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Stellar winds from solar-metallicity and metal-rich massive stars

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Abstract

We discuss theoretical predictions and observational findings obtained for radiatively driven winds of massive stars, with emphasis on their dependence on metallicity. If these winds are not strongly clumped or the clumping properties are independent of metallicity z, theory and observations agree very well, and mass-loss rates and terminal velocities scale as $\dot{M} \propto z^{0.62 \pm 015}$ and $v_\infty \propto z^{0.13}$, respectively. This dependence could be validated only for winds with solar and sub-solar abundances, due to missing super-solar metallicity test cases. The actual values for the mass-loss rates are uncertain, due to unknown clumping properties of the wind, and currently accepted numbers might be overestimated, by factors in between ~2 and 10.

1.1 Introduction

Massive stars and their winds are crucial for the chemical and dynamical evolution of galaxies through their input of radiation, energy, momentum, and nuclear processed material. In the distant Universe, massive stars dominate the integrated UV-light of very young galaxies (e.g., Steidel et al. 1996; Pettini et al. 2000), and even earlier they are the suspected sources of the re-ionization of the Universe (Bromm et al., 2001).

Together with rotation, stellar winds control the specific evolution in the upper HRD ($M_{\rm zams} \gtrsim 10\,{\rm M}_\odot$), by affecting time-scales, chemical profiles, surface abundances and luminosities. E.g., changing the mass-loss rates of massive stars by only a factor of two has a dramatic effect on their evolution (Meynet et al., 1994).

In the following, we will review important theoretical and observational aspects of these winds, with emphasis on their dependence on metallicity. Finally, we will comment on recent evidence which indicates that currently accepted mass-loss rates may need to be revised downwards, by as much as a factor of ten.

1.2 Radiation driven winds: Theoretical predictions

Stellar wind from hot stars are accelerated by radiative *line*-driving, with typical mass-loss rates, $\dot{M}$, of the order of $0.1\ldots 10 \cdot 10^{-6}\,\mathrm{M}_{\odot}/\mathrm{yr}$, (resulting in a significant mass fraction to be lost during their evolution), and terminal wind velocities, v_{∞}, of the order of 200 $\mathrm{km\,s^{-1}}$(A-supergiants) to 3 000 $\mathrm{km\,s^{-1}}$(hot O-dwarfs). In parallel with the line absorption of stellar photons, radial momentum is transferred to the absorbing ions (mostly metals), which is redistributed to the bulk matter (H/He) via Coulomb collisions. In order to become efficient, this process requires a large number of stellar photons, i.e., a high luminosity $L \propto R_{\star}^2 T_{\mathrm{eff}}^4$ (supergiants or hot dwarfs), and a large number of absorbing lines close to the flux maximum with high interaction probabilities. The latter constraint inevitably leads to a *metallicity dependence* of mass-loss. Pioneering investigations have been performed by Lucy & Solomon (1970) and Castor, Abbott & Klein (1975), with further improvements regarding a quantitative description/application by Friend & Abbott (1986) and Pauldrach, Puls & Kudritzki (1986). The latest review on this topic has been given by Kudritzki & Puls (2000).

The total radiative line acceleration, $g_{\mathrm{rad}}^{\mathrm{lines}}$, consists of the individual contributions, $\Sigma g_{\mathrm{rad}}^{i}$, where the corresponding line transitions can be either optically thin or thick, with

$$g_{\mathrm{rad}}^{\mathrm{thin}} \propto L_{\nu}^{i} k^{i}, \qquad g_{\mathrm{rad}}^{\mathrm{thick}} \propto L_{\nu}^{i} \frac{\mathrm{d}v/\mathrm{d}r}{\rho}.$$

L_{ν}^{i} is the luminosity at frequency of line i, $k^{i} \propto \chi^{i}/\rho$ the dimensionless line-strength, χ the frequency integrated line opacity and ρ the density. Because of the large number of lines being present *and needed* to accelerate the wind (our data base comprises roughly 4 million lines from 150 ions), a statistical approach is well suited, and the above sum can be approximated by an integral over the line-strength distribution, $N(k)$. From early on, it turned out that this distribution closely follows a power law, $\mathrm{d}N(k)/\mathrm{d}k \approx k^{\alpha-2}$, where α is of the order of 0.6…0.7 under typical conditions (cf. Fig. 1.1, left). Details can be found, e.g., in Puls et al. (2000). By means of this distribution and integrating over all (optically thin and thick) lines, the line acceleration turns out to dependent on the luminosity and the spatial

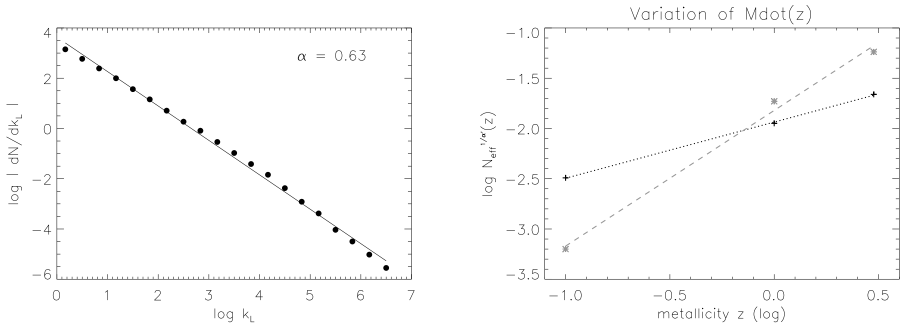

Fig. 1.1. Left: Logarithmic plot of the line-strength distribution function for an O-type wind of 40 000 K, and corresponding power-law fit. Right: Predictions from line-statistics. Dependence of mass-loss (via $N_{\rm eff}^{1/\alpha'}$, cf. Eq. 1.1) on metallicity, for $T_{\rm eff}$= 40 kK (black) and Teff = 10 kK (grey). The slopes are 0.56 and 1.35, respectively. Adapted from Puls et al. (2000).

velocity gradient(!),

$$g_{\rm rad}^{\rm lines} = \Sigma_i g_{\rm rad}^i \rightarrow \int\int g_{\rm rad}^i(\nu,k){\rm d}N(\nu,k) \propto N_{\rm eff}\, L \left(\frac{{\rm d}v/{\rm d}r}{\rho}\right)^{\alpha},$$

with $N_{\rm eff}$ the so-called effective (flux-weighted) number of lines.

Scaling laws. Inserting this expression into the hydrodynamical equation of motion, the latter can be solved, together with the equation of continuity, (almost) analytically (e.g., Kudritzki et al. 1989), and the resulting wind parameters obey the following scaling laws (rotation neglected)

$$\dot{M} \propto N_{\rm eff}^{1/\alpha'}\, L^{1/\alpha'}\, (M(1-\Gamma))^{1-1/\alpha'} \quad (1.1)$$

$$v_\infty \approx 2.25\frac{\alpha}{1-\alpha} v_{\rm esc}, \qquad v_{\rm esc} = \left(\frac{2GM(1-\Gamma)}{R_\star}\right)^{1/2} \quad (1.2)$$

$$v(r) = v_\infty\,(1-\frac{R_\star}{r})^{\beta}, \quad \beta \approx 0.8(\text{O-stars})\ldots 2(\text{BA-supergiants}). \quad (1.3)$$

Γ is the Eddington factor (Thomson-scattering diminishes the effective gravity), α the power-law index of the line-strength distribution function, and $\alpha' = \alpha - \delta$, with $\delta \approx 0.1$ the so-called ionization parameter.

Wind-momentum luminosity relation. Exploiting the fact that α' is close to 2/3, the so-called modified wind-momentum rate, $D_{\rm mom}$ (Kudritzki et al., 1995; Puls et al., 1996), becomes almost independent of mass:

$$D_{\rm mom} = \dot{M} v_\infty (R_\star/R_\odot)^{1/2} \propto N_{\rm eff}^{1/\alpha'} L^{1/\alpha'} \quad (1.4)$$

$$\log D_{\rm mom} \approx \frac{1}{\alpha'}\log L + \text{const(z, spectral type)}. \quad (1.5)$$

This *wind-momentum luminosity relation* (WLR) constitutes one of the most important predictions of radiation-driven wind theory, and can be applied at least in two ways. (i) From spectral analyses of large samples of massive stars, one can construct *observed* WLRs, and calibrate them as a function of spectral type and metallicity z ($N_{\rm eff}$ and α' depend on both parameters). The derived relations can then be used as an independent tool to measure extragalactic distances from the wind-properties, effective temperatures and metallicities of distant stellar samples. (ii) Observed WLRs can be compared with *theoretical* predictions in order to test the validity of the theory itself.

Predictions from line statistics. Since a higher metallicity translates into higher opacities, an increase in abundance leads to a larger number of lines which can accelerate the wind. Denoting the *global* metallicity by z (normalized to the solar value), it turns out that the effective number of lines scales via $N_{\rm eff} \propto z^{1-\alpha}$, and thus, via Eq. 1.1

$$\dot{M}, D_{\rm mom} \propto z^{\frac{1-\alpha}{\alpha'}}. \tag{1.6}$$

For O-type winds then ($\alpha \approx 2/3$), this means a scaling with $z^{0.6}$, whereas for A-supergiant winds ($\alpha \approx 0.4\ldots0.5$) a dependence of $z^{1.3\ldots2}$ is predicted (cf. Fig. 1.1, right). **For** (so far hypothetical) **massive star winds with $z = 2$, this implies a factor of 1.5 to 2.8 higher mass-loss rates, compared to winds of solar composition.**

Not only the global abundance affects the wind, but also the specific composition. Due to a different line-strength statistics, lines from Fe-group elements and light elements (CNO and similar) have a different impact on the wind properties. In particular, Fe-group elements dominate the acceleration of the lower wind, and thus determine $\dot{M}$, whereas lines from light elements dominate the acceleration of the outer wind, and thus determine v_∞. For details, see Puls et al. (2000), but also similar results from hydrodynamical calculations by Pauldrach (1987), Vink et al. (1999, 2001) and Krticka (2006).

Predictions from hydrodynamical models. The most frequently quoted predictions for the wind properties of OB-type stars result from the hydrodynamical models provided by Vink et al. (2000), summarized by them in terms of a "mass-loss recipe". These predictions are in very good agreement with independent models by Kudritzki (2002, $v_\infty \propto z^{0.12}$), Puls et al. (2003) and Krticka & Kubat (2004). Similar approaches have been used to predict the metallicity dependence. In particular, Vink et al. (2001) derive $\dot{M} \propto z^{0.69}$ for O-stars and $\dot{M} \propto z^{0.64}$ for B-supergiants, and Krticka (2006) found $\dot{M} \propto z^{0.67}$, $v_\infty \propto z^{0.06}$ for O-stars. Note that these results

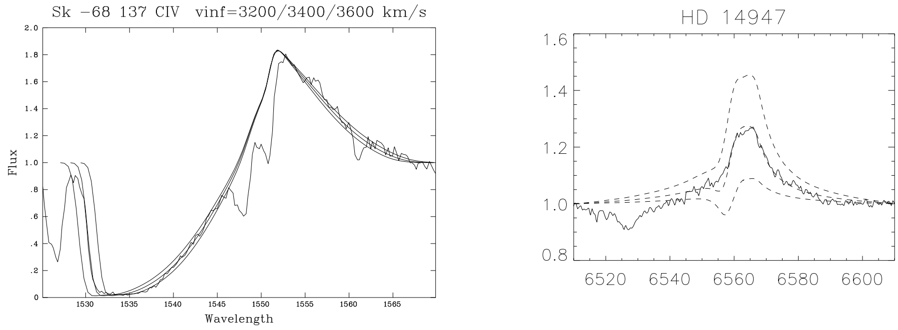

Fig. 1.2. Left: Derivation of v_∞ from UV P Cygni lines (here, from C IV1548/50). From Kudritzki (1998). Right: $\dot{M}$ from H_α. Synthetic profiles (dashed) from models varied by ± 30% in $\dot{M}$. Figure adapted from Puls et al. (1996).

are in very good agreement with the results from line-statistics alone (see above). With respect to the winds of Wolf-Rayet, which depend strongly on the Fe-content, we refer to the work by Gräfener & Hamann (2005, see also Gräfener, *this volume*), Vink & de Koter (2005), and Crowther & Hadfield (2006, and Crowther, *this volume*).

1.3 Results derived from observations

The derivation of stellar/wind parameters from observations via *quantitative spectroscopy* requires the assumption of a physical model (incorporated into the atmosphere codes which synthesize the spectra). Most of the results presented in the following base on a standard, 1-D description with a *smooth* wind (but see Sect. 1.4). The different parameters have to be derived by suitable diagnostics:

- photospheric parameters: $T_{\rm eff}$, $\log g$, Helium content from optical lines and NLTE atmospheres (incl. wind).
- wind parameters: v_∞(Fig. 1.2, left), $\dot{M}$, velocity law from UV P-Cygni lines and/or optical/IR (emission) lines (H_α- Fig. 1.2, right, He II4686, Br_α), $\dot{M}$ also from the radio free-free excess.
- stellar radius: from distance, V-band magnitude and theoretical fluxes (reddening!).
- metallicity: from spectrum (UV and optical) and models.

During the last decade, a large number of such spectroscopic investigations have been conducted. In Table 1.1 we have compiled important contributions regarding OBA-stars *and their winds* (excluding Galactic Center

Table 1.1. *Quantitative spectroscopy of OBA-stars and their winds in the Galaxy and the MCs, by means of spherically extended model atmospheres*

diag.	authors	atmospheric model	sample
H_α	Lamers & Leitherer (1993)	approx.	Galactic O-stars
	Puls et al. (1996)	approx.	Galactic/LMC/SMC O-stars
	Kudritzki et al. (1999)	NLTE/unblanketed	Galactic BA-supergiants
	Markova et al. (2004)	approx.	Galactic O-stars
UV	Bianchi & Garcia (2002)	NLTE/WM-basic	Galactic O-stars
	Garcia & Bianchi (2004)	"	Galactic O-stars
	Martins et al. (2004)	NLTE/CMFGEN	SMC O-dwarfs
UV + optical	Crowther et al. (2002)	NLTE/CMFGEN	LMC/SMC O-supergiants
	Hillier et al. (2003)	"	SMC O-supergiants
	Bouret et al. (2003)	"	SMC O-dwarfs
	Martins et al. (2005)	"	Galactic O-dwarfs
	Bouret et al. (2005)	"	Galctic O-stars
optical	Herrero et al. (2002)	NLTE/FASTWIND	Cyg-OB2 OB-stars
	Repolust et al. (2004)	"	Galactic O-stars
	Trundle et al. (2004)	"	SMC B-supergiants
	Trundle & Lennon (2005)	"	SMC B-supergiants
	Massey et al. (2004/05)	"	LMC/SMC O-stars
	Mokiem et al. (2005)	"	Galactic O-stars
	Crowther et al. (2006)	NLTE/CMFGEN	Galactic B-supergiants
	Mokiem et al. (2006a/b)	NLTE/FASTWIND	SMC/LMC OB-stars

CMFGEN (Hillier & Miller 1998), WM-basic (Pauldrach et al. 2001), FW (Puls et al. 2005).

objects; see Najarro, *this volume*). Most of them have been performed by means of *line-blanketed* NLTE atmosphere codes.

Taken together, the most important results of these investigations can be summarized as follows. Compared to previous investigations, the $T_{\rm eff}$-scale has become lower, due to line-blanketing effects. The mass-loss rates in the SMC (and in the LMC, see below) are systematically smaller than in the Galaxy, though the scatter is large. The observed WLRs meet the theoretical predictions, except for (i) O-supergiants with rather dense winds (which might be explained by wind-clumping, see Sect. 1.4) (ii) low luminosity O-dwarfs with much lower observed wind-momenta than predicted (the reason for this is unclear) and (iii) a large fraction (but not all) of B2/3 supergiants, where again the observed wind momenta are "too low" (unexplained as well).

O-star wind momentum rates from the FLAMES survey of massive stars. Using the FLAMES multi-object spectrograph attached to the VLT, a large collaboration of colleagues have conducted a programme to

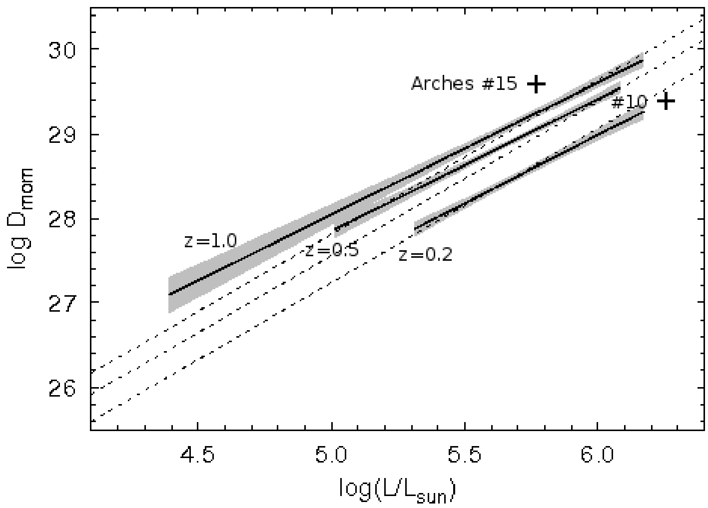

Fig. 1.3. Observed WLRs for the Galaxy and the MCs, as derived by Mokiem et al. (2007, see also de Koter 2007). The grey shaded areas denote the 1-σ confidence interval, and the dashed lines represent the theoretical predictions from Vink et al. (2000, 2001). For comparison, we have overplotted the wind-momentum rates from 2 Of$^+$ stars in the Arches cluster, both of them with $T_{\rm eff} \approx 30$ kK, as analyzed by Najarro et al. (2004). Original figure from Mokiem et al. (2007).

investigate the stellar content of clusters of different ages in the Galaxy and the Magellanic Clouds (for the introductory publication, see Evans et al. 2005). With respect to massive stars, roughly 60 O-/early B-stars from the SMC/LMC have been analyzed in a *homogeneous and objective* way. This has been achieved by means of an "automatic" analysis method combining a genetic algorithm (PIKAIA, Charbonneau 1995) used to obtain the optimum fit and FASTWIND (see Table 1.1) to calculate the synthetic spectra. The method itself has been presented (and tested) by Mokiem et al. (2005), and the analysis of the SMC/LMC data is described in Mokiem et al. (2006a,b).

By combining these data with data from previous investigations, the "observed" metallicity dependence of $\dot{M}$ and $D_{\rm mom}$ could be derived with an unprecedented precision,

$$\dot{M} \propto z^{0.62 \pm 0.15}, \qquad v_\infty \propto z^{0.13}$$

where the scaling-law for v_∞ had been obtained much earlier, by Leitherer et al. (1992). Both results are in very good agreement with the theory (cf. Sect. 1.2 and Fig. 1.3).

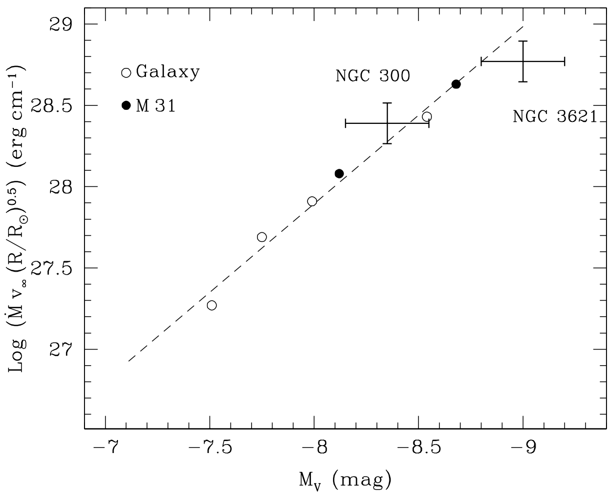

Fig. 1.4. WLR for Galactic and extra-galactic A-supergiants. Data from Kudritzki et al. (1999, Galaxy), McCarthy et al. (1997, M31), Bresolin et al. (2001, M31, NGC 3621) and Bresolin et al. (2002, NGC 300). Regarding the M31 objects, see also Przybilla (*this volume*). Figure from Bresolin et al. (2002).

Beyond the Local Group. The availability of 8m-class telescopes allows to extend our investigations to objects in more distant galaxies, not only in the Local Group but also beyond, when concentrating on the visually brightest stars in the sky, the A-supergiants. Examples for recent results are given in Fig. 1.4, which shows that the slope of the corresponding WLR is consistent with the theoretical prediction in this parameter range ($\alpha' \approx 0.4$). So far, no object with *clear* evidence for super-solar metallicity has been found (see Lennon, *this volume*). Further work has been presented by Bianchi et al. (1996, UV analyses of M31/M33 OB-sgs), Smartt et al. (2001, UV/optical analyses of M31 B-sgs), Urbaneja et al. (2003, optical analysis of NGC 300 B-sgs), Urbaneja et al. (2005, optical analyses of M33 B-sgs) and Trundle (*this volume*, M31 B-sgs).

1.4 The impact of wind-clumping

From what has been discussed so far, it seems that the outflows from luminous OBA-stars are well understood. There is, however, accumulating evidence that currently accepted mass-loss rates *may* need to be revised downwards *by as much as a factor of ten*, as a consequence of previously neglected wind "clumping" which affects most mass-loss diagnostics.

Such revisions, of course, would have dramatic consequences, not only for the stellar evolution (Sect. 1.1) but also regarding the feed-back from massive stars. In the following, we will summarize the status quo, whereas a more detailed discussion can be found in Puls et al. (2006, 2007, and references therein).

The present hypothesis states that clumping (if present) is a matter of *small-scale* density inhomogeneities in the wind, 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). Diagnostics that are linearly dependent on the density (e.g., UV resonance lines) are insensitive to clumping, whilst those sensitive to ρ^2 (such as H_α or free-free radio emission) *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 (1984); Schmutz (1995) and Puls et al. (2006).

Until now, 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). Nevertheless, it took some while to incorporate clumping into the *atmospheric models* of massive stars, firstly for Wolf-Rayet (WR) atmospheres, in particular to explain the strength of the observed electron scattering wings of emission lines (Hillier, 1991) and the presence and variability of sub-structures in these lines (e.g., Moffat & Robert 1994).

The diagnostics of OB-star winds, on the other hand, did not require (significant) clumping until recently, particularly because of the very good agreement between the theoretically predicted and observed WLRs (see above). A pure coincidence of this agreement seemed to be rather unlikely.

Though there is still almost no *direct* observational evidence (but see Eversberg et al. 1998), to date a number of indirect indications favour the presence of wind-clumping in OB-star winds, and we like to stress here three important aspects.

(i) From detailed investigations of large samples of Galactic 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 WLR (see Sect. 1.3), 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. Indeed, an analogous correction has been applied in the investigation by Mokiem et al. (2007, see Fig. 1.3).

(ii) A compelling, independent indication of clumping comes from analyses of the UV P-Cygni P V 1118/28 resonance line doublet (Massa et al., 2003; Fullerton et al., 2006) observed by *FUSE*. Because phosphorus has a low cosmic abundance, this doublet never saturates in normal OB stars, providing useful estimates of $\dot{M}$ *when* P^{4+} is the *dominant ion* – as it is implied at least for mid-O star winds (see also Puls et al. 2007). These mass-loss rates turned out to lie considerably below those inferred from other (clumping-sensitive) diagnostics such as H_α or radio emission. The most reasonable way to reconcile both results is to invoke extreme clumping in the wind ($f_{\rm cl} \approx 100$), with actual mass-loss rates being *much* lower than previously thought, by a factor of $\gtrsim 10$.
(iii) If clumping were present indeed, there is, of course, the additional question regarding the radial stratification of $f_{\rm cl}$. To this end, Puls et al. (2006) performed a self-consistent analysis of H_α, IR, mm and radio fluxes, thus sampling the lower, intermediate and outer wind in parallel, on basis of a sample of 19 well-known Galactic O-type supergiants and giants. 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 is consistent with the arguments outlined in (i) and earlier findings by Drew (1990).

Unfortunately, the latter analysis is hampered by one severe restriction. Since *all* employed diagnostics 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* $\dot{M}$ *remains unresolved.*

Implications. *If*, on the one hand, the latter hypothesis were true, i.e., the outer winds were unclumped, the results obtained by Puls et al. (2006) would be consistent with theoretical WLRs. In this case then, one would meet a severe dilemma with the results from the FUV, 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).
If, on the other hand, the FUV values were correct, the outer wind must be significantly clumped, and the present match of "observed" and predicted WLRs would indeed be only coincidentally. 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 has been suggested by Smith & Owocki (2006), namely that the "missing" mass-loss in the O-star phase might be compensated by a higher mass-loss in the LBV phase during brief eruptions.

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