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Stellar winds from massive stars - What are the REAL mass-loss rates?

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Abstract. We discuss recent evidence that currently accepted mass-loss rates may need to be revised downwards, as a consequence of previously neglected "clumping" of the wind. New results on the radial stratification of the corresponding clumping factors are summarized. We investigate the influence of clumping on the ionization equilibrium of phosphorus, which is of major relevance when deriving constraints on the clumping factors from an analysis of the FUV Pv resonance lines.

1. Introduction

While our understanding of the outflows from luminous OB-stars was thought to be well established, recent evidence indicates that currently accepted mass-loss rates *may* need to be revised downwards *by as much as a factor of ten.* This is a consequence of previously neglected "clumping" of the wind, which affects mostly those diagnostics which are sensitive to the *square* of the density, ρ (such as recombination lines or free-free continua).

Considering that numerous stellar-evolution calculations have demonstrated that changing the mass-loss rates of massive stars by even a factor of two has a dramatic effect on their evolution (e.g., Meynet et al. 1994), it is evident that such revisions would have enormous implications, not only regarding evolution, but also regarding the feed-back from massive stars. In this article, we will summarize the knowledge which has been accumulated lately and consider the question concerning the REAL mass-loss rates from massive star winds.

2. Standard mass loss diagnostics of luminous OB-stars

Traditionally, the mass-loss rates, $\dot{M}$, of luminous OB stars have been inferred from, primarily, three types of measurement (see also de Koter, this volume):
1. The strengths of UV P-Cygni profiles were the first diagnostics to be used to measure wind-densities. This approach has been pioneered by Lamers & Morton (1976) in their work on the "Mass ejection from the O4f Star Zeta Puppis", where they derived a mass-loss rate of $7.2 \pm 3.2 \cdot 10^{-6} M_{\odot} \mathrm{yr}^{-1}$, a number which is still valid! The most commonly used method to analyze P-Cygni lines is the so-called SEI-method (Lamers et al. 1987), which has been firstly applied

by Groenewegen & Lamers (1989). Though most of the UV P-Cygni lines are resonance lines from dominant ions being *linearly* dependent on density and thus remaining uncontaminated from *direct* clumping effects (but see Sect. 7.), only the product $\dot{M}q$ can be inferred from these lines, where q is the ionization fraction of the corresponding ion. Moreover, most of these lines are inevitably saturated in stars with strong winds, since they arise from *abundant* elements, and only lower limits on $\dot{M}$ can be provided in these cases.
2. Thermal radio and FIR continuum emission samples the outermost and intermediate region of the wind ($\mathcal{O}(100,\, 10\, R_\star)$), respectively. The corresponding methods base on the work by Wright & Barlow (1975)/Panagia & Felli (1975) (radio) and Lamers & Waters (1984a,b) (IR-excess). They have been applied, e.g., by Abbott et al. (1981) and Lamers & Leitherer (1993) to derive OB-star radio mass-loss rates, and by Lamers et al. (1984) to investigate the IR excess of ζ Pup by means of IRAS observations. Since the involved processes are dominated by free-free and bound-free transitions which scale with ρ^2, inferences from the measurements are extremely sensitive to clumping in the wind.
3. H_α emission, usually modelled using NLTE atmosphere codes, also depends on ρ^2, and is therefore also sensitive to clumping, but samples the innermost portion of the wind ($\lesssim 2R_\star$). The idea to exploit H_α as a standard mass-loss indicator goes back to Klein & Castor (1978), and has been firstly applied by Leitherer (1988), Drew (1990) and Lamers & Leitherer (1993). Further refinements have been provided by Puls et al. (1996).

3. Clumping – some basic facts

The present hypothesis states that clumping is a matter of *small-scale* density inhomogeneities in the wind[1], which redistribute the matter into clumps of enhanced density embedded in a rarefied, almost void medium. The amount of clumping is conveniently quantified by the so-called clumping factor, $f_{\rm cl} \geq 1$, which is a measure of the over-density inside the clumps (compared to a smooth flow of identical average mass-loss rate).[2] As already pointed out, diagnostics that are linearly dependent on the density are insensitive to clumping, whilst those sensitive to ρ^2 will tend to overestimate the mass-loss rate of a clumped wind, by a factor $\sqrt{f_{\rm cl}}$. For further details, see, e.g., Abbott et al. (1981), Lamers & Waters (1984b), Schmutz (1995) and Puls et al. (2006).

Until to date, the most plausible physical process responsible for small-scale structure formation in massive star winds is the so-called line-driven instability, found already in the first time-dependent hydrodynamical simulations of such winds (Owocki et al. 1988); for recent investigations, see Runacres & Owocki (2002, 2005) with respect to 1-D simulations and Dessart & Owocki (2003, 2005) for first attempts to include 2-D processes.

Though predicted from the earliest hydro-models on (and even before, see Lucy & Solomon 1970), it took some while to incorporate clumping into the

[1] in contrast to large-scale inhomogeneities such as co-rotating interaction zones (e.g., Cranmer & Owocki 1996 and references therein).

[2] An alternative description bases on the volume-filling factor, $f_{\rm V} = f_{\rm cl}^{-1}$.

atmospheric models of massive stars, firstly for Wolf-Rayet (WR) atmospheres, in order to explain
(a) the strength of the observed electron scattering wings (ρ-dependent) *in parallel* with the strength of the underlying (ρ^2-dep.) emission lines (Hillier 1991),
(b) the so-called momentum problem of WR winds (e.g., Schmutz 1995),
(c) the presence and variability of sub-structures in WR emission lines, by invoking supersonic turbulence leading to clumping factors of the order of $f_{\rm cl} \approx 9$ (Moffat & Robert 1994).

4. No clumping in OB-star winds?

In contrast to the case of WR winds, the diagnostics of OB-star winds did not render any necessity for (significant) clumping until recently. In particular, two major arguments supported the view of a rather smooth, almost unclumped flow:

1. The investigations by Lamers & Leitherer (1993) and Puls et al. (1996) showed that H_α *and* radio mass-loss rates are similar for a large sample of stars (but see also Drew (1990) who noted a discrepancy by a factor of two, the former being larger). Since H_α forms in the lower and the radio emission in the outer wind, this would imply a similar degree of clumping in both regions, which seemed to be improbable and is also in contradiction to theoretical predictions.
2. The observed *wind-momentum rates* were found to be in rather good agreement with theoretical predictions for this quantity, obtained from different, independent investigations (Vink et al. 2000, Kudritzki 2002, Puls et al. 2003, Krticka & Kubat 2004). A pure coincidence of this agreement seemed to be rather unlikely.

Taken together, it was concluded that clumping effects in OB-star winds should be negligible.

5. Indications of (significant) clumping in OB-star winds

As stated in the introduction, recent evidence points to the notion that this conclusion might be incorrect. In the following, we will summarize the different indications for significant clumping in OB-star winds accumulated so far. From the observational side, there is, to our knowledge, only one *direct* evidence for clumping. From a temporal analysis of He II 4686, Eversberg et al. (1998, in particular their Fig. 2) found "outward moving inhomogeneities" in the wind of ζ Pup, from regions near the photosphere out to 2 $R_\star$.

All other evidence is indirect, and the derived clumping factors cover a large range.

(a) From polarimetry and using simplified models, clumping factors of the order of $f_{\rm cl}$=2 are found (Davies, this volume).

(b) The analysis of radio and submm data from ϵ Ori and ζ Pup (Blomme et al. 2002, 2003) indicates a clear submm excess in both cases, which can be explained by (enhanced) clumping in the intermediate wind ($\approx 10R_\star$) (see also Blomme, this volume).

(c) NLTE model atmosphere analyses of UV spectra (partly incl. the optical range) of various O-stars indicate clumping factors of the order of $f_{\rm cl} = 10\ldots50$, but show that only few lines are suited to discriminate between clumped and unclumped flows. From these analyses (cf. Table 1), it was concluded that clumping, if present, should begin rather close to the wind base, at a few tens of km sec^{-1}. This finding is in contrast to hydrodynamical simulations, which show that the line-driven instability needs a certain time to grow and to become non-linear, so that significant clumping is expected not before 1.2 to 1.3 $R_\star$.

Table 1. Evidence of clumping from UV diagnostics (NLTE).

authors	objects	indicator	$f_{\rm cl}$	comments
Crowther et al. (2002)	AV232(O7Iaf+) SMC	P V	10	other lines barely affected by clumping
Hillier et al. (2003)	AV83(O7Iaf+) SMC	P V/strong UV photo-sph. lines	10	if clumping is important, it must begin at relatively low velocities (30 km/s!)
Bouret et al. (2003)	SMC dwarfs	O V	significant	
Bouret et al. (2005)	HD 190429A (O4If) HD 96715 (O4V((f))	P V, O V, N IV	25 50	reduction of $\dot{M}$ by factors of 5 and 7 clumping must start at the wind base

(d) From detailed investigations of the wind-momentum rates of a large sample of O-stars, Puls et al. (2003), Markova et al. (2004) and Repolust et al. (2004) found that supergiants with H_α in emission lie above the theoretical wind-momentum luminosity relation (WLR), whereas the rest fits almost perfectly. Since the WLR should be independent of luminosity class (e.g., Puls et al. 1996), this discrepancy was interpreted in terms of clumpy winds, with $f_{\rm cl} \approx 5$, and mass-loss rates reduced by factors between 2 and 3.

(e) A compelling, independent indication of clumping comes from SEI analyses of the P-Cygni P V $\lambda\lambda1118, 1128$ resonance line doublet (Massa et al. 2003, Fullerton et al. 2006, see also Massa, this volume), which has only become widely accessible since the launch of *FUSE*. Because phosphorus has a low cosmic abundance, this doublet never saturates in normal OB stars, providing useful estimates of not only $\dot{M}q$ (cf. Sect. 2.) but also $\dot{M}$ itself, *when* P^{4+} is the *dominant ion* – as it is implied at least for mid-O star winds. These mass-loss rates turned out to lie considerably below those inferred from other diagnostics such as H_α or radio emission. The most reasonable way to reconcile these results is to invoke extreme clumping in the wind (P V as a resonance line remains insensitive to *direct* clumping effects), indicating clumping factors of the order of $f_{\rm cl} \approx 100$ (or even more). Accordingly, the actual mass-loss rates should be *much* lower than previously thought, by a factor of $\gtrsim 10$. Further comments are given in Sect. 7.

(f) Using similar methods, Prinja et al. (2005) showed that the unsaturated P Cygni lines in lower luminosity B supergiants give, again, a factor of 10 lower mass-loss rates than theoretically expected. Crowther et al. (2006, see also Crowter, this volume), on the other side, found reasonable agreement between observed and predicted mass-loss rates for early/mid BIa supergiants, with similar (though unconstrained) clumping factors in the lower and intermediate wind.

6. A combined Ha/IR/mm/radio analysis

Whereas most of the above investigations are concerned with a *global* (i.e., radially almost constant) clumping factor or derive this quantity for certain wind regions only, there is, of course, the additional question regarding the radial stratification of $f_{\rm cl}$. To this end, Puls et al. (2006) recently performed a self-consistent analysis of H_α, IR, mm and radio fluxes, thus sampling the lower, intermediate and outer wind in parallel. This study comprises a sample of 19 Galactic O-type supergiants and giants with well known stellar parameters (from Markova et al. 2004, Repolust et al. 2004 and Mokiem et al. 2005), employing own measurements/archival data for H_α, IR/mm fluxes (*SCUBA*) and new *VLA* observations, including objects with H_α in absorption, i.e., low density winds.

A major result of this investigation is that in *weaker* winds the clumping factor is the same in the inner ($r < 2R_\star$) and outermost regions. However, for *stronger* winds, the clumping factor in the inner wind is larger than in the outer one, by factors of 3 to 6. 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 mass-loss rates then, we find $\dot{M}(\text{radio}) \approx \dot{M}(H_\alpha)$ for weak winds with H_α in absorption, whereas for all stars with H_α in emission we obtain $\dot{M}(\text{radio}) \approx 0.4 \ldots 0.5\, \dot{M}(H_\alpha)$, consistent with the arguments given by Markova et al./Repolust et al. and the earlier findings by Drew (1990).

Unfortunately, this analysis is hampered by one severe restriction. Since *all* diagnostics employed have a ρ^2 dependence, only *relative* clumping factors could be derived, normalized to the values in the outermost, radio-emitting region. In other words, $\dot{M}(\textsc{real}) \le \dot{M}(\text{radio})$, since until now the clumping in the radio emitting region is still unknown. Only if $f_{\rm cl}(\text{radio})$ were unity, we would have $\dot{M}(\textsc{real}) = \dot{M}(\text{radio})$. Thus, the issue of absolute values for $\dot{M}$ still remains unresolved.

7. The PV problem

The major result of the investigation by Fullerton et al. (2006) (see Sect. 5.) is displayed in Fig. 1. In this figure, they have plotted, as a function of $T_{\rm eff}$ and luminosity class, the quantity

$$q_{\rm est} = \frac{\langle \dot{M} q \rangle_{\rm obs}}{\dot{M}_{\rm Ha/radio}} \quad \rightarrow \frac{\langle \dot{M} q \rangle_{\rm obs}}{\dot{M} \sqrt{f_{\rm cl}}} \quad \rightarrow \frac{\langle q \rangle}{\sqrt{f_{\rm cl}}}, \tag{1}$$

for P^{4+}, where angle brackets denote spatial averages. The quantity in the nominator has been measured from the Pv lines, and the corresponding H_α/radio

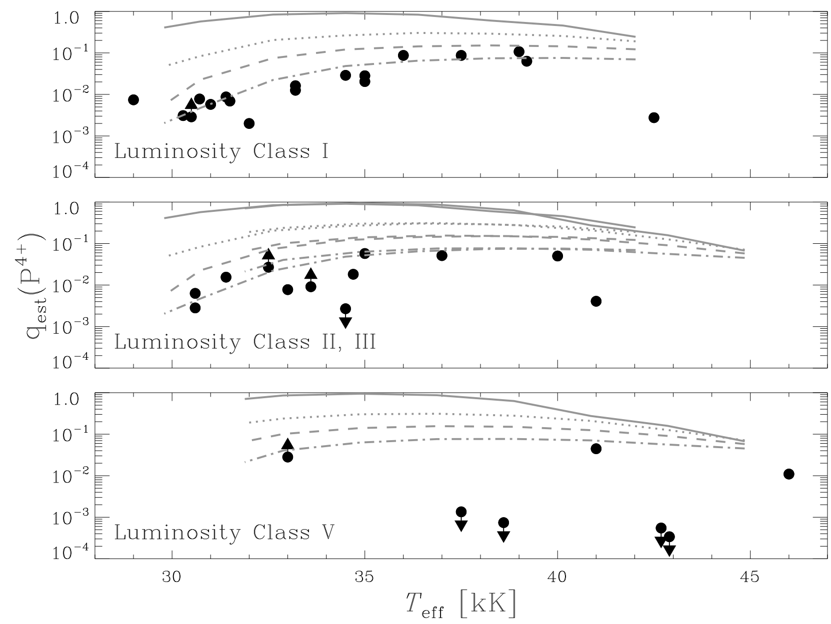

Figure 1. Derived estimates for $q_{\rm est}$ (Eq. 1) of P^{4+}, as a function of $T_{\rm eff}$ and luminosity class (for details, see Fullerton et al. 2006). Overplotted are predicted values for this quantity, as obtained from own calculations. Bold: unclumped models; other curves: clumped models, with $f_{\rm cl}$= 9, 36, 144 (dotted, dashed, dashed-dotted), respectively.

mass-loss rates have been taken from the literature. If the winds were unclumped, $q_{\rm est}$ would correspond to the average ionization fraction of P^{4+}, whereas for clumped winds this quantity is modified by $f_{\rm cl}^{-0.5}$. Fullerton et al. now argue that P^{4+} should be a dominant ion at mid O-type, and in this case the derived clumping factor would be $f_{\rm cl} = \mathcal{O}(100)$ at $T_{\rm eff}\approx$ 40,000 K. Additionally, however, they report on test calculations performed with *unclumped* models which show that, on the contrary, P^{4+} should become a dominant ion only below O7. If this were true, Fig. 1 would imply $f_{\rm cl} \approx 10,000$ in this temperature regime!

Since this is VERY unlikely, we have investigated the influence of clumping on the ionization fraction of P^{4+}. Due to the enhanced density inside the clumps, stronger recombination is expected (this is the *indirect* effect of clumping), which should change the picture (see also Bouret et al. 2005). By means of our model atmosphere code FASTWIND (Puls et al. 2005) and using the phosphorus model atom provided by Pauldrach et al. (2001), we have calculated a sequence of clumped models with $\dot{M}\sqrt{f_{\rm cl}}$ = const, i.e., models which have identical ρ^2-diagnostics mass-loss rates. As shown in Fig. 2, increased clumping indeed shifts P^{4+} as a dominant ion towards higher $T_{\rm eff}$: for unclumped models, it is dominant at O8/7, whereas for the largest clumping factors it dominates at O5.

Using these models then, the "observed" run of $q_{\rm est}$ can be reproduced with highly clumped models ($f_{\rm cl}$= 144, see Fig. 1), for almost all luminosity classes and except for the very hottest temperatures (see below). Thus, our calculations confirm the hypothesis stated by Fullerton et al., i.e., clumping *is* possible to

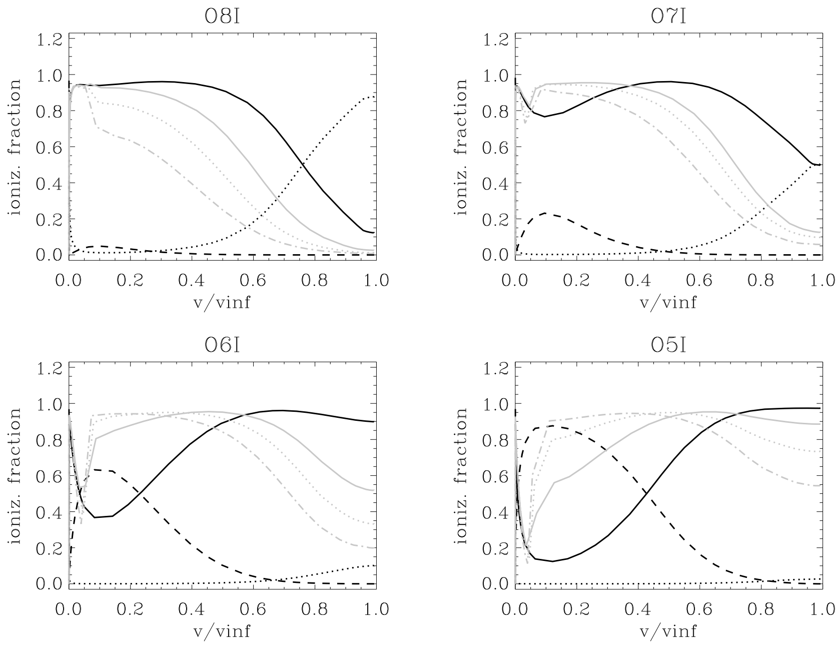

Figure 2. Ionization fractions of phosphorus, as a function of velocity and spectral type, for supergiants. Black: Unclumped models (bold - Pv, dotted - Piv, dashed - Pvi). Grey: Ionisation fractions of Pv, for clumped models with $f_{\rm cl}$= 9, 36, 144 (bold, dotted, dashed), respectively.

explain the observations, and mass-loss rates might indeed be lower by factors of 10 or even more.

8. Implications

As we have seen, there seems to be a (physical) difference between thinner and thicker winds. For thinner winds, there is a similar degree of clumping in the lower and outer wind, whereas for thicker winds clumping is stronger in the lower part. The actual mass-loss rates depend on the clumping in outer wind, which is still an unsolved issue.

If the outer winds were unclumped, our results would be consistent with theoretical WLRs. In this case then, one would meet a severe dilemma with the results from the F(UV), which might hopefully be explained by additional effects from X-rays emitted due to clump-clump collisions (Feldmeier et al. 1997, Pauldrach et al. 2001). X-rays might also help to solve the problem encountered for Pv at highest $T_{\rm eff}$.

If, on the other hand, the (F)UV values were correct, the outer wind must be significantly clumped, and the present match of "observed" and predicted WLR would indeed by only coincidental. This scenario would imply a number of severe problems, not only for radiation driven wind theory, but, most importantly, concerning the stellar evolution in the upper HRD and related topics. A possible way out of the latter problem has been suggested by N. Smith (this volume).

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