Interacting Winds from Massive Stars
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Spectral analyses of Wolf-Rayet winds

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Abstract. The analysis of Wolf-Rayet spectra requires adequate model atmospheres which treat the non-LTE radiation transfer in a spherically expanding medium. Present state-of-the-art calculations account for complex model atoms with, typically, a few hundred energy levels and a few thousand spectral lines of He and CNO elements. In the most recent version of our model code, blanketing by millions of lines from iron-group elements is also included.

These models have been widely applied for the spectral analysis of WN stars in the Galaxy and LMC. WN spectra can be well reproduced in most cases. WC stars have not yet been analyzed comprehensively, because the agreement with observations becomes satisfactory only when line-blanketed models are applied.

The introduction of inhomogeneities (clumping), although treated in a rough approximation, has significantly improved the fit between synthetic and observed spectra with respect to the electron-scattering wings of strong lines. The mass-loss rates obtained from spectral analyses become smaller by a factor 2–3 if clumping is accounted for.

A pre-specified velocity law is adopted for our models, but the radiation pressure can be evaluated from our detailed calculation and can be compared a posteriori with the required wind acceleration. Surprisingly we find that the line-blanketed models are not far from being hydrodynamically consistent, thus indicating that radiation pressure is probably the main driving force for the mass-loss from WR stars.

1. The state of the art

The so-called standard model for WR atmospheres is based on the simplifying assumptions of spherical symmetry, homogeneity and stationarity of the flow. The velocity law is assumed *ad hoc* (usually in the form of the so-called β law, mostly choosing $\beta = 1$), i.e. the hydrodynamic problem is not consistently solved. A specific model atmosphere is described by the following parameters: mass-loss rate $\dot{M}$, luminosity L, stellar radius R_* (taken at a defined optical depth, e.g. $\tau_{\rm Rosseland} = 20$), the terminal wind velocity v_∞, and the chemical composition. The effective temperature T_* follows from L and R_* via Stefan-Boltzmann's law.

Two features have been incorporated into the model calculations more recently. One concerns a first-order treatment of inhomogeneities. It is assumed that the wind consists of "clumps" in which the density is enhanced by a factor of D over the average value, while the interclump space is void (which implies

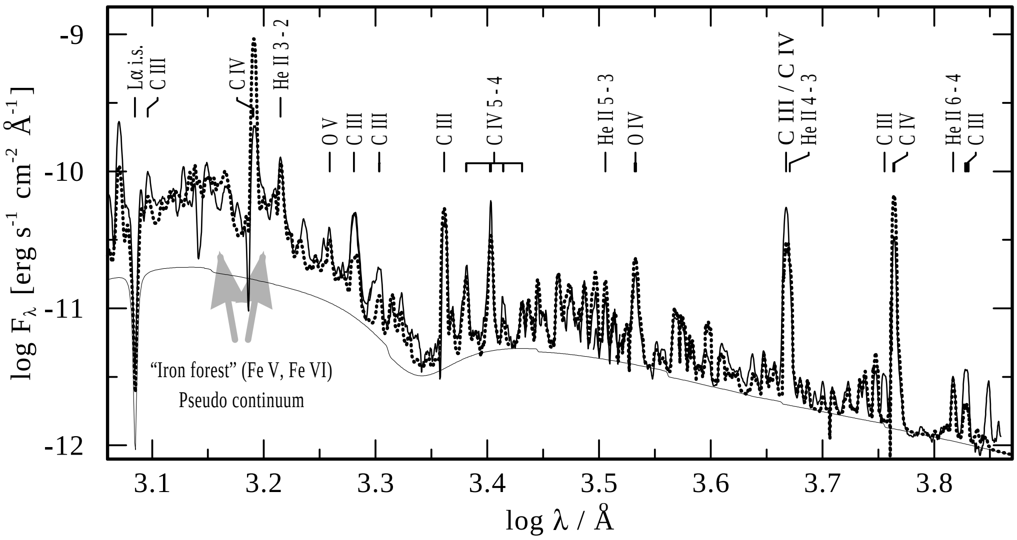

Figure 1. Observed spectrum (solid line) of WR 111 (WC5), compared to a model (dotted line) with the following parameters: v_∞ = 2000 km/s, $\log L/L_\odot = 5.68$, $T_* = 141$ kK, $\log[\dot{M}/(M_\odot \mathrm{yr}^{-1})]$ = -4.80, $D = 10$, composition He/C/O = 55/40/5 (by mass), $E_{b-v} = 0.28$ mag, distance modulus $DM = 11.09$ mag. The smooth line represents the theoretical stellar continuum, demonstrating that the "forest" of iron lines in the UV forms a strong pseudo-continuum.

that the clumps fill D^{-1} of the volume). Further it is assumed that the clumps have small size, compared to the photon's free path, which means that the radiative transfer can be treated as for a smooth medium. The main impact of clumping ($D > 1$) is a reduction of the empirically derived mass-loss rates by a factor $\sqrt{D}$. Clumping reduces the electron-scattering wings of strong emission lines. This improves the detailed agreement between calculated and observed line profiles and provides a handle to determine D from spectral fits. Existing analyses conclude $D = 4...10$ being typical for WR stars (Hamann et al. 1998b).

Another recent improvement of the models concerns the inclusion of line-blanketing by iron-group elements (Hillier & Miller 1998, Gräfener et al. in prep.). In contrast to static atmospheres, the expansion causes a frequency coupling by Doppler shifts. This prevents a sampling or re-ordering technique. Instead, all opacities must be treated at their proper frequency. The only approximation concerns the grouping of the energy levels into a small number of non-LTE "superlevels".

2. Analyses, results

Unblanketed "standard" model calculations have been widely applied to Galactic and LMC stars of the WN sequence (e.g. Hamann et al. 1998a). Analyses of WC stars are still rare (e.g. Dessart et al. 2000), because only the recent models accounting for clumping and line-blanketing can adequately describe their complex spectra (Hillier & Miller 1999). In Fig. 1 the emergent flux from a clumped, line-blanketed model is plotted together with the observed spectrum. The energy distribution fits nicely over the whole spectral range from the UV to the visual, and most lines including the strong "iron forest" are roughly reproduced, although discrepancies still exist in some details.

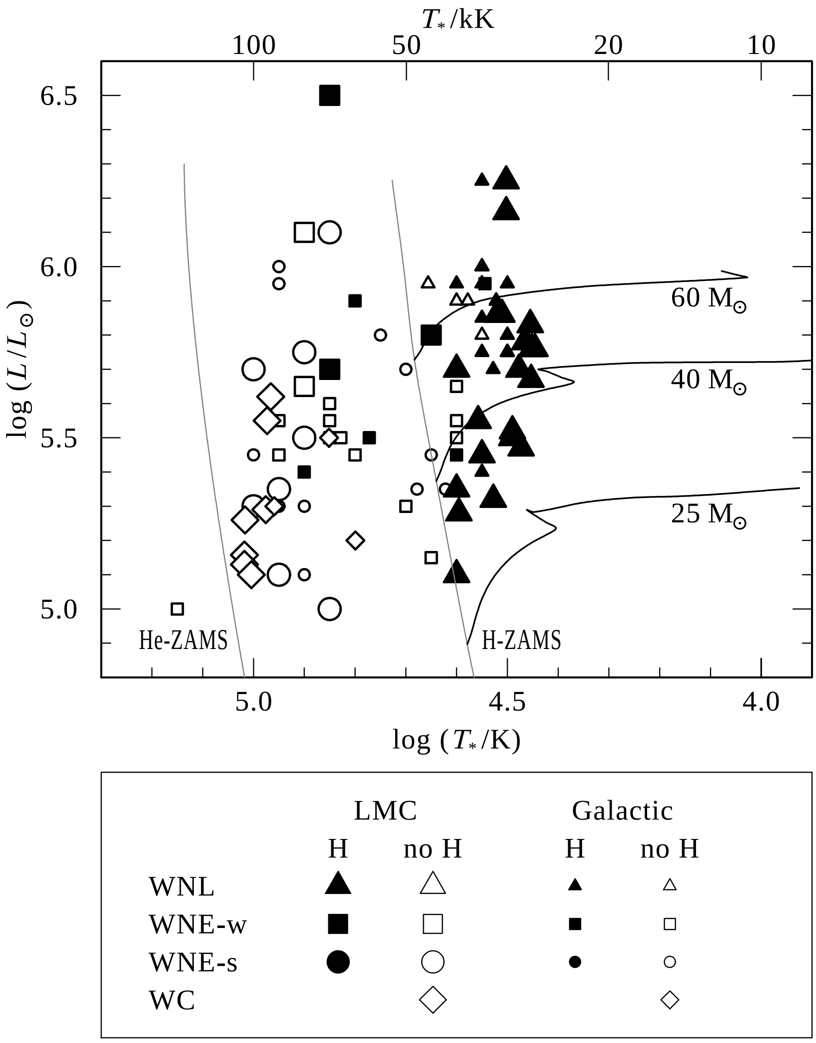

Figure 2. Positions of Wolf-Rayet stars in the Hertzsprung-Russell diagram. Different symbols indicate the subtype, the presence of hydrogen, and the LMC or Galactic membership, as explained in the supplementary box. The analyses are compiled from Crowther et al. (1995a), Crowther & Smith (1997), Dessart et al. (2000), Gräfener et al. (1998), Hamann & Koesterke (1998a, 2000). The helium and hydrogen Zero-Age Main Sequence and a few standard evolutionary tracks leaving from the main sequence (from Schaller et al. 1992) are shown for orientation.

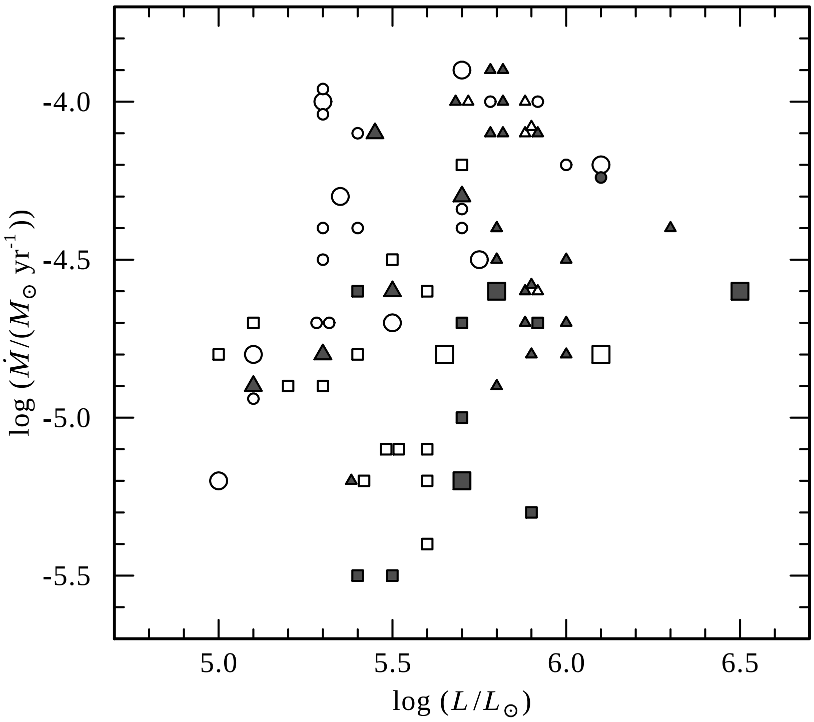

Figure 3. Empirical mass-loss rates of WN stars versus luminosities. The results are from the same analyses quoted in the caption of Fig. 2, and the meaning of the different symbols is also the same. Obviously there is no tight correlation between these parameters.

The empirical positions of the WR stars in the Hertzsprung-Russell diagram are displayed in Fig. 2. With only few exceptions, the late-type WN stars (WNL) are found on the cooler side of the hydrogen ZAMS and show some hydrogen. Almost all hydrogen free stars, the early-type WN stars with weak (WNE-w) or with strong (WNE-s) lines as well as the WC stars, lie between the hydrogen and the helium main sequence. Remarkable is the wide span of luminosities from 10^5 to $10^{6.5} L_\odot$. Note that for the LMC stars (big symbols) these results do not suffer from uncertainties in the distance.

In Fig. 3 the empirical mass-loss rates are plotted versus luminosity. Obviously there is no tight correlation, not even for the subgroup of hydrogen-free stars. Nugis & Lamers (2000) found some correlation between $\dot{M}$, L and composition in their independent data, but also with a huge scatter. If not due to the inaccuracy of the present analyses, there must be another parameter determining the mass-loss from WR stars which still has to be identified.

3. Wind driving

Hydrodynamically consistent models for Wolf-Rayet winds do not exist yet, and there is an ongoing debate about the driving forces. Our model atmospheres account for all radiative-transfer effects like multiple scattering and the line-

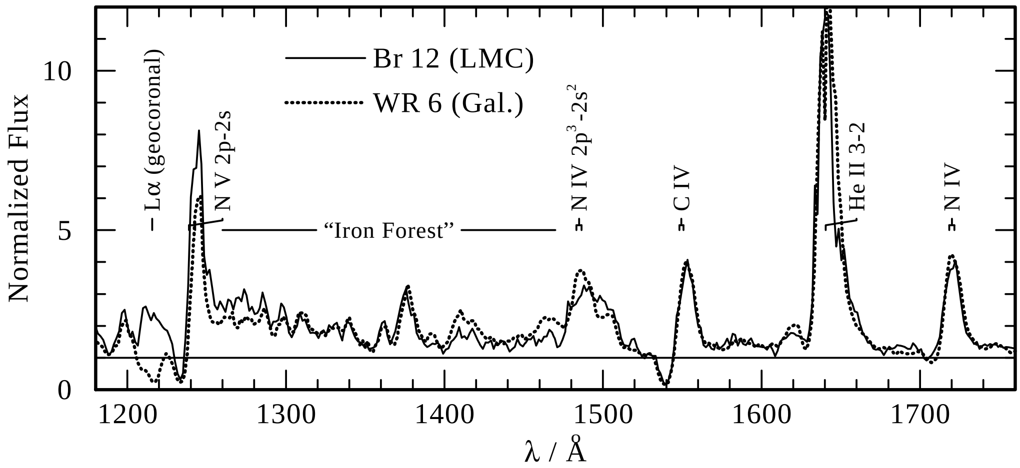

Figure 4. Observed spectra of the Galactic WN star (WR 6) and the LMC star Br 12. Albeit the LMC star is expected to show weaker lines because of lower metallicity and, in consequence, lower mass-loss, the stars are actually spectroscopic twins with the same line strength in helium, nitrogen, carbon and the "iron forest".

continuum interaction consistently, and include iron line blanketing. Thus we can calculate *a posteriori* the available radiation pressure quite accurate. As a remarkable result, we find only rather small discrepancies between requested and available radiative acceleration. A factor of two larger radiation pressure would be able to drive the observed WR wind at any radius. This remaining lack of force can be attributed to the incompleteness of opacities (e.g. the neglection of abundant elements like Si, Mg and Ne), and to the hydrodynamical inconsistency of the velocity field. We consider these results as indication that WR winds are accelerated by radiation pressure.

In case of radiation-driven stellar winds, the mass-loss rate should scale with the metallicity. However, we find no clear evidence that WN stars in the LMC show weaker winds than their Galactic counterparts. In Fig. 4 we demonstrate that the *observed* spectra of WR 6 (Galaxy) and Br 12 (LMC) are extremely similar, although in the latter all lines should be weaker because of a weaker wind, and the N and Fe lines even weaker because of the smaller abundance of these species. Thus, either there is no difference in metallicity, or the mass-loss rate is not determined by radiation pressure, or at least $\dot{M}$ does not scale with the square-root of metallicity as predicted by the simplified theories.

In addition to the radiative forces, WR winds might be *initiated* by stellar pulsations. So-called strange-mode instabilities are theoretically predicted for wide parts of the upper HRD, and with highest amplitude for WR models (Glatzel et al. 1999). An example is shown in Fig. 5. In contrast to these one-dimensional simulations, in reality the stellar surface will probably move in non-radial modes which are less easy to observe. In any case, if those pulsations exist they might contribute to the acceleration of deeper layers. Interesting consequences would result for the generation of inhomogeneous structures (blobs), shocks and X-rays.

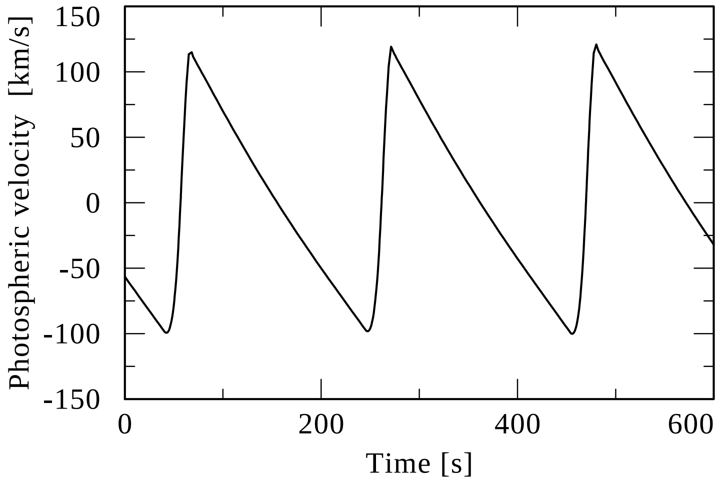

Figure 5. Velocity of the stellar surface due to strange-mode pulsations (simulations from Glatzel, priv. comm.). The shown calculations refer to a WN star with $T_* = 114\,\mathrm{kK}$, $\log L/L_\odot = 5.05$, $M = 9\,M_\odot$ and account for non-linear effects, but are restricted to one dimension, i.e. to radial modes.

Concluding, we state that the observed WR spectra can be reproduced by state-of-the-art model atmospheres with reasonable accuracy, allowing to perform quantitative spectral analyses. The radiation pressure provided by blanketed models is almost sufficient to explain the wind acceleration. However, the mass-loss rates do not show the correlation with luminosity and metallicity as expected for radiation driven winds, possibly indicating that other effects (pulsations?) are involved in initiating the wind at its base.

References

Crowther P.A., Hillier D.J., Smith L.J., 1995, A&A 293, 172

Crowther P.A., Smith L.J., 1997, A&A 320, 500

Dessart L., Crowther P.A., Hillier D.J., et al., 2000, MNRAS 315, 407

Glatzel W., Kiriakidis M., Chernigovskij S., Fricke K.J., 1999, MNRAS 303, 116

Gräfener G., Hamann W.-R., Hillier D. J., Koesterke L., 1998, A&A 329, 190

Hamann W.-R., Koesterke L., 1998a, A&A 333, 251

Hamann W.-R., Koesterke L., 1998b, A&A 335, 1003

Hamann W.-R., Koesterke L., 2000, A&A 360, 647

Hillier D.J., Miller D.L. 1998, ApJ 496, 407

Hillier D.J., Miller D.L. 1999, ApJ 519, 354

Nugis T., Lamers H.J.G.L.M., 2000, A&A 360, 227

Schaller G., Schaerer D., Meynet G., Maeder A., 1992, A&AS 96, 269