LINE PROFILE VARIABILITY DUE TO SMALL- AND LARGE-SCALE STRUCTURES IN WINDS OF HOT, MASSIVE OB-STARS

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Open issues of physics of stellar atmospheres and winds
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Wind model

- Winds of hot, massive OB-stars are driven by metal-line scattering of the star's intense continuum radiation field
- Castor et al., 1975 - the first quantitative description of line-driving (CAK model - standard wind model). Assumptions: steady-state, spherically symmetric, homogeneous outflow in radiative equilibrium
- Observational findings - non-stationarity, inhomogeneous (clumped), shocks and deviation from spherical symmetry and radiative equilibrium
- Winds of hot, massive OB-stars are highly structured on a broad range of spatial scales - observationally as well as theoretically well established (Puls et al., 2008)

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Why these phenomena are ignored?

- amplitude of deviation from the standard model are not very large (standard analyses yield reliable average model of the stellar winds)
- 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

Time-dependent line profile variability

The atmospheres and winds of most early-type stars are intrinsically variable on time scales ranging from hours to years

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Importance of studies of time-dependent nature of hot-star winds

- provide constraints on the mechanisms of mass loss via fast winds
- provide informations of stellar surface structure
- provide constraints on the fundamental nature of massive stars

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- periodic variability in photospheric absorption lines (often identified with radial or nonradial pulsations of the underlying star)
- variability in UV P Cygni type wind lines
- Origin of these variations involve the existence of highly-structured, non-spherically symmetric winds

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Two principal forms of structure

- small-scale stochastic fluctuations, intrinsic to the wind itself
- large-scale structure, induced by changes in the underlying star (can substantially modify the overall wind)

Variability in UV P-Cygni line profiles

Data sourses: `Aerobee`, `Copernicus`, `IUE`, `FUSE`

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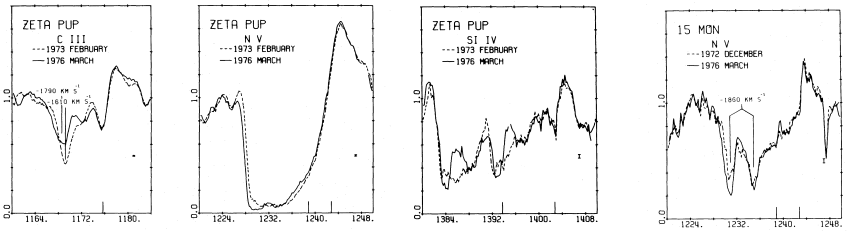
- **NACs** - Narrow Absorption Components
  - optical depth enhancements in the absorption troughs of P-Cygni profiles
  - have been observed in the broad P-Cygni profiles of UV resonance lines (C IV, N V, Si IV, Si III, O VI)
  - some first observations of NACs using `Copernicus` data
    - Underhill (1975)
    - Marton (1976)
    - Snow & Marton (1976)
    - Snow (1977)
  - important tracers of the dynamics of line driven winds in massive hot stars

Narrow absorption components (NACs)

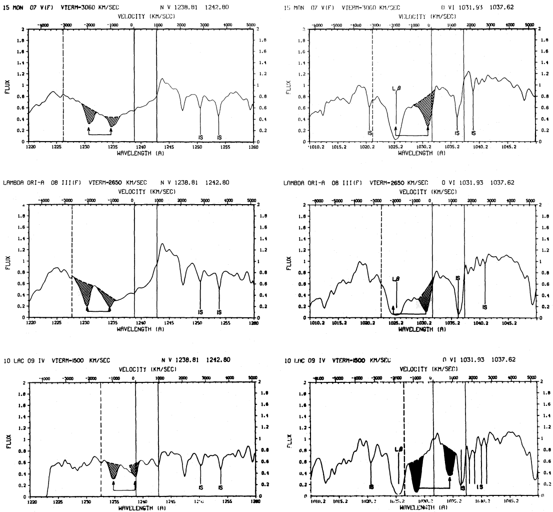
Snow (1977) - long-term changes in UV P-Cygni profiles - comparison between two scans (taken about 4 yr apart 1978-1981) of the UV line profiles of 15 stars



- NACs do not change in velocity
- the strength of NACs can change drastically

Narrow absorption components (NACs)

Lamers, Gatheir & Snow (1982) - `Copernicus` data of 26 OB-stars



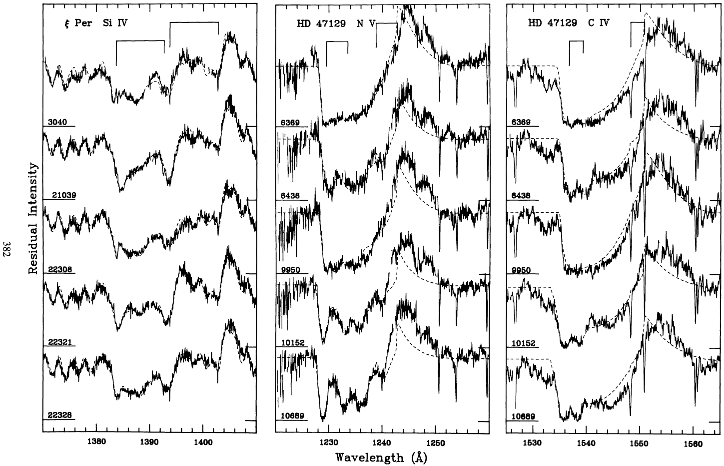
Narrow absorption components (NACs)

Lamers, Gatheir & Snow (1982) - `Copernicus` data of 26 OB-stars

- 17 stars have NACs in O VI, N V, Si IV and Si III lines
- the velocity of the center of the narrow component is correlated with the terminal velocity of the wind $\approx 0.74 \pm 0.1\, V_\infty$
- the width of the narrow component is about $0.18 \pm 0.1\, V_\infty$
- the column density of the narrow component is not correlated with T_{eff} nor with the mass-loss rate
- the optical depth at the center of the narrow component is about 2-10 times larger
- possible explanations:
  - NACs could be due to ejection of shells or puffs
  - NAs may be explained by assuming two-component wind

Narrow absorption components (NACs)

Prinja & Howarth (1986) - large survey of 203 Galactic O stars observed with IUE; NACs universal phenomena



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Discrete absorption components (DACs)

- NACs are the end product of DACs
- DACs are observed to propagate blue-wards through the UV line profiles on time scales comparable to the stellar rotation period (Massa et al., 1995, Howart et al., 1995, Kaper et al., 1996, Prinja et al., 2002)
- accelerate slowly compared with the expected wind flow
- DACs are always presented in multi-epoch observations of the same star and pattern of variability is always similar
- more frequently recurring DACs are in stars with higher v sin i

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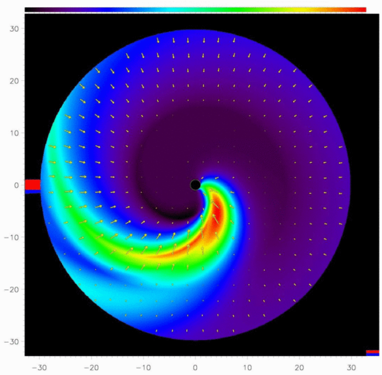
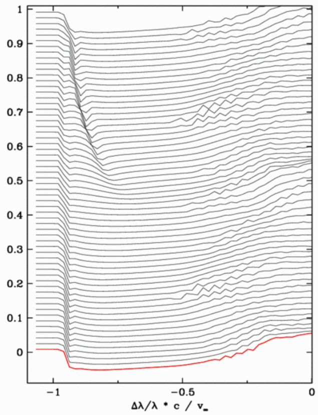
Possible origin - Co-rotating Interaction Regions (CIRs)

- Mullan (1984) - CIRs are large-scale azimuthal structures extending from the base of the wind to its outer regions (cyclical variability)
- 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





Co-rotating Interaction Regions

Which physical processes may perturb the star's surface and generate CIRs

- magnetic field (large- and small-scale magnetic fields) - David-Uraz 2013
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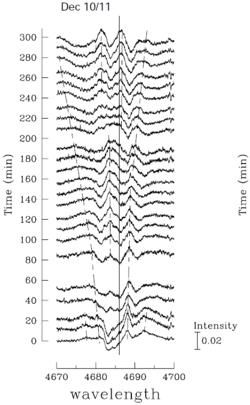
- Cranmer & Owocki (1996) showed by hydrodynamical simulations that DACs can occur as a consequence of magnetic footpoints on the stellar surface
- Non-radial pulsations of O stars have timescales much shorter than the DAC recurrence timescales (de Jong et al. 1999; Henrichs 1999)

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



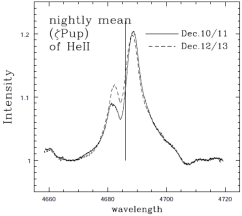
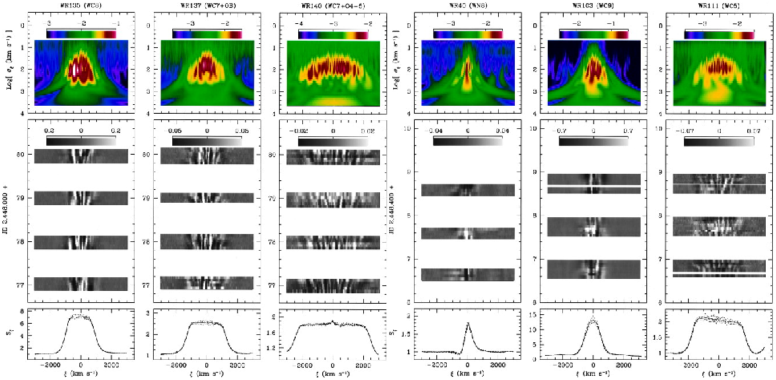


FIG. 1.—Residuals of He II 4686 for ζ Pup on 1995 December 10/11 and 12/13. The vertical axis gives the intensity and the time, respectively. The scale for the residual intensities is indicated. Dashed lines trace detected variations during the night. Vertical solid lines indicate the rest wavelength.

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

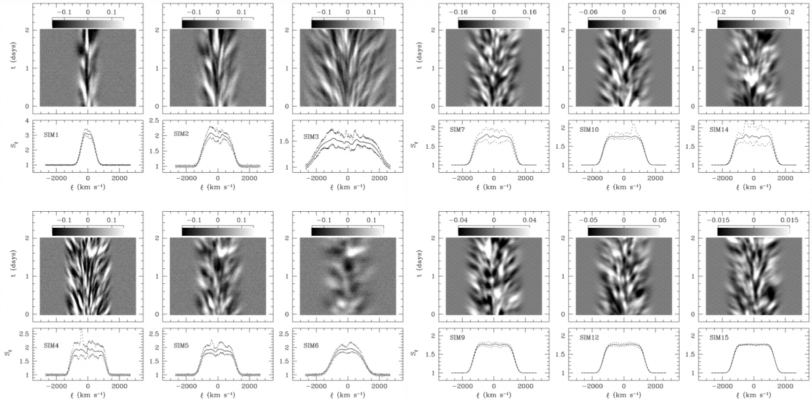
- Line Profile Variability (LPV) - Lépine & Moffat (1999), ApJ, 514, 909L



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

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