Clumping in Hot Star Winds
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Clumping in hydrodynamic atmosphere models

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We investigate the effect of wind clumping on the dynamics of Wolf-Rayet winds, by means of the Potsdam Wolf-Rayet (PoWR) hydrodynamic atmosphere models. In the limit of micro-clumping the radiative acceleration is generally enhanced. We examine the reasons for this effect and show that the resulting wind structure depends critically on the assumed radial dependence of the clumping factor $D(r)$. The observed terminal wind velocities for WR stars imply that $D(r)$ increases to very large values in the outer part of the wind, in agreement with the assumption of detached expanding shells.

1 Hydrodynamic PoWR models

The new hydrodynamic PoWR models are the first model atmospheres that solve the full wind hydrodynamics in line with a detailed NLTE radiative transfer. The models have been applied to different Wolf-Rayet (WR) subtypes, from H-free WC stars with extremely hot core temperatures (Gräfener & Hamann 2005) to late-type WN stars with much lower temperatures and considerable amounts of hydrogen at their surfaces (Gräfener & Hamann 2006, 2007). The basic result from these computations is that the enhanced WR-type mass loss is primarily triggered by the proximity to the Eddington limit.

When stars approach the Eddington limit their effective surface gravity is reduced. The large density scale height then supports the formation of optically thick stellar winds. For such winds the critical point is located at large optical depth, close to the point of zero effective gravity (see Nugis & Lamers 2002). Their mass loss thus depends on the flux-mean opacity in deep atmospheric layers, and on the Eddington factor Γ_e. Particularly because of the ρ,T–dependence of the mean opacity, these winds have qualitatively different properties than classical OB star winds (see Gräfener & Hamann 2006, 2007).

The large optical depth of their stellar winds is chiefly responsible for the observed properties of WR stars. Photons are typically absorbed and re-emitted τ^2 times, which causes the large observed wind momenta ($\dot{M}v_\infty \approx \tau \cdot L/c$). The efficient re-distribution of ionizing photons in the wind leads to recombination cascades which are responsible for the observed emission line spectra. Note that the dominance of recombination processes leads to an over-population of excited energy levels which is the basic reason for the sensitivity to wind clumping (see Sect. 2).

Large Eddington factors are a prerequisite for the formation of WR-type winds. According to our models the most massive stars can reach this state already at the end of their main-sequence lifetime, i.e., still in the pase of central H-burning. Less massive objects enter the Wolf-Rayet stage after the onset of He-burning. For two extremely luminous, H-rich WNL stars in Carina OB 1 (WR 22 and WR 25) we derive masses of at least 80–100 $M_\odot$. Such stars are presumably the direct descendants of the most massive stars in the galaxy (Gräfener & Hamann 2007).

2 The role of wind clumping

Wind clumping is routinely taken into account in spectral analyses to fit the electron scattering wings of strong WR emission lines. Its main effect is that the mean $<\rho^2>$ increases and the derived mass loss rates, relying on ρ^2-diagnostics, decrease with $\dot{M} \propto 1/\sqrt{D}$ (see Hamann & Koesterke 1998). In our previous work we have shown that clumping also affects the wind acceleration in O supergiant (Gräfener et al. 2002, Gräfener & Hamann 2003) and WR star winds (Gräfener & Hamann 2005, 2007). The specific choice of the clumping factor $D(r)$ has a major influence on the wind dynamics in our models.

The reason for this is that due to the increase of $<\rho^2>$ in a clumped wind, more excited energy levels are populated by recombination. For the weak lines connected to these levels, a clumped wind thus mimics the opacity of an un-clumped wind with a factor of $\sqrt{D}$ larger density. The radiative force from these lines in a clumped wind is thus similar to an un-clumped wind with higher density. In effect the wind acceleration is larger by a factor $\sqrt{D}$.

At this point it is necessary to emphasize that we assume small-scale clumps, or micro-clumping in our models. In this limit the separation between clumps is so small that the mean opacity can be used in the radiative transfer. In the limit of large clump separation, or macro-clumping, the optical depth of individual clumps may become large. Brown et al. (2004) have shown that in this case the radiative ac-

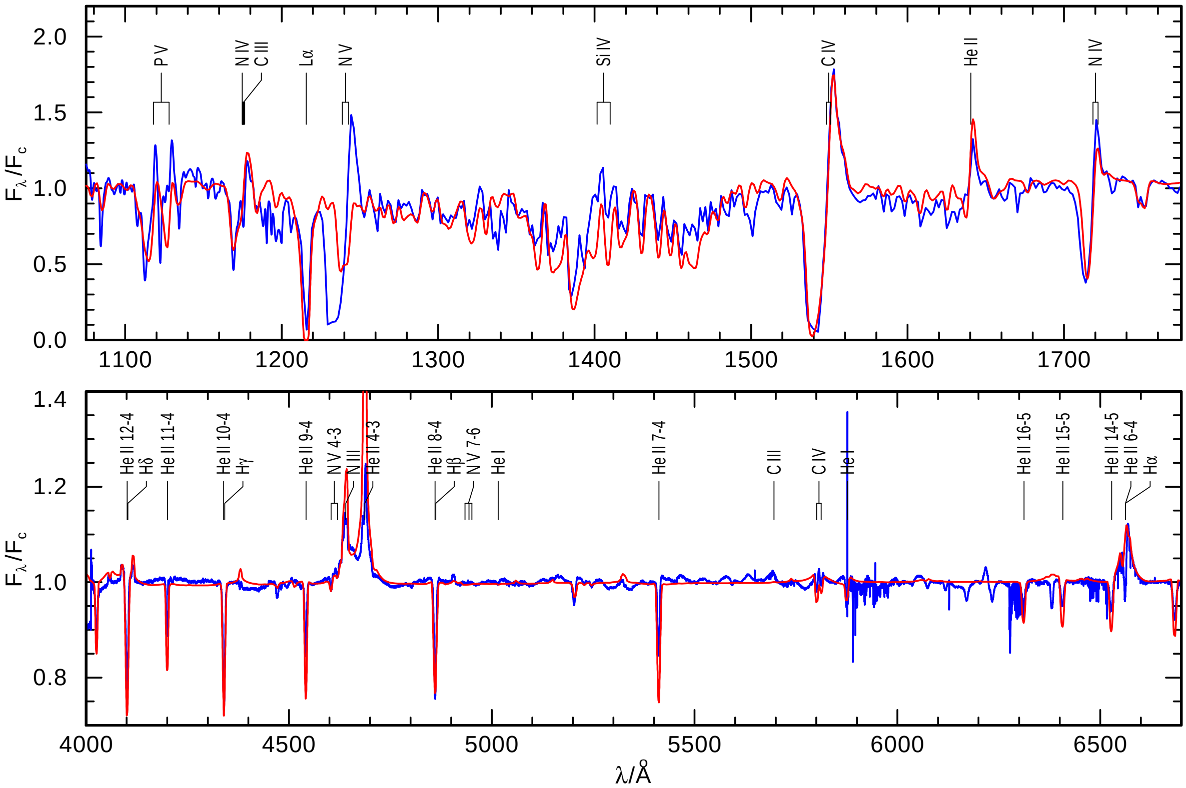

Figure 1: Self-consistent wind model for ζ Pup, with an increasing clumping factor ($D \propto v$, see text for more details). For a metallicity of $Z = 2/3\,Z_\odot$ the observed spectrum is reproduced with a very low mass loss rate ($\dot{M} = 7.4\,10^{-7} M_\odot/\mathrm{yr}$). Note that the discrepancy for the N V resonance line at 1240 Å is presumably caused by the neglect of X-ray radiation in this model.

celeration is reduced by geometrical effects. Moreover, Oskinova et al. (2007) have demonstrated that macro-clumping can considerably affect the spectral line diagnostics. We thus have two counteractive effects which may both affect our results. Micro-clumping increases the radiative acceleration with $a_{\mathrm{rad}} \propto \sqrt{D}$, and macro-clumping decreases a_{rad} dependent on the detailed clump-geometry. In our present models only micro-clumping is taken into account.

First results from our hydrodynamic models clearly favor large clumping factors. WR wind models with the typical observed values around $D = 10$ underestimate the terminal wind speeds of early to intermediate subtypes (WC 5 and WN 6–7). To fit the observed wind velocities, larger clumping factors of the order of $D \approx 40$ are needed (see Gräfener & Hamann 2005). Our models with $D = 10$ thus underestimate a_{rad} in the outer wind layers by a factor of two. Admittedly, a part of this deficiency might be due to the neglect of trace elements like Ne, Ca, and Mg in our models. On the other hand, a very plausible solution of this problem is the assumption of a radially increasing clumping factor.

For radially increasing $D(r)$ the electron scattering wings, which are formed close to the star, still indicate low clumping factors while the clumping factors can be much larger in the outer wind where the acceleration to v_∞ takes place. Note that such an increase of D is indeed expected due to the wind expansion. E.g., for a geometry with spherically expanding, detached shells of constant thickness, the clumping factor would increase with $D \propto v$. First test models for WNL stars indeed provide larger terminal wind speeds, even slightly above the observed values.

3 Low O star mass loss rates

From the strength of the unsaturated P V resonance lines in OB star spectra, clumping factors of the order of 10–100 have recently been deduced (Crowther et al. 2002, Hillier et al. 2003, Bouret et al. 2003, 2005, Fullerton et al. 2006). If micro-clumping dominates, the observed mass loss rates should thus be revised downward by factors of 3–10. For the common OB star wind models this would however introduce massive problems. While the observed mass loss rates go down, the predicted values are expected to increase due to micro-clumping (see the previous section). For the classical wind models it is thus necessary to introduce a combination of micro and macro-clumping to retain consistency (See also de Koter & Muijres, and Krtička et al., this volume). The strong downward revision of the OB star mass loss rates could be avoided in this way.

From a spectroscopic point of view the introduction of macro-clumping is however unnecessary. Models with micro-clumping reproduce the observed spectra of OB stars in an impressive way (e.g., Bouret et al. this volume). It remains to be shown if the same fit quality can be achieved under realistic model assumptions for macro-clumping. Moreover, the analysis of X-ray line profiles by Cohen et al. (this volume) strongly favors micro-clumping. In the present work we address the question if micro-clumping alone can account for the observed spectral properties of OB stars and the wind acceleration simultaneously.

Note that the classical wind models for OB stars generally employ the Sobolev approximation for the spectral line transfer. On the other hand, stellar atmosphere models like the CMFGEN code by Hillier & Miller (1998) and the PoWR models are based on a detailed radiative transfer in the CMF. These models reproduce the observed wind momenta of WR and OB stars only, if clumping factors of the order of 10 or larger are assumed (Gräfener et al. 2000, 2002, Gräfener & Hamann 2005, Herald et al. 2001, Hillier 2003, Hillier et al. 2003). The reason for the differences with respect to the Sobolev models is not yet fully understood (but see the discussion in Hillier et al. 2003 and the recent work by Lucy 2007). Nevertheless, it seems that the introduction of macro-clumping can be avoided for the CMF models because they predict a priori lower mass loss rates.

For our present OB star models we assume an outward increasing clumping factor, in analogy to our previous WR models. However, we only prescribe the growth rate of the clumping factor close to the stellar photosphere From $D = 1$ at $\tau_{\rm Ross} = 0.35$ to $D = 3$ at $\tau_{\rm Ross} = 0.03$ (which corresponds to a radius of $1.2\,R_\star$). Above this point we assume an increase with $D \propto v$, as expected for detached spherical shells of constant thickness. For the ζ Pup model in Fig. 1 this leads to a significant amplification of the clumping factor up to $D \approx 300$, just because of the wind expansion. Above $\approx 10\,R_\star$ a point is reached where the thermal pressure within a shell would exceed the external pressure due to the wind acceleration. From this point on we let the clumps expand with sonic speed, which leads to a fast decline of D. With an extremely low mass loss rate of $7.4\,10^{-7} M_\odot/{\rm yr}$ the model reproduces the observed strength of Hα and slightly underestimates P V. Under the assumption of pure micro-clumping, our present models thus seem to favor very low mass loss rates for OB stars.

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Feldmeier: Abbott (1982) showed that the flux distribution as function of frequency and the opacity distribution match very well, which is the reason for the efficient wind driving of O stars. WR stars should be even more efficient in wind driving. But your plot suggests that there is an offset between the flux and opacity distribution. Is this a contradiction?

Gräfener: The flux is partly blocked in the photosphere by Fe lines. This is something which would not happen if you use Sobolev approximation or if you treat the lines as scattering lines. And it definitely lowers the radiative acceleration.

Puls: At which radius is the density contrast decreased in ζ Pup (in order to obtain a correct radio flux)?

Gräfener: The decrease due to gas pressure sets in at $10\,R_*$, well before the radio regime.

Hillier: In the inner wind for ζ Pup there are obviously issues with the effect of microturbulence on the line force. However, in the outer wind I think you are significantly underestimating the line force by not including Ar, Ne, Cl, etc. In the outer wind, CMFGEN does not have significant problems in getting the appropriate line force, in fact with a small volume filling factor we can have the opposite problem (too much line force).

Gräfener: Alright, so I should include these elements, too.

Cassinelli: It appears your clumping occurs very close to the photosphere. How could clumps occur here?

Gräfener: Yes, the clumping sets in well below the sonic point and thus affects the mass loss rate. One could explain this for instance by the ideas of Shaviv about the formation of a photospheric structure when a star approaches the Eddington limit. Nevertheless, even if the formation of the clumps is difficult to explain I find it interesting that it is possible to produce O stars with low mass loss rates in this way, which are in agreement with the observed spectral diagnostics.

Owocki: Sobolev theory can in principle include multiple scattering or even branching of lines. So when you cite that there is a difference between Sobolev and CMF I think it is important to examine whether it is these effects of failure of Sobolev localization due to, e.g. large microturbulent broadening.

Gräfener: Yes it is important to find the reason. Concerning the line blocking I see the possibility that the treatment of line opacities as pure scattering opacity might be responsible. Generally, NLTE effects can change things, e.g. in case of an outward increasing line source function.

Ignace: IR forbidden lines form at very large radii in WR winds. A useful test of spectral models would be to reproduce observed line ratios, such as [Ne II] / [Ne III].