Clumping in O-type Supergiants

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We have analyzed the spectra of seven Galactic O4 supergiants, with the NLTE wind code CMFGEN. For all stars, we have found that clumped wind models match well lines from different species spanning a wavelength range from FUV to optical, and remain consistent with Hα data. We have achieved an excellent match of the P V $\lambda\lambda$1118, 1128 resonance doublet and N IV λ1718, as well as He II λ4686 suggesting that our physical description of clumping is adequate. We find very small volume filling factors and that clumping starts deep in the wind, near the sonic point. The most crucial consequence of our analysis is that the mass loss rates of O stars need to be revised downward significantly, by a factor of 3 and more compared to those obtained from smooth-wind models.

1 Introduction

Massive O-type stars stars are characterized by dense, highly-supersonic mass outflows. These stellar winds have a significant effect on the stars' evolution, as O stars will loose a sizable fraction of their total mass during their lifetime. Mass-loss rates are therefore a crucial parameter of stellar evolution models. Aside from their effect on the ultimate evolution of the stars, the deposition of mechanical energy and momentum have a greatly impact on the circumstellar environment and play a prominent role in the chemical and dynamical evolution of galaxies. Establishing reliable mass-loss rates of O stars is therefore a crucial undertaking which impacts a broad segment of Astrophysics.

The winds of O-type stars are radiatively driven. This process is unstable and, theoretically, should lead to the formation of structures (clumps, shocks) and the emission of X-rays. Observationally, there is growing evidence that O stars have highly structured winds: *i)* Discrete Absorption Components are observed in O-star wind line profiles, and might indicate the propagation of disturbances throughout the wind *ii)* Spectral properties of X-ray line profiles observed with Chandra and XMM-Newton are best explained by considering highly fragmented (or porous) winds, starting close to the photosphere *iii)* NLTE analyses with state-of-the-art atmosphere models require the use of inhomogeneous (clumped) winds to simultaneously fit UV and optical wind line profiles, as well as IR and radio fluxes (e.g. Bouret et al. 2005; Puls et al. 2006). Fullerton et al. (2006) also had to consider highly clumped winds to reconcile $\dot{M}$q(P^{+4}) with mass-loss rates measurent

from radio and Hα emission. A consequence of the introduction of clumping is that the inferred mass-loss rates had to be revised downward by a factor 3 or more, compared to those obtained from smooth-wind models, with strong consequences on the predicted evolution of O-type stars.

While these results show that we cannot trust the mass-loss rates derived from homogeneous models, we cannot conclude that the revised values from the clumped wind models can be adopted just yet because of the crude physical description of clumping in current models. It is thus essential to investigate if a consistent picture can be drawn from the different diagnoses of wind clumping, P V $\lambda\lambda$1118-1128, O V λ1371, N IV λ1718, He II λ4686 and Hα, ensuring that these are not spuriously affected by abundance or ionization effects.

We have selected 7 galactic early-type O supergiants (spectral types O4 If+ to O6.5 Iaf) to derive their properties and address these issues. These stars, namely HD 14947, HD 15570, HD 16691, HD 190429A, HD 66811 (ζ Puppis), HD 163758 and HD 210839 (λ Cephei) are considered as "bona fide" as possible objects representative of early-O supergiants, whose strong winds are expected to exhibit most conspicuous signatures of clumping.

2 Observational material

We have extracted IUE short wavelength, large aperture, high resolution spectra from the IUE Newly Extracted Spectra (INES) archive. The SWP spectra cover the spectral range, $\lambda\lambda$1150-2000 Å, at a resolving power $R = 10,000$. The spectra of all stars show a large number of narrow lines of interstellar

(IS) origin. This becomes an issue for HD 15570, for which it dominates the whole UV spectrum.

All stars but ζ Puppis have been observed with the FUSE $30'' \times 30''$ LWRS aperture. The nominal spectral resolution is 20,000 and the wavelength range goes from 905 Å to 1187 Å. The processed FUSE spectra have been retrieved from MAST. For ζ Puppis, we used the COPERNICUS spectra available from MAST.

Northern stars were observed with the ELODIE spectrograph at Observatoire de Haute-Provence, while southern stars were observed with the ESO/FEROS spectrograph at La Silla Observatory. The spectral resolution is R=42,000 and 45,000 (for ELODIE and FEROS, respectively). The wavelength coverage is 3895-6815 Å for ELODIE, 3700-9000 Å for FEROS. The exposure time were chosen to ensure a signal-to-noise ratio of at least 100 at 5200 Å. Each order was normalized by a polynomial fit to the continuum; the successive orders were then merged to reconstruct the full spectrum for each star.

3 Spectral Modeling

The spectral analysis has been performed using model atmospheres calculated with the unified model code CMFGEN (Hillier & Miller 1998). We use a hydrostatic density structure computed with TLUSTY (Lanz & Hubeny 2003) in the deep layers, and the wind part is described with a standard β-velocity law. The photosphere and the wind are connected below the sonic point at $v(r) \approx 15$ km s^{-1}.

To investigate spectral signatures of clumping in the winds of our sample stars, and its consequences on the derived wind parameters, we have thus constructed clumped wind models with CMFGEN. A simple, parametric treatment of wind clumping is implemented in CMFGEN, which is expressed by a volume filling factor, f, and which assumes a void interclump medium and the clumps to be small compared to the photons mean free path. The filling factor is such that $\bar{\rho} = f\rho$, where $\bar{\rho}$ is the homogeneous (unclumped) wind density. The filling factor decreases exponentially with increasing radius (or, equivalently, with increasing velocity) $f = f_\infty + (1 - f_\infty)\exp(-v/v_{cl})$, where v_{cl} is the velocity at which clumping starts. By default, we have adopted $v_{cl} = 30$ km s^{-1}, that is, clumps start forming just above the sonic point (cf. Bouret et al. 2005) some specific cases, we had to tune v_{cl} to improve the fit to some observed lines, but we kept in within a few tenths of stellar radii above the photosphere (i.e. $v_{cl} \leq 150$ km s^{-1}).

4 Results

Clumping related quantities ($\dot{M}$, v_{cl} and f_∞) have been derived from P V $\lambda\lambda$1118-1128, O V λ1371, N IV λ1718, in the FUV/UV domain. We found that Si IV $\lambda\lambda$1394, 1403 are also sensitive to clumping, especially for the cooler stars of the sample, where Si IV is the dominant ions of Silicium. In the optical, clumping sensitive lines are primarily He II λ4686 and Hα, although all the lines (including photospheric lines) we looked at presented some sensitivity to the adopted filling factor (and scaled $\dot{M}$). For photospheric lines, this is essentially caused by a lower wind contribution (emission) in clumped models, thus producing deeper absorption, compared to smooth-wind models.

We find that only clumped wind models consistently improve the match to lines from FUV to the optical wavelength range. The dramatic improvement of the fits to the lines listed hereabove is presented in Fig. (1) and Fig. (2). The winds of our sample stars are highly clumped, as expressed by very small volume filling factors: $0.01 \leq f_\infty \leq 0.08$. In most cases clumping must starts deep in the wind, just above the sonic point $v_{cl} \approx 30$ km s^{-1}.

For ζ Pup and λ Cep (both being rapid rotators), we had to use $v_{cl} \approx 130$ km s^{-1} to reduce emissivity in the lower wind and improve the fit to the central absorption seen on the Hα profile (Fig. 1).

Lower mass-loss rates are derived from the clumped models, here by a factor of 3 to 10, with respect to those derived form smooth-wind models, which is expected to significantly alter the predicted evolution of O-type stars.

We emphasize that for all but one star, we succeeded in matching the observed profiles of P V $\lambda\lambda$1118-1128 with the reduced solar abundances for Phosphorus from Asplund et al. (2005). This suggests that the very low mass-loss rates we derive do not result from any uncertainty about the exact abundance of this element, and further confirm that the ionization structure of Phosphorus in our models is correct. For HD 190429A, the best fit to the P V FUV resonance doublet is then obtained for P/P$_\odot$ = 0.7, further confirming the apparent depletion in phosphorus of this star (see Bouret et al. 2005).

References

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Puls, J., Markova, N., Scuderi, S., et al. 2006, A&A, 454, 625

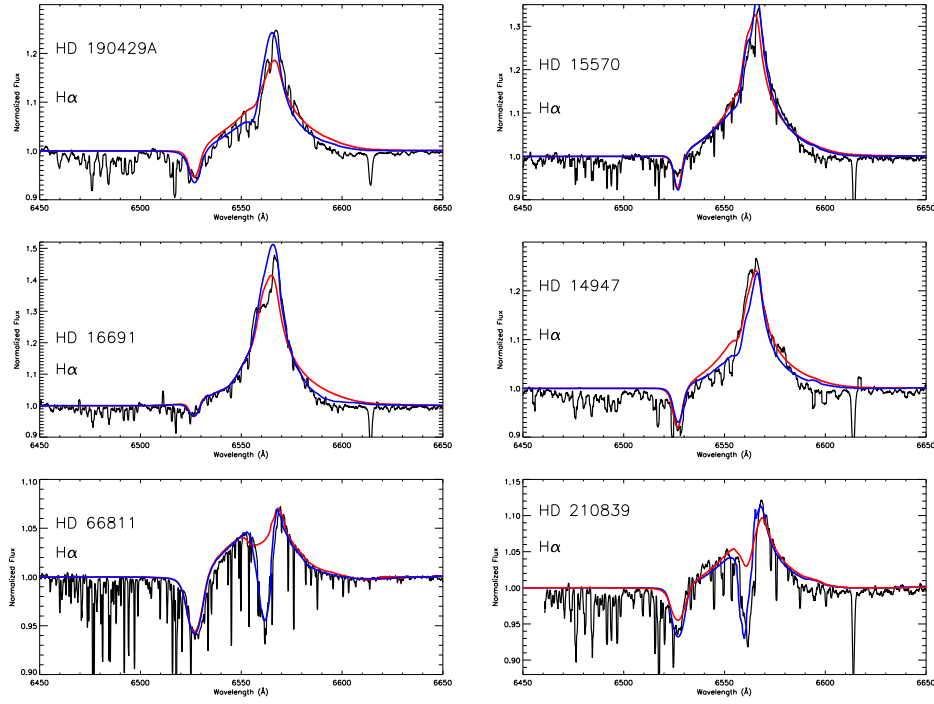Figure 1: Best fit to observed Hα line profiles (black line) of 6 stars of our sample, obtained with smooth (red line) and clumped (blue line) models
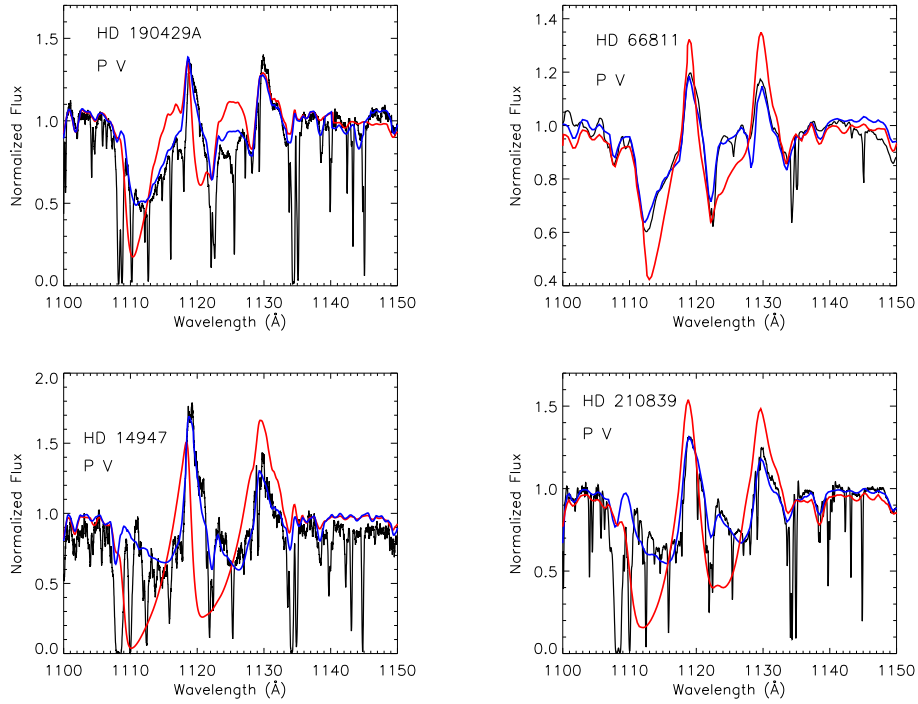
Figure 2: Best fit to observed P V λλ1118, 1128 line profiles (black line) of the four O4 If+ stars of our sample, obtained with smooth (red line) and clumped (blue line) models

Cohen: Please keep an open mind about X-ray profiles: whether they really imply that large scale clumping exists or whether the data simply imply $\dot{M}$ reductions. Can you comment on the relatively high smooth $\dot{M}$ for ζ Pup?

Bouret: Thanks for your comment. Concerning your question, I do not think you can say the smooth $\dot{M}$ is high; it is in any case compatible with values published elsewhere (for instance Puls et al. 2006). $\dot{M}$ depends strongly on the distance adopted for ζ Pup. In the present case, the lower value $d \approx 460$ pc is used.

Moffat: Just because the models seem to fit the observed spectrum fairly well does not necessarily mean that the model is correct. It is a necessary condition but not sufficient. So, my question is, how confident are you that your description of clumping and its consequence is correct?

Bouret: True! Nevertheless I would like to stress for instance that our clumped models match the two P v resonance lines very well, providing strong evidence that the wind ionization is correct and that there is no particular issue such as covering factors with our treatment of clumps.

Puls: Just let me mention that He II 4686 in ζ Pup and λ Cep is strongly variable on (rather) short time scales. So it might be not so problematic that you cannot fit one specific observation.

Bouret: Very good point indeed. It is one of the issues of this work that we try to derive parameters from data obtained in some cases about 25 years apart. And short-term variability does not help either.

Najarro: What is the effect of such strong clumping on the cores of the Balmer lines and He I lines? Do they not get too deep?

Bouret: As I said in my talk, we first derive the stellar parameters (including $\dot{M}$) from the UV and FUV spectra and when we look at the optical spectrum, we find that Balmer lines and some He lines are too weak in the model. This is caused indeed by wind filling, and a very efficient way to reduce that is to introduce clumping. Lines then get deeper, in better agreement with the observations most of the time, although in some cases they might get too deep indeed.