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# Validity of Clumping Approximations for Mass-Loss Rates Determination

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**Abstract.** Clumping in stellar winds of hot stars is a possible consequence of radiative-acoustic instability appearing in solutions of radiative-hydrodynamical equations. However, clumping is usually included into stellar atmosphere modeling and radiative transfer calculations in a highly approximate way via a global free parameter called the clumping factor. Using different values of clumping factors, many researchers succeeded to fit the observed spectra better and to correct empirical mass-loss rates. This usually leads to a conclusion that the stellar wind is clumped. To understand how clumping may influence theoretical predictions of mass-loss rates, different clumping properties have to be taken into account. If clumping appears already below the critical point, the mass-loss rate is changed.

## 1. Introduction

Many inhomogeneous structures in different astronomical objects have been directly observed, in supernova remnants, planetary nebulae, or just recently structures in the envelope of the red supergiant $\alpha$ Ori (Kervella et al. 2011). Consequently, there is no reason to assume that the winds of hot stars are perfectly homogeneous.

However, there are no such direct observations of wind structures available. The presence of clumping was inferred from line profile variability (e.g. Eversberg, Lépine, & Moffat 1998; Lépine & Moffat 1999; Markova et al. 2005; Hamann, Feldmeier, & Oskinova 2008). Indirect evidence of clumping comes from X-ray observations (Oskinova, Feldmeier, & Hamann 2004). Another evidence of clumping follows from detection of X-ray flaring in Vela X-1, caused probably by wind clumps falling onto a neutron star (Fürst et al. 2010).

The generally accepted origin of clumping in hot star winds is the radiative-acoustic instability, supported by several numerical simulations (see the review by Sundqvist et al., these proceedings). An alternative explanation using adiabatic fluctuations (Chiueh 1997) did not attract attention of researchers. However, the recent interesting idea of the influence of subphotospheric convection (Cantiello et al. 2009) offers a possibility for the existence of clumps in the part of the wind below the critical point, where the numerical wind simulations do not predict it (e.g. Feldmeier 1995; Runacres & Owocki 2002). It seems that the most probable clumping scenario consists of multiple clump formation mechanisms. Although there is a lot of unknown parameters about clump formation, distribution, and properties, to find some kind of description of clumping is very important.

## 2. Description of Clumping

### 2.1. Void Interclump Medium

Due to missing direct observation of wind clumps the detailed treatment of clumping is usually restricted to using free parameters. This approach was previously used for the description of condensations in nebulae by Osterbrock & Flather (1959) for the case of the Orion nebula, where they assumed void intercondensation medium and used the size of condensations as the free parameter, since the observational data available to them did not allow to resolve details. Contemporary advanced observational techniques made the usage of the free parameter unnecessary.

The assumption of the void interclump medium is a common one for the description of a clumped wind. In other words it means that all matter is concentrated into clumps in vacuum. Such medium can be described by means of one free parameter, which may be either the *(volume) filling factor*:

$$f = \frac{V_{\text{clumps}}}{V_{\text{wind}}}, \tag{1}$$

a fractional volume which contains material at higher density (referred to as the filling fraction by Owocki & Cohen 2006), or the *clumping (correction) factor*:

$$D = C_c = f_{\text{cl}} = \frac{\langle \rho_{\text{clumps}} \rangle}{\langle \rho_{\text{wind}} \rangle} = \frac{1}{f}. \tag{2}$$

Just one of these two adjustable parameters is sufficient. However, there is no reason to assume that the parameter defined by Equation (1) or (2) is depth independent. Its depth dependence follows already from the pioneering hydrosimulations of Owocki, Castor, & Rybicki (1988). Hillier & Miller (1999) introduced an expression for the depth dependence of the filling factor:

$$f(r) = f_\infty + (1 - f_\infty) \exp\left(-\frac{v(r)}{v_{\text{cl}}}\right), \tag{3}$$

where $f_\infty$ corresponds to Equation (1) and $v_{\text{cl}}$ is the location in the wind where clumping becomes important. Many radiative transfer calculations have been done using this expression. Recently, Puls et al. (2006) tried to determine the depth dependence of the filling factor from observations.

### 2.2. Dense Interclump Medium

The assumption of the void interclump medium simplifies the description of clumping. The non-void interclump medium was assumed already by Abbott, Bieging, & Churchwell (1981), however, it was abandoned by later studies. Recently the idea of a dense interclump medium was revoked by Zsargó et al. (2008). The effect of dense interclump medium was studied in detail by Sundqvist, Puls, & Feldmeier (2010), Sundqvist et al. (2011), and Šurlan et al. (these proceedings). Inclusion of the non-void interclump medium requires an additional free parameter $d$, which relates the interclump density to the clump density or to the density of the smooth wind.

### 2.3. Clump Properties

In most radiative transfer calculations with clumping it is assumed that clumps are optically thin, which means that clumps are smaller than the mean free path of photons. This assumption is sometimes referred to as the "microclumping". However, it is more natural to assume that clumps may be optically thick in some frequencies. These clumps are larger than the mean free path of photons, which may happen both in continua and lines. This situation is being referred to as the "macroclumping" (Oskinova, Hamann, & Feldmeier 2007) or "porosity" (Owocki & Cohen 2006).

Since 3-D hydrodynamical simulations of the wind are not available, there is no hint what the shape of clumps may be. In the parametric treatment using the clumping factor, nothing is explicitly assumed about the clump shape and sizes. In more detailed calculations, different shapes were assumed, like spheres (Šurlan et al., these proceedings), cubes (Muijres et al. 2011), or shell fragments (Oskinova et al. 2004). On the other hand, it is not clear how important is the detailed clump shape, probably a more important factor is the distribution of clumps due to the stochastic nature of clumping.

The common assumption of most calculations is a smooth velocity field both inside and outside clumps. However, as follows from hydrodynamical simulations, assuming non-monotonic field inside clumps is probably closer to reality (see Owocki 2008). This generalization was studied in more details by Sundqvist et al. (2010, 2011, and these proceedings) and Šurlan et al. (these proceedings). Note, however, that inhomogeneous velocity field can affect only spectral lines.

## 3. Influence of Clumping on Empirical Mass-Loss Rates

Mass-loss rates for particular stars are usually determined from the comparison of model emergent radiation with observations. The emergent radiation is usually calculated assuming (i.e. for *given*) velocity $v(r)$ and density $\rho(r)$ structure (and, consequently, the mass-loss rate $\dot{M}$ and the terminal velocity $v_\infty$). The velocity structure is usually assumed to obey the so-called $\beta$-velocity law $v = v_\infty\,(1 - R_*/r)^\beta$, where $R_*$ is the stellar radius and $\beta$ is a free parameter. Note that this type of dependence was already derived by Milne (1926) and Chandrasekhar (1934) with $\beta = 0.5$. Today's estimates of this value are a bit higher.

The mass-loss rates are usually determined using different parts of the stellar spectrum, like the radio flux, infrared flux, H$\alpha$ line, UV resonance lines, and using synthetic spectra from model atmospheres. Various determination methods were reviewed by Puls, Vink, & Najarro (2008). Different diagnostics result in different mass-loss rates (e.g. Bouret et al. 2003; Fullerton, Massa, & Prinja 2006). Clumping in stellar winds is the suggested and promising way out from this problem.

Hillier (1991) tested clumping by artificial periodic variation of $\rho(r)$. Later Hillier & Miller (1999) introduced a depth variable filling factor [(Eq. (3)], which became a common method for inclusion of clumping in line formation calculations. Since many studies found that mass-loss rates with clumping taken into account in this way fit observations better, then the conclusion about the presence of clumping was drawn.

### 3.1. Unsaturated Resonance Lines

Saturated resonance ultraviolet lines fit theoretical spectra usually well, but their sensitivity to changes of wind parameters is relatively low. On the other hand, if lines are not saturated, they become a sensitive diagnostics tool. This happens for resonance lines of less abundant ions like S ɪᴠ, S ᴠ, Si ɪᴠ, or P ᴠ. The case of the Si ɪᴠ resonance line (1393.76 and 1402.77 Å) was recently studied by Prinja & Massa (2010) and from similar line strengths of the resonance doublet they concluded that the wind is clumped, since in the opposite case the line ratio should be 2.

The case of the resonance lines of P ᴠ (1117.98 and 1128.01 Å) is more famous. The possible importance of this doublet for mass-loss rate determination was pointed out by Crowther et al. (2002). Massa et al. (2003) and later Fullerton et al. (2006) found a discrepancy in mass-loss rate determination and concluded that either the mass-loss rates determined from P ᴠ resonance lines are wrong (which may be corrected by inclusion of wind clumping) or the abundance of P ᴠ is lower.

To test the abundance of P ᴠ, Krtička & Kubát (2009) studied the NLTE ionization balance of phosphorus in the wind. Using the code of Krtička & Kubát (2004), they calculated the phosphorus ionization balance both with and without X-rays and found that the changes were insignificant. Consequently, the abundance of P ᴠ is not lowered by the presence of X-rays, which supports the clumping hypothesis. However, Waldron & Cassinelli (2010) suggested that XUV radiation may be important for phosphorus ionization balance, but detailed NLTE calculation is still missing.

## 4. Influence of Clumping on Predicted Mass-Loss Rates

While it is basically known how clumping (treated in the parametric way using the volume filling factor) influences the empirical determination of mass-loss rate for *given* velocity and density structure, the situation is less clear for the case of mass-loss rate predictions.

The solution of hydrodynamic equations for given basic stellar parameters (e.g. the effective temperature $T_{\rm eff}$, luminosity $L_*$, and radius $R_*$) and the radiation at the lower boundary give the density $\rho(r)$ and velocity $\upsilon(r)$ structure of the wind. Values of the mass-loss rate $\dot{M}$ and terminal velocity $\upsilon_\infty$ follow directly from the determined structure, they are usually called predicted. The principal question is, how clumping influences predicted values of $\dot{M}$ and $\upsilon_\infty$.

This was studied by Krtička et al. (2008a,b) using the stationary hydrodynamic code for NLTE stellar winds (Krtička & Kubát 2004), which consistently calculates the radiative force without using the CAK parameters ($k$, $\alpha$, and $\delta$). Clumping was treated in an approximate way [$\rho_{\rm clump} = C_c\langle\rho\rangle$; cf. Eq. (2)] and void interclump medium was assumed. This assumption modified the opacity and emissivity in a different way for lines and continua, consequently the radiative force was modified. Both optically thin and optically thick clumps were tested. They found that if clumping starts below the critical point, then the mass-loss rate increases. If clumping starts above the critical point, then the mass-loss rate does not change, but the terminal velocity increases. Clumps larger than the Sobolev length result in the decrease of the mass-loss rate. Clumping also influences the ionization balance, which has a strong impact on the line force and, consequently, wind acceleration. Muijres et al. (2011) studied the effect of different portions of clumped and unclumped parts of the wind and different clump sizes (assuming that clumps are cubes). They used the Monte Carlo wind code of Vink, de Koter, & Lamers (2000, 2001) and found that optically thin clumps increase the mass-loss rate, whereas optically thick clumps decrease the mass-loss rate.

## 5. Conclusions

The problem of P v mass-loss rate determination has not been satisfactorily solved yet. While X-rays do not seem to alter the ionization balance of P v, the case of XUV radiation has still to be tested by detailed consistent NLTE calculations.

The dependence of mass-loss rates on clumping has still not been analyzed in a big detail yet. Available results show that clumping below the critical point may have strong influence on predicted mass-loss rates. Although results of hydrodynamical simulations do not support clumping below the sonic point, there is a possibility of creating clumps by other mechanisms. Detailed hydrodynamical calculations are needed.

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## Discussion

*Vink*: With respect to the onset of clumping: another clumping diagnostic involves the variations in linear polarization. If you produce a clump *in* the wind, this produces linear polarization but at the same time, the void you leave behind produces polarization that cancels out. In other words, the observations of time variable polarization indicate that the clumping does not start in the wind, but that it is already present in the photosphere.

*Kubát* : Yes, this could be another argument supporting the onset of clumping at the bottom of the wind.

*Sundqvist*: Regarding Jorick's comment that spectropolarimetry results suggest that clumping is present already in the photosphere: Would this not result in detectable effects on the photospheric diagnostics?

*Vink*: It is tempting to link Matteo's subsurface convection zones to wind clumping and photospheric velocity fields, perhaps related to microturbulence.

*Owocki*: Regarding polarization, remember that hot stars also show evidence for large-scale structure, e.g. DACs, etc., and it is likely that this is more important for explaining near-zero polarization. The issue is how such large-scale structure co-exists with small-scale, stochastic structure developing from the line-driven instability.

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