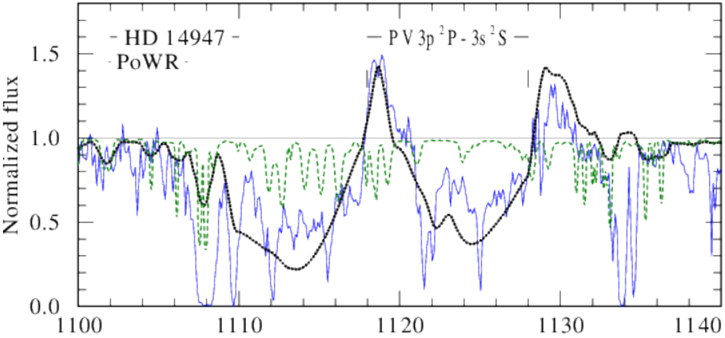

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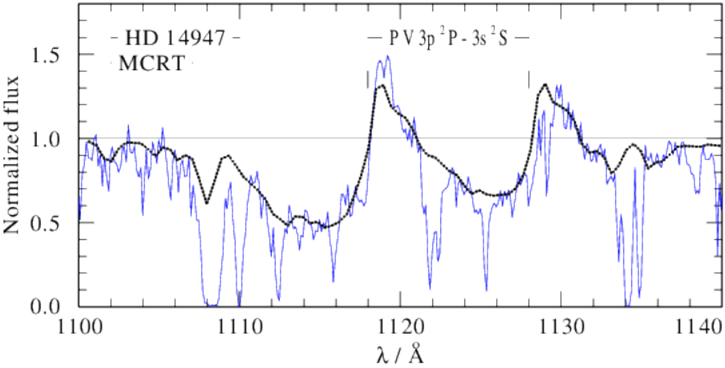

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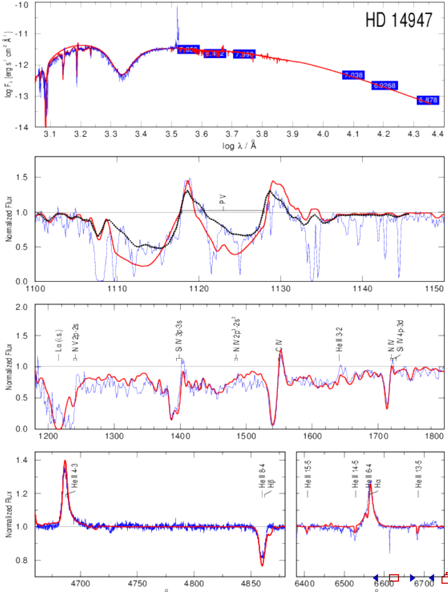

Open questions

- What is origin of structures (mechanism responsible for them)?
- What impact the time-dependent structures have on the determination of mass-loss rates from spectroscopic diagnostics?
- Full 2-D and 3-D time-dependent hydrodynamic wind model - more informations about properties of structures
- Non-LTE radiative transfer in inhomogeneous medium