Clumping in Hot Star Winds
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Constraints on wind clumping from the empirical mass-loss vs. metallicity relation for early-type stars

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We present the latest results on the observational dependence of the mass-loss rate in stellar winds of O and early-B stars on the metal content of their atmospheres, and compare these with predictions. Absolute empirical rates for the mass loss of stars brighter than $10^{5.2} L_{\odot}$, based on Hα and ultraviolet (UV) wind lines, are found to be about a factor of two higher than predictions. If this difference is attributed to inhomogeneities in the wind this would imply that luminous O and early-B stars have clumping factors in their Hα and UV line forming regime of about a factor of 3–5. The investigated stars cover a metallicity range Z from 0.2 to 1 $Z_{\odot}$. We find a hint towards smaller clumping factors for lower Z. The derived clumping factors, however, presuppose that clumping does not impact the predictions of the mass-loss rate. We discuss this assumption and explain how we intend to investigate its validity in more detail.

1 Introduction

In the context of the *VLT-FLAMES Survey of Massive Stars* (Evans et al. 2005, 2006) we studied the stellar and wind properties of close to 100 O- and early B-type stars in several young clusters in the Magellanic Clouds. The data was complemented by a set of Galactic stars (Mokiem et al. 2005). One of the goals of this VLT Large Program is to establish the empirical relation between mass loss and metal content. Theoretical predictions of this relation assume a power-law dependence, i.e. $\dot{M} \propto Z^m$ where $m \sim 0.7$ (Vink et al. 2001, Krtička 2006). So far, a robust empirical value of m was lacking. The reasons for this are both observational and theoretical in nature. The total number of stars that need to be observed and analyzed in order to obtain a meaningful value of m is large, at least 20–30 per galaxy (amounting to 60–90 stars for the Galaxy and Magellanic Clouds). The quantitavive spectral modeling that is required is complex, as non-LTE effects, line blocking/blanketing and an accelerating outflow need to be accounted for. Fortunately, the last decade has shown great progress in both instrumentation developments on large telescopes as well as in the development of (more) realistic stellar atmosphere models.

The most recent step forward in the modeling technique has been the development of an automated fitting method, opening up a means to analyse large samples in a homogeneous way (Mokiem et al. 2005). This valuable asset in the quest for the $\dot{M}(Z)$-relation is briefly discussed in Section 2. The empirical $\dot{M}(Z)$-relation is presented in Section 3 with special emphasis on constraints on the small scale clumping properties implied by the results. In Section 4 we discuss effects of clumping on the predictions of mass-loss rates. We end with conclusions.

2 Spectral analysis

To facilitate a homogeneous analysis we apply an automated spectral fitting method capable of global optimization in a multi-dimensional parameter space of arbitrary size (see Mokiem et al. 2005 for details). The method consists of two main components, the non-LTE stellar atmosphere code FASTWIND by Puls et al. (2005) and the genetic algorithm based optimization routine PIKAIA from Charbonneau (1995). Genetic algorithms represent a class of heuristic optimization techniques, which are inspired by the notion of biological evolution by means of natural selection. Like genes are the coded parameters in case of real life evolution, in our case these can be expressed by the fundamental parameters of the star. So far, the fitted parameters are the effective temperature, surface gravity, luminosity $L_{\star}$, helium abundance, turbulent velocity, mass-loss rate, rate of acceleration and terminal velocity v_{∞} of the outflow, and projected rotational velocity.

The fitness criterion is defined such that individual spectral lines can be assigned weighing factors. Though in principle any line can be modeled we concentrated on optical lines, making Hα the most important mass-loss diagnostic. The modeling technique is sufficiently powerful to exclude – if necessary – the Hα line core, which may suffer from nebular contamination, from the fitting process though clearly this will be reflected in the associated error bars. The error bars are derived from the fitness properties around the global fit optimum, and will show a degenerate result if the lines lack sensitivity to a certain parameter (for instance mass loss) or when a combination of parameters yields a similar fit quality.

3 The empirical dM/dt(Z) relation

With the lion's share of the data analyzed using the automated fitting method, Mokiem et al. (2007b), based on results presented in Mokiem et al. (2005, 2006, 2007a), determined the empirical relation between mass loss and surface metallicity. The outcome is shown in Fig. 1 in terms of the so-called modified wind momentum – luminosity (WLR) relation,

$$\begin{aligned} \log D_{\rm mom} &\equiv \log(\dot{M} v_\infty \sqrt{R_\star}) \\ &\simeq x \log(L_\star/L_\odot) + \log D_\circ \end{aligned} \tag{1}$$

where $R_\star$ is the stellar radius. The metallicity dependence of $D_{\rm mom}$ is contained in the relative offset of the curves for the individual galaxies. The solid lines represent the empirical result for Galactic ($Z = Z_\odot$), LMC ($0.5\,Z_\odot$) and SMC ($0.2\,Z_\odot$) stars; one sigma confidence intervals are shown as grey areas. One finds

$$\dot{M} \propto Z^{0.83\pm0.16}. \tag{2}$$

Also shown in Fig. 1 are the theoretical predictions of $D_{\rm mom}(L_\star)$ by Vink et al. (2001) using dashed lines. Note that the empirical curves lie above the predictions (for each galaxy). The reason may be the neglect of small scale clumping in the spectral analysis. As the (wind) emission in Hα is the result of recombination, the line strength scales with the square of the density. This implies that $\dot{M}(\text{clumped wind}) \times \sqrt{f} = \dot{M}(\text{smooth wind})$, where f is the clumping factor. Hence, clumping would decrease the empirical curves allowing for a match with predictions.

Therefore, Fig. 1 allows for the following statements regarding clumping: *i)* As the slopes of the non-clumping corrected empirical and theoretical WLRs are very similar over a wide range in wind strengths, clumping is not a strong function of the wind density. *ii)* Taken at face value, the offset at $L_\star = 10^{5.75} L_\odot$ corresponds to a clumping factor $f \sim 5$ for Galactic stars, and $f \sim 3$ for SMC stars. The LMC value is intermediate between these two. We note that the uncertainties on these estimates are such that it is premature to firmly conclude that clumping is a function of metal content. This issue requires a more detailed investigation.

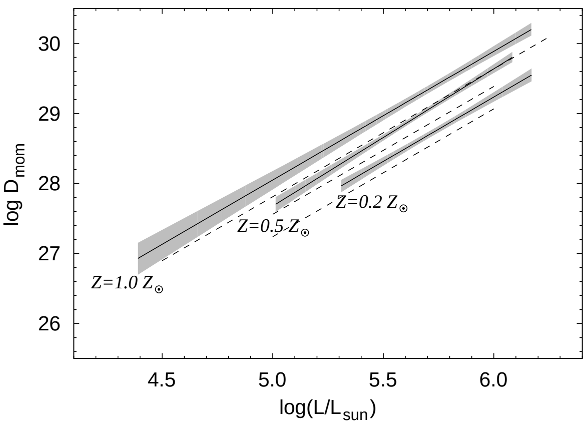

Figure 1: Confrontation between the empirical (solid lines; grey areas denote error bars) and theoretical (dashed lines) modified wind momentum – luminosity relation for Galactic (top), LMC (middle), and SMC (bottom) stars. The empirical results imply a systematically larger $D_{\rm mom}$, which may be due to clumping. From Mokiem et al. (2007b).

4 The effect of small scale clumping on mass-loss predictions

The predictions of $D_{\rm mom}(L_\star)$ assume a smooth wind, therefore the above statements are only valid if clumping does not affect the theoretical mass-loss rates. Is this presumption correct?

One-dimensional time-dependent simulations of the line-driving process shows that extensive but highly unstable wind structure arises quite naturally (e.g. Owocki & Puls 1999). Typically (given assumptions on the line source function) this structure is dominated by reverse shocks that separate high-speed, low-density rarefactions from slower, high-density compressions. In the absence of explicit perturbations, it is essentially found that the mean flow dynamics relax to a steady state (smooth wind) solution. This would imply that, in the context of these models, clumping does not affect the mass loss properties.

Recent determinations of the empirical clumping stratification in O star winds (Puls, these proceedings; Najarro et al., these proceedings) reveal a $f(r)$ that is not compatible with that implied by the line-driven instability mechanism: where observations show that clumping is strong near the photosphere relative to regions further out in the wind, the opposite behavior is predicted. It is currently unknown whether the *ad hoc* inclusion of strong perturbations at the base of the wind would significantly alter the predicted (mean) mass-loss rate. What's more, the line-driven instability computations so far do not account for the feedback of ionization/excitation changes as a result of structure formation. Such a feedback may be expected to have an effect on the predicted mass loss (see below). The above arguments therefore warrant caution regarding the current paradigm of the impact of wind structure on $\dot{M}$, i.e. that there would be no significant effect.

4.1 Predictions of mass loss in clumped winds

We have taken first steps towards a consistent implementation of structure inhomogeneities in our Monte Carlo method to predict the mass-loss rates of early-type stars (documented in de Koter et al. 1997 and Vink et al. 2000). The problem involves many issues, including: *a)* the feedback of clumping on the ionization and excitation of the gas; *b)* the spatial dimension of the 'clumps' relative to that of the region in which a spectral line can absorb. The latter may be estimated from the (direction dependent) Sobolev length. Two limiting cases can be identified: the size of the clumps is large or small relative to the Sobolev length. *c)* The velocity dispersion of material inside individual clumps, as well as the velocity dispersion of the clump ensemble. *d)* The radial behavior of the clumping and of the velocity dispersions mentioned above. *e)* The potential occurrence of 'porosity', which may occur in a medium in which the clumps are optically thick for continuum radiation.

If we adopt a constant clumping factor throughout the photosphere and wind, we find that if we single out effect *a* the predicted mass-loss is *increased*. This is consistent with results obtained by Krtička (these proceedings). To match the discrepancy in mass loss between theory and observations only a mild value of f – a few – is required though we point out that this assumes a clumping factor that is constant throughout the photosphere and wind. If clumping is negligible in the photosphere, larger values of f may be required. Still, these pilot calculations imply that *if* an inhomogeneous wind is only affected by feedback effects on the state of the gas, a match of the empirical and theoretical WLR seems to require only very mild clumping (recall that clumping also *decreases* the empirical $\dot{M}$).

A more consistent approach of clumping, accounting for more of the above listed effects, is underway.

5 Conclusions

A confrontation of the empirical and theoretical modified wind momentum – luminosity relation can be used to constrain the clumping properties of the winds of luminous O- and early-B stars. If clumping does not affect the amount of mass-loss that is driven by line radiation pressure, this confrontation implies clumping factors $3 - 5$. A clumping factor $f \sim 5$ is found for Galactic stars, while for SMC stars $f \sim 3$. This may hint towards smaller clumping factors for lower Z (but see Marchenko 2007), though uncertainties are presently too large to make a firm statement about this.

Predictions of the line-driven instability of stellar winds (see e.g. Owocki & Puls 1999) do not predict that the rate of mass loss suffers from wind inhomogeneities. However, we have pointed out that not all effects of clumping have been accounted for in these simulations. For instance, the feedback of clumping on the ionization and excitation (not accounted for in these simulations) leads to a higher predicted mass loss. Taking this into account, only very mild clumping factors would be required to match the empirical and theoretical WLR.

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Massa: I am a little surprised that the change in mass loss rates caused by clumping is so large since weak lines are important drivers and they are insensitive to clumping.

de Koter: The mass loss rates that are shown in the calculations are underpredicted because they do not account for the velocity dispersion inside clumps and of the clump ensemble. We are working to implement this.

Puls: As Jirí Krtička will show tomorrow, the reduction of the acceleration has a similar dependence on α (thin vs. thick lines) as the line force itself, i.e. only the optically thin lines are affected.

de Koter: After verifying with Krtička it turns out that for the same set of assumptions (clump size large relative to Sobolev line region; constant clumping factor; feedback on ionization included) we recover the same dependence of mass loss on clump size.

Cassinelli: You showed some models with "enhanced driving" of a sector within a clump. However, would this not imply a sector with a different velocity gradient from the rest of the clump, and if this is the case, it seems that it would drive the clump apart very quickly. I would think that a persisting clump would have no velocity gradient across it and the whole clump is at the same velocity.

de Koter: An enhanced driving only results from the effect that a clumped medium has on the ionization structure.

Feldmeier: Since the clump size is much larger than the photon mean free path, you are in the limit of macroturbulence. So you should seperately solve the complete radiative transfer for each single realisation of the wind structure, and take the average $\langle I_{\rm emerg} \rangle$ from all these realisations. How do you do the radiative transfer?

de Koter: So far the feedback of clumping on the ionization/excitation structure is done in the limit of optically thin clumps.

Owocki: For this kind of simulation, is the rather smooth velocity law inside the clumps not more important than the large variations in the surrounding, optically thin medium?

de Koter: In the calculations that I have shown, the velocity dispersion inside a clump is essentially the velocity gradient of the smooth flow times the size of the clump. The ensemble of clumps is assumed to follow the smooth flow to achieve a meaningful comparison with the velocity pattern implied by, for instance, the line driven instability. This needs to be accounted for in our Monte Carlo method. Such a comparison will also require that we do not account for the feedback of a clumped structure on the ionization structure of the medium (which has an impact on the driving). This is done in our models (so we need to switch this off). The latter effect by itself causes an increase of the predicted mass loss. Obviously, we are also interested in implementing empirical clumping structures, which appear to deviate from those predicted by the line driven instability, to see the effect on the mass loss rate.

Hillier: In your procedure to compute $\dot{M}$ you use the global momentum balance of the wind. This technique will clearly be sensitive to the details of clumping in the wind. An alternative technique is to determine $\dot{M}$ by solving the momentum equation below the critical point. This has the advantage that it will be insensitive to details of the clumping in the wind, although a disadvantage is that it may be sensitive to microturblence.

de Koter: We are in the process of implementing the local momentum balance in our Monte Carlo code. As I explained in my reply to Stan's question, the inclusion of a velocity dispersion is the next step.

Gräfener: What kind of clumping geometry did you assume? I guess that a patchy structure would influence your results considerably and also the spectral diagnostics are affected.

de Koter: We took the usual assumption that the clumps are cubes. Different clump realisations might indeed have an effect on the driving efficiency assuming a prefered direction can be assigned to the clumps. The latter may be expected given the almost radial streaming of photons.