Clumping in Hot Star Winds
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Clumping in O-star winds

J.Puls[1], N. Markova[2], F. Najarro[3] & M.M. Hanson[4]
[1] *Universitätssternwarte München, Germany*
[2] *Institute of Astronomy, Bulgarian National Astronomical Observatory, Smolyan, Bulgaria*
[3] *Instituto de Estructura de la Materia, CSIC, Madrid, Spain*
[4] *Department of Physics, The University of Cincinnati, Cincinnati, OH 45221, USA*

We review various diagnostics of clumping in O-star winds, with special emphasis on its radial stratification. Implications and problems are discussed, and promising NIR methods are presented.

1 A word of warning

Instead of a conventional introduction, let us begin with a word of warning: *Almost all evidence for clumping in OB-stars is only indirect* (except for the detection of "outward moving inhomogeneities" in He II λ4686 from ζ Pup, Eversberg et al. 1998), and relies strongly on our belief in results from theoretical modeling: (i) time-dependent hydrodynamic simulations predict a highly structured wind due to the line-driven instability; (ii) spectroscopic NLTE analyses based on homogeneous models produce lines in different wavelength bands which do not fit the observations simultaneously; (iii) predictions from wind models do not agree with "observed" mass-loss rates. Moreover, there are several phenomena which strongly suggest that the "standard model" of a stationary, homogeneous wind needs to be revised: The denser, but also line-driven Wolf Rayet star winds display moving substructures on top of emission lines and reveal inconsistencies between the strengths of recombination lines and their electron scattering wings. Other clues are provided by the presence of X-Ray emission in single stars ($\rightarrow$ shocks) and "black throughs" in saturated P Cygni lines ($\rightarrow$ non-monotonic velocity fields).

2 Indications of significant clumping in OB-star winds

Various diagnostics have been used to derive constraints on the clumping properties of OB stars in different wavelength bands. Typical examples from the recent few years are cited in the following (but see also the references given therein).

• From radio/submm observations, Blomme et al. (2002: ε Ori; 2003: ζ Pup) found a submm-*excess*, suggesting the intermediate wind to be clumped.

• Assuming optically thin clumps and a void interclump medium, NLTE model atmosphere analyses of UV and optical spectra of O-star winds allowed to derive clumping factors, $f_{\rm cl} = <\rho^2> / <\rho>^2$, of order 10…50, with clumping starting already close to the wind base (Crowther et al. 2002, Hillier et al. 2003, Bouret et al. 2003, 2005 and this volume).

• From the mismatch of predicted and derived wind-momentum rates of O-type supergiants, Markova et al. (2004) and Repolust et al. (2004) suggested this disagreement to be the consequence of wind-clumping: Any ρ^2 dependent diagnostics such as H_α over-predicts the mass-loss rate by a factor of $\sqrt{f}_{\rm cl}$, when the analysis is performed using a smooth model, but the wind consists of optically thin clumps. Both analyses implied clumping factors of the order of 5 to 7.

• The greatest challenge for the standard model resulted from the analysis of the unsaturated FUV resonance doublet of P V for a large sample of O-stars (see Fullerton et al. 2006 and this volume): mass-loss rates derived from these lines were found to be a factor of 10 (or more) lower than those obtained from H_α and radio emission. Interpreted in terms of wind clumping, this would correspond to $f_{\rm cl} \geq 100$!

3 A combined Hα/IR/mm/radio analysis

Recently, Puls et al. (2006) were able to derive constraints on the radial stratification of the clumping factor, by simultaneously modeling H_α and the IR/mm/radio emission from a sample of 19 O-stars with well-known parameters. This is possible since H_α and the IR form in the lower/intermediate wind (1-5 $R_\star$) whereas the mm/radio emission forms in the outer regions (10-50 $R_\star$).

Notably, the derived stratification does not or only marginally agree with the theoretical predictions, the latter suggesting the maximum of the clumping factor to be reached in the intermediate wind (10-20 $R_\star$, see Fig. 1). In contrast, our analysis indicates that in *denser* winds considerable clumping is present already close to the star (in agreement with other investigations, see above), which then remains rather constant over a large volume before decreasing in the outer wind. On average, the ratio of clumping factors in the inner and outer wind is of the order 3 to 6. For the best constrained object, ζ Pup, we found that the maximum of $f_{\rm cl}$ is reached already in the innermost wind region.

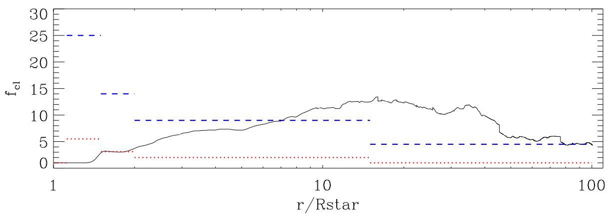

Figure 1: Theoretical predictions for the clumping factor (solid, from Runacres & Owocki 2002), compared to "observed" results from ζ Pup. The red (dotted) solution corresponds to an unclumped outer wind (from Puls et al. 2006), whereas the blue (dashed) solution (with an assumed $f_{\rm cl}$= 4.5 in the radio-emitting region) gives the same fit quality, when the mass-loss rate is reduced by a factor of $1/\sqrt{4.5}$. See text.

For *weaker* winds, on the other hand, the clumping factor is the same in the inner ($r < 2R_\star$) and outermost regions. (Due to missing diagnostics, the intermediate wind remains unconstrained.) This finding points to a physical difference in the clumping properties of weaker and stronger winds, and may be related to the excitation mechanism of the structure formation. In terms of "conventional" mass-loss rates, we find $\dot{M}$(radio) $\approx \dot{M}$(H$_\alpha$) for weak winds with H$_\alpha$ in absorption, whereas for all stars with H$_\alpha$ in emission we obtain $\dot{M}$(radio) $\approx 0.4\ldots0.5\,\dot{M}$(H$_\alpha$).

A major shortcoming of our investigation is that only *relative* clumping factors could be derived, normalized to the values in the outermost, radio-emitting region, since *all* considered diagnostics depend on ρ^2. This dilemma is illustrated by the two different solutions for the run of $f_{\rm cl}$ in the wind of ζ Pup (Fig. 1), which cannot be discriminated by our analysis. In other words, $\dot{M}$(REAL) $\le \dot{M}$(radio), since until now the clumping in the radio emitting region is still unknown. Only if $f_{\rm cl}$(radio) were unity, we would have $\dot{M}$(REAL) $= \dot{M}$(radio). Thus, the issue of absolute values for $\dot{M}$ still remains unresolved, though - at least for the analyzed sample - the observed wind-momentum luminosity relation (WLR) would agree quite nicely with the predicted one (Vink et al. 2000) if one assumes the outer wind to be unclumped!

4 Implications - problems

In the latter case then, most results obtained from the F(UV) would become questionable and would need to be re-interpreted. A possible way out of the apparent dilemma has been suggested by Oskinova et al. (see Hamann, this volume), who argue that *porosity* effects are able to diminish the effective (line-)opacities and thus would lead to lower clumping factors/higher mass-loss rates than implied by the F(UV) analyses assuming optically thin clumps exclusively.

If, on the other hand, those values were correct, we would have to conclude that the outer wind is significantly clumped, and that the suggested match of observed and predicted WLR is purely coincidental. This, of course, would imply severe problems for radiation driven wind theory (see Krticka and de Koter, this volume), and, most importantly, for the stellar evolution in the upper HRD (Hirschi and Smith, this volume).

Before final conclusions are possible, a number of open problems have to be solved. Since any instability needs some time to grow and to become non-linear, our present treatment of clumping is most likely inadequate in those regions where the instability is not fully grown. In these (lowermost) wind regions, the assumption of a void inter-clump matter is certainly questionable. For diagnostics exploiting optically thick lines, the present treatment of the velocity field is certainly wrong (see Owocki, this volume). And finally, as has been suggested recently by Lucy (2007), the influence of photospheric micro-turbulence on the wind-properties needs to be investigated in more detail.

5 Future perspectives: NIR spectroscopy

Independent clues on the degree of clumping and its stratification are imprinted into IR lines, due to their extreme sensitivity on mass-loss/clumping effects. For objects with large $\dot{M}$, Br$_\alpha$ samples the intermediate wind, enabling us to derive constraints on the (local) clumping factor, and in combination with other indicators (UV, H$_\alpha$, Br$_\gamma$, Pf$_\gamma$), to derive "true" mass-loss rates. For objects with weak winds, on the other hand, this line provides not just upper limits (as H$_\alpha$) but *reliable* constraints on $\dot{M}$. Our models predict a narrow emission peak, superimposed on rather shallow Stark-wings, where the peak height reacts strongly on $\dot{M}$ (increasing with decreasing $\dot{M}$), enabling a measurement of even the weakest wind strengths and, again in combination with other diagnostics, insight into their clumping properties.

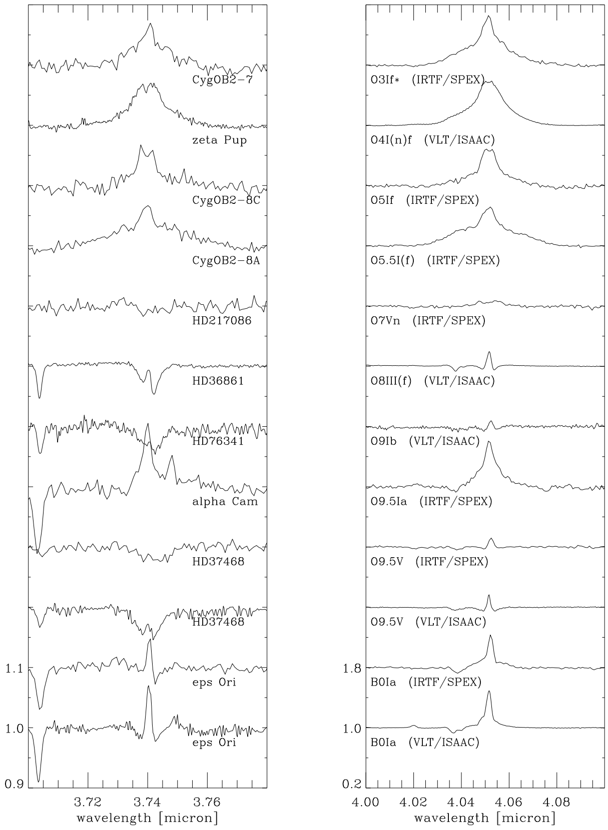

Figure 2: HeI3.70 + Pf$_\gamma$ (left) and Br$_\alpha$(right) for a sample of OB stars with thin and thick winds, as observed by ISAAC@VLT and SPeX@IRTF (observations by Puls, Hanson & Najarro).

During a recent project, we obtained high S/N ($>$ 150) L'-band spectra of ten OB stars covering Br$_\alpha$, Pf$_\gamma$ and HeI3.70 (Fig. 2). A comparison of these spectra with our model predictions (Fig. 3) clearly demonstrates the potential of NIR line diagnostics (see also Najarro, this volume).

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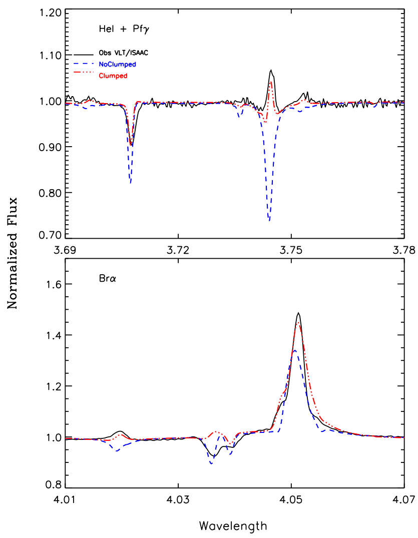

Figure 3: L'-Band diagnostics for ε Ori, by means of unclumped (blue, dashed) and clumped (red, dashed-dotted) models. The need for clumping is clearly visible. The derived $\dot{M}$ is a factor of ≈ 3 lower than implied by unclumped models. From Najarro et al., in prep for A&A.