Wolf-Rayet Stars
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Macroclumping in WR 136

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Macroclumping proved to resolve the discordance between different mass-loss rate diagnostics for O-type stars, in particular between Hα and the P V resonance lines. In this paper, we report first results from a corresponding investigation for WR stars. We apply our detailed 3-D Monte Carlo (MC) line formation code to the P V resonance doublet and show, for the Galactic WNL star WR 136, that macroclumping is require to bring this line in accordance with the mass-loss rate derived from the emission-line spectrum.

1 Introduction

State-of-the-art model-atmosphere codes which are commonly used for analyses of WR star spectra usually treat inhomogeneities in the wind in a simplified manner. It is assumed that clumps are optically thin at all frequencies. Density inside clumps is described using a clumping factor D, which relates it to the smooth wind density with the same mass-loss rate. The interclump space is assumed to be void while the velocity of clumps corresponds to the adopted velocity law of the wind. The main consequence of this formulation (the so-called "microclumping" approach) is that mass-loss rates derived from recombination lines are overestimated by a factor $\sqrt{D}$ when microclumping is neglected, and have to be reduced. The resonance lines, which depend only linearly on density, are not sensitive to microclumping.

As a possible solution for this problem, Oskinova et al. (2007) suggested a *macroclumping* approach, in which the clumps are not restricted to be optically thin at all frequencies. For ζ Pup they showed that resonance lines are sensitive to macroclumping and, consequently, macroclumping can reconcile the discrepancy between mass-loss rates derived from the recombination Hα line and the P V resonance doublet ($\lambda\lambda$ 1118, 1128 Å). Therefore, in order to get these mass-loss rate diagnostics in agreement there is no need for reduction of the mass-loss rate and for the use of stronger clumping in the wind. This result was confirmed by Šurlan et al. (2013) by analysing a sample of O-type stars using a 3-D Monte Carlo Radiative Transfer (MCRT) code for inhomogenuous winds.

While the discordance between different mass-loss rate diagnostics was explained this way for O-type stars, it is not yet known to which extent macroclumping affects the winds of WR stars. Here we present preliminary results obtained for the Galactic WNL star WR 136.

2 Observational data, models and fitting procedure

Observational data. Optical and low-resolution `IUE` spectra are the same as used in the paper by Hamann et al. (2006), where also the procedure of spectra normalization is described. High-resolution `FUSE` spectra in the range of the P V resonance doublet where retrieved from the `MAST` (http://archive.stsci.edu) archive. These UV spectra have been divided by the reddened model continuum for normalization.

1-D spherically symmetric wind models. Models for WR 136 are calculated with the Potsdam Wolf-Rayet (`PoWR`) 1-D code (for more details see Hamann & Gräfener 2004). Detailed model atoms of the most relevant elements and line blanketing with the iron-group elements treated in the super-level approach were taken into account. The clumping parameter is set to $D = 4$. The Doppler velocity $v_{\rm D}$, which reflects random motions on small scales ("microturbulence"), is set to 100 km s^{-1}. The supersonic part of the wind is described with the β-law. with exponent $\beta = 1$. Mass-loss rate and wind velocity are among the free parameters of the models.

WR 136 has been analyzed already with `PoWR` models by Hamann et al. (2006). We adopt the stellar and wind parameters from this paper, but calculate a new `PoWR` model that now accounts additionally for the elements Si and P. Only H, He, C, N, and a generic iron-group atom were included in the previous model. The mass fractions of all elements used in the model now are: 0.78, 0.2, 1.0×10^{-4}, 0,015, 6.6×10^{-4}, 5.8×10^{-6}, and 1.4×10^{-3} for H, He, C, N, Si, P, and the Fe-group element, respectively.

3-D Monte Carlo Radiative Transfer clumped wind model. To model the P V resonance line profile, we use our 3-D MCRT code for clumped winds. The code is adequate to simulate the effects of clumping on resonance line formation (of both singlets and doublets). For more details about this code see Šurlan et al. (2012).

In the wind, a random distribution of spherical clumps is created. These clumps move with the velocity v_β according to the β-law, but they also may have an additional internal velocity gradient described with the velocity deviation parameter $m = v_{\rm dis}/v_\beta$, where $v_{\rm dis}$ is the velocity dispersion inside the clump. The number density of clumps obeys the continuity equation. The density in the clumps and in the interclump medium is specified from the mass-loss rate and the clumping parameters.

Clumps are described with following parameters (see Šurlan et al. 2012): clump separation parameter (L_0), clumping factor (D), interclump density factor (d), on-set radius of clumping ($r_{\rm cl}$), and velocity deviation parameter (m).

The line scattering is assumed to be isotropic in the comoving frame of reference, while the frequencies are completely redistributed over the Doppler-broadened opacity profile. The line opacity is computed according to the mass-loss rate, element abundance, and ionization fraction.

Fitting procedure. The PoWR model, which gave a reasonable fit to the observed spectral energy distribution and the line spectrum of WR 136, yields the stratification of the the P V ionization fraction which is now used as input for the MCRT calculation. Moreover, the "photospheric" spectrum underlying the P V resonance doublet is simulated with a model where P and Si lines are suppressed, and then used as incident radiation at the inner boundary for the 3-D MCRT code. The clumping parameters are then determined by optimizing the fit to the P V resonance doublet.

3 Results of models fitting

The final result of the modelling is given in Fig. 1, model parameters are in the figure caption. As it can be seen in Fig. 1, the obtained P V line profile with the PoWR code is much stronger than the observed one. Much better agreement with observations is achieved with the 3-D MCRT code which includes macroclumping. The P V doublet is severely blended by a doublet (not resonance!) of Si IV at $\lambda\lambda$ 1122.49, 1128.34 Å. In the O stars, these subordinate lines appear only as small absorptions, but in the WR 136 spectrum these lines form large emissions, which are seen in the observations and also modeled in the PoWR model of Fig. 1. To get a better insight into the importance of particular clumping parameters, we did several additional calculations.

Number of clumps. The total number of clumps ($N_{\rm cl}$) in the 3-D MCRT code is controlled by the parameter L_0. The smaller L_0 is, the more clumps are generated.

First, we calculate the P V line profile assuming a smooth wind which shows deeper absorption and higher emission compared to the observation (see the dotted orange line in Fig. 2). To test the macroclumping effect, we then calculate a clumped wind model by setting $L_0 = 2.3$, which implies only 115 clumps within $100\,R_*$ (cf. Eq. 24 in Šurlan et al. 2012) and hence corresponds to an extremely porous wind. The other clump parameters are set to $d = 0$, $r_{\rm cl} = 1$, and $m = 0$. As a result, the calculated P V line profile is drastically reduced (green line with crosses in Fig. 2) and now weaker than observed. A satisfactory fit is obtained by setting $L_0 = 1.8$, which implies 237 clumps. Now, the strength of the emissions and the depth of the absorptions are better reproduced (see the black line with asterisks in Fig. 2). If we increase the number of clumps further by setting $L_0 = 0.9$, which implies 1763 clumps, the obtained line profile shows a deeper absorption and slightly higher emission than observed (see the purple line with triangles in Fig. 2.

From these tests we can conclude that a reasonable fit of the P V resonance doublet requires a wind that is extremely porous (only ≈200 clumps within $100\,R_*$). For O star winds we estimated a smaller average clump separation (see Šurlan et al. 2013).

Inter-clump medium. The density between clumps is described with the interclump medium density parameter d (see Sect. 2.1.2. in Šurlan et al. 2012). Using this parameter, a two-component wind is created with dense clumps and non-void interclump medium. We set $L_0 = 2.3$, $r_{\rm cl} = 1$, and $m = 0$, and then increase d until satisfactory agreement is reached. As the parameter d increases, the depth of absorptions becomes deeper while the emission changes only slightly. We find that for $d = 0.003$ a reasonable fit to the observation can be achieved. However, different combinations of L_0 and d may give equally good agreement with observations. Therefore, it is not possible to say with confidence which combination of L_0 and d corresponds to reality. A completely void interclump space is certainly unrealistic, as we had also found for O-type stars (Šurlan et al. 2013).

Velocity dispersion – "vorosity". For line formation in an expanding atmosphere, the porosity effect is enhanced. Since the clumps move with different velocities, gaps in the coverage of Doppler shifts may occur. This "vorosity" effect depends on the range of Doppler shifts which is covered by one individual clump. This range is characterized in our formalism by the velocity deviation parameter m (see Eq. 20 and Fig. 3 in Šurlan et al. 2012). Guided by hydrodynamical simulations, we assume a negative velocity gradient inside the clumps. The clump center and the ambient interclump medium is set to move monotonically according to the β-law. We set $L_0 = 2.3$, $r_{cl} = 1$, and $d = 0.003$ while m is varied. Increasing the value of m leads to an extension of the absorption beyond v_∞, thus softening the blue edge of the P V line profile (see the difference between the blue edge of the black dotted line profile in Fig. 1 and the profiles in Fig. 2). Similar results were obtained for O-type stars (see the upper panel of Fig. 8 in Šurlan et al. 2013). We find here that "vorosity" does not influence the overall line strength significantly.

Onset of clumping. In Fig. 2 it can be seen that the part of the P V line profile which corresponds to the inner wind cannot be reproduced with the clumped wind model where clumping develops at the wind base (i.e. photosphere). Even if matter is added between clumps, the calculated profiles show stronger emissions. To improve the fit of this part of the P V line profile we vary the parameter r_{cl} which controls the radius where clumping sets in. When we increase r_{cl}, more absorption is added to the inner wind. For $r_{cl} = 2.8$ the level of absorption in the inner wind is reproduced (see black dotted line in Fig. 1). It seems that for the case of clumped wind and non-void interclump medium, clumps should start to develop a bit farther from the photosphere. This result is different from the case of O-type stars, where clumps seem to start at the photosphere (see Sect. 6.3 in Šurlan et al. 2013).

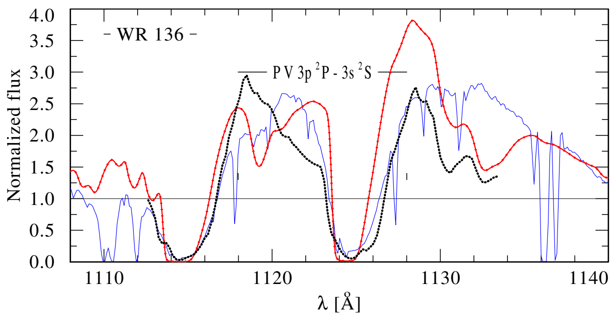

Fig. 1: Comparison between observed (thin solid blue line) and synthetic spectra of the P V line of WR 136 obtained with the PoWR code without macroclumping (red line with croses), and 3-D MCRT codes (dotted black line) with $L_0 = 2.3\,(N_{cl} = 115)$, $d = 0.003$, $m = 0.1$, and $r_{cl} = 2.8$.

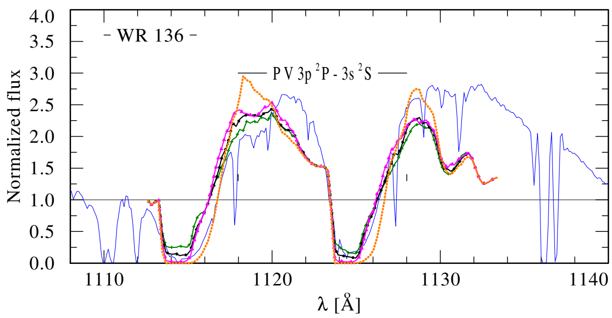

Fig. 2: Comparison between observed (thin solid-blue line) and calculated P V line profiles of WR 136 calculated with 3-D MCRT code for different numbers of clumps. The green line with crosses is calculated with $d = 0$, $r_{cl} = 1$, $m = 0$, and $L_0 = 2.3\,(N_{cl} = 115)$. The black line with asterisks and the purple line with triangles differ only by $L_0 = 1.8\,(N_{cl} = 237)$ and $L_0 = 0.9\,(N_{cl} = 1763)$, respectively. The dotted orange line corresponds to the smooth wind. The blending Si IV emission lines at 1122.49, 1128.34 Å are omitted in these models for consistency.

4 Summary

From analyzing the spectrum of WR 136 with the `PoWR` and 3-D MCRT codes, we demonstrate that macroclumping has impact on the formation of resonance lines.

a) A smooth wind cannot reproduce the observed P V line profile, when the mass-loss rate is adopted according to the emission-line spectrum. The porosity seems to be pronounced (only ≈200 clumps within 100 R_*).

b) Different combinations of the clump-separation parameter L_0 and the interclump density factor d can reproduce the observation equally good, i.e. the interclump density remains unconstrained.

c) The results are not sensitive to the velocity dispersion within each clump ("vorosity"), except of an additional blue-shift of the P-Cygni absorption edge.

We intend to study a larger sample of WR stars in order to better understand the inhomogeneous structures of their winds.

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Richard Ignace: 1) Comment: Expressing onset of clumping in speed may be more interesting than in radius. 2) Do the clump and inter-clump components follow the same velocity law?

Brankica Kubátová: 1) Yes, I agree. Good suggestion. I'll prepare the plot for the Proceedings.

2) We assume that the inter-clump velocity follows the smooth-wind velocity law, while velocities within clumps have an additional contribution defined by the velocity deviation parameter m, where $m = V_{\mathrm{dis}}(r)/V_{\mathrm{smooth}}(r)$. The velocity inside each clump has a negative velocity gradient.

Andy Pollock: With such a small number of clumps as about 100, would you expect to see line profile variability in the P V profile?

Brankica Kubátová: I would expect to see line profile variability in the P V profile with such a small number of clumps. But more details how line profile variability would look like depending on different numbers of clumps we can confirm after we have obtained results from our new version of 3D MCRT code with time evolution of clumps. I hope it will be soon.