Phosphorus ionization in massive star winds

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Abstract: The observed wind line profiles of phosphorus P V in the spectra of hot stars are significantly weaker than theory predicts. Lower abundance of the phosphorus ion P V in massive stars could explain weaker profiles of the resonance ultraviolet doublet 1118, 1128 Å. Using full NLTE calculations, we show that high-energy radiation, both X-ray and XUV, can not be the solution of weak P V line profiles. Our three-dimensional radiative transfer calculations with porosity, interclump medium, and "vorosity" show that optically thick clumping is the most probable reason for weaker P V resonance line profiles in the spectra of massive hot stars, even in the case of a relatively low clumping factor of 10.

Mass-loss rate determination

1. create atmosphere + wind model
2. calculate emergent radiation
3. compare with observations

- theoretical flux prediction should fit radiation at all wavelengths
- different parts of the spectrum should give the same results

Mass loss rates from different determination tools (Hα line, FUV P V lines, radio continuum) do not match (Fullerton et al., 2006).

P V lines predict a lower mass-loss rate.

Phosphorus

- solar phosphorus abundance (Asplund et al., 2009)
  $\log \epsilon_{\mathrm{P}} = 5.41 \pm 0.03$
  $N(P)/N(H) = 2.57 \cdot 10^{-7}$
- ⇒ lines of phosphorus are not saturated, even in dense winds (Massa et al., 2003)
- sensitive to changes in opacity

P V 1118, 1128 Å line profiles

transition between $3s^2S_{1/2}$ and $3p^2P^{\mathrm{o}}_{1/2,3/2}$ levels

- observed by Copernicus, FUSE
- disagreement between observed and theoretical profiles
  found by
  - detailed NLTE 1-D modeling (both photosphere and wind) for several stars from Magellanic Clouds (Crowther et al., 2002; Hillier et al., 2003) and several galactic stars (Bouret et al., 2005, 2012)
  - simplified modeling for a large sample of stars (Fullerton et al., 2006)
- ***possible solution:*** lower abundance of P V can be achieved by:
  - lowering the total phosphorus abundance
  - lowering the P V ionization fraction

Phosphorus abundance

The abundance of phosphorus in selected O supergiants derived using NLTE model atmosphere analysis by Bouret et al. (2012). Solar abundance from Asplund et al. (2009).

star	sp. type	$\log \epsilon_{\mathrm{P}}$
HD 16691	O4 If	5.05
HD 66811	O4 I(n)fp	5.05
HD 190429A	O4 If	5.26
HD 15570	O4 If	5.06
HD 14947	O4.5 If	5.25
HD 210839	O6 I(n)fp	4.70
HD 163758	O6.5 If	5.02
HD 192639	O7.5 Iabf	5.07
Sun		5.41

lower than solar
is it real?

P V ionization fraction

- P V is a dominant phosphorus ion in O-type stars (follows from the solution of equations of statistical equilibrium)
- P V fraction can be lowered by changing the radiation flux (e.g. X-ray and XUV radiation emission)

Enhanced X-ray radiation

Studied by Krtička & Kubát (2009) using detailed NLTE calculations.

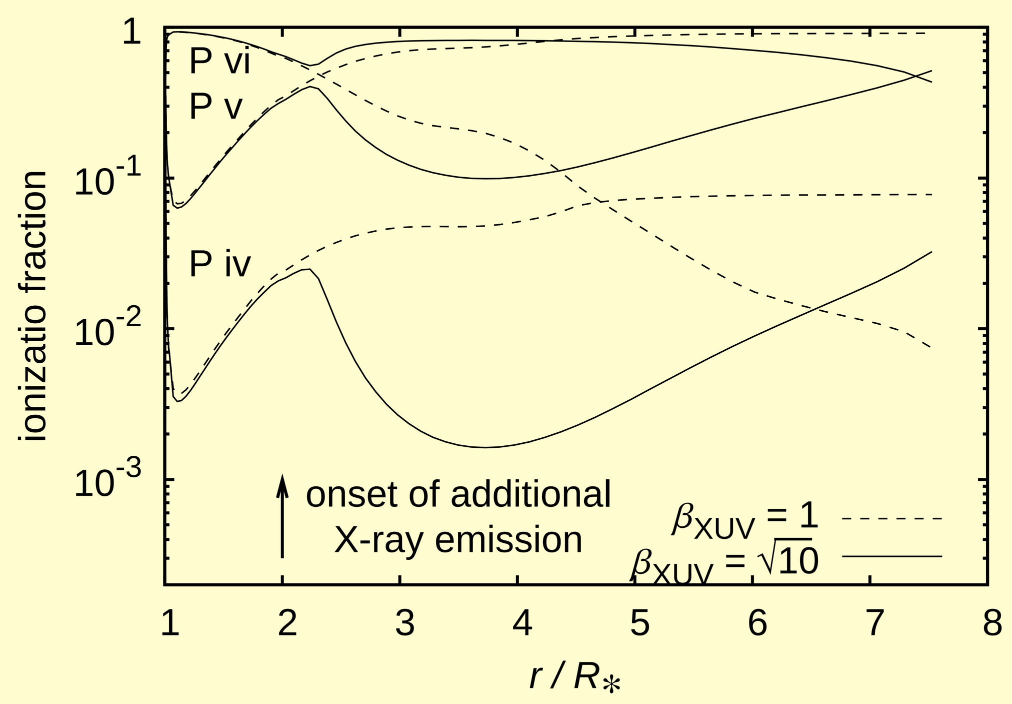
- assumption: X-ray radiation originates in shocks
- ionizing radiation is enhanced
- both direct and Auger ionization included

no significant effect on P V ionization equilibrium

Enhanced XUV radiation

- suggested by Waldron & Cassinelli (2010)
- studied in detail by Krtička & Kubát (2012) using detailed NLTE calculations

example: $T_{\mathrm{eff}} = 40\,000$ K, $\dot{M} = 3 \cdot 10^{-6} M_{\odot} \mathrm{yr}^{-1}$
higher β_{XUV} ⇒ higher XUV radiation



higher XUV radiation lowers P V ionization fraction

However, the effect on other ions is similar.

Higher XUV radiation changes ionization fractions of C IV, N IV, O III, O IV, Si IV – wind driving ions.

structure of absorption coefficient changes
⇒ lower wind acceleration

higher XUV radiation lowers wind terminal velocity

more details in Krtička & Kubát (2012)

Clumping

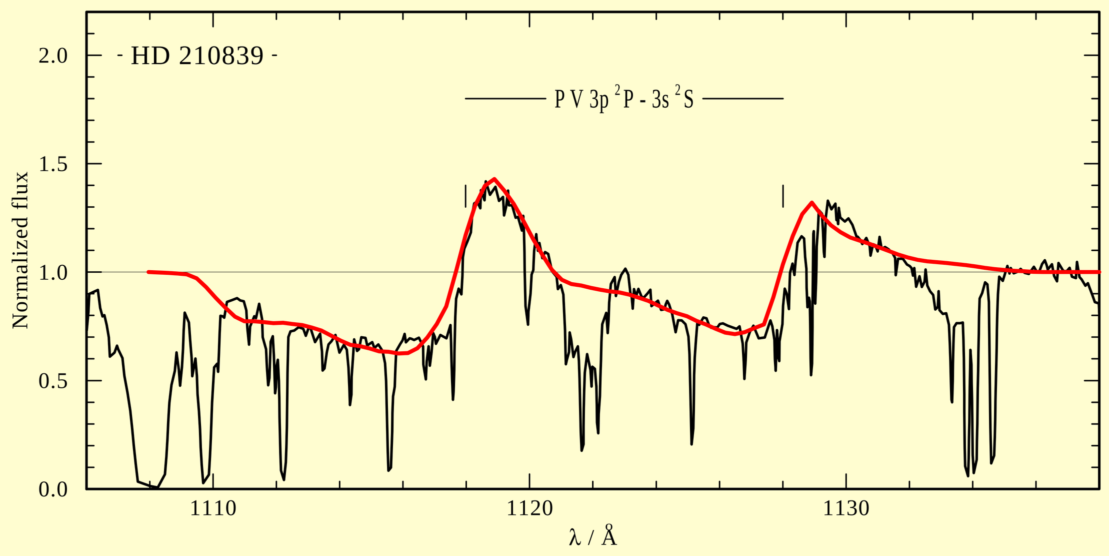
- formation of inhomogeneties (clumps) in the wind
- *microclumping* – clumps are optically thin, standard way of calculation of clumping influence
- *macroclumping* – clumps may be optically thick

1-D spherically symmetric NLTE wind model codes use the assumption of optically thin clumps (microclumping)

Profiles with clumping

- macroclumping requires 3-D radiation transfer (code described in Šurlan et al., 2012)
- clumping in velocity ("vorosity"), non-void interclump medium also included
- clumping described by more parameters

example: P V resonance doublet for λ Cep
clumping factor $D = 10$
interclump factor $d = 0.03$
velocity dispersion $v_{\mathrm{dis}} = 0.01$



black – observed spectrum, red – macroclumping included.

macroclumping improves the fit using a small clumping factor

Conclusions

- phosphorus ionization has no anomalies in O star winds (Krtička & Kubát, 2012)
- large change of phosphorus abundance is not necessary
- using macroclumping P V resonance lines may be fitted (Šurlan et al., in preparation)

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