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Spectrum formation in clumped stellar winds: consequences for the analyses of Wolf-Rayet spectra

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Abstract. Inhomogeneous Wolf-Rayet type stellar winds are modeled in a first-order approximation, assuming that small-scale clumps are distributed with a constant volume filling factor within an interclump space which is void. Model calculations as well as analytical considerations show that the main spectral features, i.e. the strength of the emission lines, are approximately invariant if the enhanced density in the clump medium is compensated by a suitable scaling of the mass-loss rate. Hence, to the first order the mass-loss rate is the only empirical parameter which is affected by the application of clumped models for spectral analyses.

In clumpy atmospheres the electron-scattering line wings become weaker than in homogeneous models. This effect can be used to determine the degree of clumping empirically. We select Wolf-Rayet stars of different spectral subclasses and compare their spectra with adequate models, varying the clumpiness. In all cases, the homogeneous model can be definitely ruled out because it predicts electron scattering wings that are significantly stronger than observed. If the clumps fill 1/4 of the volume, the line wings are in reasonable agreement, while for a filling factor of 1/16 the wings are possibly too shallow, but still compatible with the observation within the error margin. Adopting a filling factor of 1/4 (i.e. the density in the clumps is enhanced by a factor of four, compared to a smooth model with same mass-loss rate) as a typical value, the empirical mass-loss rates become smaller by a factor of two than obtained with homogeneous models.

Key words: radiative transfer – stars: atmospheres – stars: fundamental parameters – stars: mass loss – stars: Wolf-Rayet

1. Introduction

Wolf-Rayet (WR) spectra are characterized by bright and broad emission lines which are formed in strong stellar winds, and adequate models are prerequisite for their quantitative analysis. Corresponding techniques for calculating the non-LTE radiative transfer in spherically expanding atmospheres became available during the last decade (e.g. Hillier 1987a,b; Wessolowski et al. 1988), and are progressively applied to observations in order to determine the parameters of these stars (as recent examples, see e.g. Crowther & Smith 1997, or Hamann & Koesterke 1998). These so-called standard models for WR atmospheres are based on the assumptions of spherical symmetry, homogeneity and stationarity of the flow.

The main features of WR spectra can be reproduced by standard model calculations, thus validating its basic assumptions as a reasonable approximation. However, there are specific evidences that real WR atmospheres are actually more complicated in detail. The assumptions of stationarity is questioned by the observed line variability, e.g. explained as migrating optical depth enhancements by Prinja & Smith (1992). Polarization also shows stochastic variability (e.g. Brown et al. 1995). Theoretical modelling of radiation-driven winds predict hydrodynamical instabilities leading to shocks, density enhancements and rarefactions (e.g. Owocki et al. 1988, Owocki 1994, Feldmeier 1995). The X-ray emission generally detected from WR stars (e.g. Pollock et al. 1995, Wessolowski et al. 1995) obviously originates from hot, shocked gas embedded in the outer atmosphere (Baum et al. 1992).

Conclusive evidence for inhomogeneities (“clumping”) in WR winds comes also from the detailed study of the line wings. Radiation transfer theory predicts that electron scattering causes a frequency redistribution of line photons (due to their low mass the electrons have a high thermal velocity). The consequences of this effect on Wolf-Rayet emission lines were demonstrated already by Hillier (1984).

Nevertheless, frequency redistribution by Thomson scattering was neglected for simplicity in the first generation of WR models used for spectral analyses (e.g. Hamann et al. 1988, Hillier 1988). Analyses of WR spectra which do account for that effect (e.g. Hamann et al. 1992, 1994, 1995a) revealed that the (homogeneous) models always tend to overestimate the strength of electron scattering wings.

Physical arguments suggest that *clumping* reduces the relative contribution of these wings. A first numerical investigation of inhomogeneous models by Hillier (1991) confirmed these expectations. His Monte-Carlo calculations indicate that the electron scattering process might be approximated, to acceptable accuracy, by assuming isotropic redistribution instead using the more accurate dipole phase function. Schmutz (1997) modeled

Send offprint requests to: W.-R. Hamann the clumping in the same approximation as we will apply in the present paper.

In the present paper we use the electron scattering wings for investigating the consequences of clumping to the analyses of WR spectra. In the following section (Sect. 2) we characterize our standard model calculations. Then we describe how the effects of clumping are accounted for in first approximation (Sect. 3). In Sect. 4 we calculate synthetic spectra for different spectral subclasses of WR stars and compare them with the observation. For selected stars of different spectral subclasses the degree of clumping (density enhancement) is roughly estimated. The consequences for the empirically derived parameters of WR stars are discussed in the concluding section (Sect. 5).

2. The standard model and the numerical techniques

The model calculations are of similar kind as described in previous papers (e.g. Hamann et al. 1994), and the reader is referred to these papers for more details and references. Only the basic assumptions and definitions are briefly repeated here.

A "standard" WR atmosphere is assumed to be expanding in a spherically-symmetric, homogeneous and stationary flow. With a given mass-loss rate $\dot{M}$, the density stratification $\rho(r)$ and the velocity field $v(r)$ are related via the equation of continuity.

The velocity field is pre-specified from plausible ad-hoc assumptions. For the supersonic part we adopt the usual β-law (cf., e.g., Hamann et al. 1993, Eq. 1) with the terminal velocity v_∞ being a free parameter. The exponent β is set to unity throughout this work. In the subsonic region the velocity field is defined such that a hydrostatic density stratification is approached.

The "stellar radius" R_*, which is the inner boundary of our model atmosphere, corresponds per definition to a Rosseland optical depth of 20. The "stellar temperature" T_* is defined by the luminosity L and the stellar radius R_* via the Stefan-Boltzmann law, i.e. T_* denotes the effective temperature referring to the radius R_*. The problem of defining a reference radius and, correspondingly, of any "effective temperature" in spherically extended atmospheres has been addressed in previous papers (e.g. Hamann 1994).

Only Doppler broadening is accounted for in the profile function of the line absorption coefficient. The Doppler-velocity $v_{\rm D}$ reflects random motion on small scales and is generally set to 100 km s^{-1}. This number has only marginal influence on the emergent line profiles; in the present context we tested that with 50 km s^{-1} the results are almost identical, but higher values have numerical advantages.

The line radiation transfer in the spherically expanding geometry is formulated in the comoving-frame of reference (CMF), treating correctly the overlap of blending lines. Continuum formation is treated with the moment equations and variable Eddington factors.

The equations of statistical equilibrium account for all relevant radiative and collisional transition rates. The temperature stratification is calculated from the assumption of radiative equilibrium. The consistent solution of both sets of equations, radiation transfer and statistical equilibrium, is achieved by "iteration with approximate lambda operators", taking advantage of "Broyden's method" in the solution algorithm (Koesterke et al. 1992). The obtained non-LTE population numbers enter the subsequent Formal Integration of the transfer equation in the observer's frame which is performed by straightforward integration along each ray.

Frequency redistribution of line photons by electron scattering is accounted by means of the appropriate angle-averaged redistribution function (Hummer 1962). The effect is only accounted for in the Formal Integration. From earlier test calculations we know that the influence of the redistribution mechanism on the "model" (i.e. on the stratification of temperature and population numbers) is negligible.

Adopting the described "standard model" assumptions, any particular WR atmosphere is specified by its basic parameters T_*, R_*, $\dot{M}$, v_∞ and chemical composition (e.g. given in the form of mass fractions $\beta_{\rm He}$, $\beta_{\rm N}$ etc.).

3. Clumping in first approximation

3.1. Formulation

For a first-order approach to clumped stellar winds, we make the following simplifying assumptions:

- The wind consists of clumps with density $D\rho(r)$, where $\rho(r)$ is the density stratification of the homogeneous model with the same mass-loss rate. The factor $D > 1$ thus gives the density enhancement, and is assumed to be constant all over the atmosphere.
- The interclump space is void. Thus the volume filling factor of the clumps is $f_{\rm V} = D^{-1}$.
- The clumps are assumed to have small size, compared to the photon free path. Thus the radiative transfer can be calculated with "effective" emissivities and opacities averaging between the clump and interclump medium.

Under these assumptions, clumping can be accounted for by limited modifications in existing model codes. The statistical equations have to be solved for the enhanced density $D\rho(r)$. The population numbers, which add up to the enhanced particle density of the clump medium, are applied as usual for the calculation of the non-LTE emissivity and opacity. However, the latter two are scaled down by the volume filling factor $f_{\rm V}$ before they enter the radiative transfer calculation.

In our code we obtain the consistent solution of the comoving frame radiative transfer equation and the equations of statistical equilibrium by an iterative scheme using approximate lambda operators. The latter are set up with the same, modified opacities which are used in the "exact" radiative transfer. The described modifications of emissivity and opacity also apply in the Formal Integral which is finally performed in the observer's frame once the population numbers are established.

3.2. Scaling properties

In the described formulation, the density enhancement D would cancel out in the emissivities and opacities, if they were linear in the density ρ. However, Wolf-Rayet spectra are known to be dominated by processes which scale with the *square* of the density. This can be concluded from the scaling property of Wolf-Rayet models, which has been discovered first by Schmutz et al. (1989). They defined a so-called transformed radius R_t as

$$R_\mathrm{t} = R_* \left[\frac{v_\infty}{2500\,\mathrm{km\,s^{-1}}} \Big/ \frac{\dot{M}}{10^{-4}\,M_\odot\,\mathrm{yr^{-1}}} \right]^{2/3} \qquad (1)$$

and found that models with same R_t exhibit the same emission line equivalent widths, irrespective of different combinations of $\dot{M}$, R_* and v_∞ (while, of course, T_*, composition etc. are fixed). This invariance was validated by various numerical experiments with reasonable accuracy. In a stricter sense, one might compare only models with same terminal velocity v_∞. Then even the line profiles and the total shape of the emergent spectra are invariant for models with same R_t, except of a scaling of the absolute flux with R_*^2. This property greatly facilitates any spectral analyses, as only two essential parameters (T_*, R_t) must be adapted.

The described invariance can be understood by adopting that the relevant emission processes scale with the square of the density. This can be seen as follows. If the emissivity (at any considered wavelength) scales with ρ^2, then the flux emitted from a volume V of that density scales with $\rho^2 V$. Keeping R_t constant implies $R_* \propto \dot{M}^{2/3}$ (Eq. 1), while we have $\dot{M} \propto \rho R_*^2$ from the continuity equation. Combining both proportionalities yields $\rho \propto R_*^{-1/2}$. Any emitting volume scales with R_*^3, and thus the emitted flux scales like $\rho^2 V \propto R_*^2$, just as empirically established. The relative spectral shape remains unchanged.

The likely physical explanation is that most continuum photons are created by free-free emission or photo-recombination, while the line photons are emitted in recombination cascades. The number of created line photons thus depends only on the corresponding recombination rate, even when they are trapped for some time in optically thick scattering lines before they escape. Both, free-free emission and radiative recombination, are ρ^2-processes.

The dominance of ρ^2 emission processes explains the invariance of the radiation field, when comparing models with same R_t but different combinations of $\dot{M}$ and R_*, as long as the model structure (stratification of population numbers) is the same. This, however, is not to be expected, as the density structure is different (namely scaling with $\rho \propto R_*^{-1/2}$, see above) and the density never can cancel out in the ratio between any ionization and recombination process. Indeed, a detailed comparison between models with same R_t reveals the expected differences in the ionization stratification. However, these differences do not, in most cases, lead to significantly different spectra. We suggest that this is due to the relatively weak dependence of ρ on R_*, and on the fact that the main emission in a specific line comes from those radial zones where the relevant ion (i.e. the next higher stage) is the dominating one.

The concept of the “transformed radius” now can be generalized for clumped models. In order to cancel out in quadratic processes, the clump density enhancement D must be compensated by diminishing the mass-loss rate by a factor $\sqrt{D}$. Thus we define

$$R_\mathrm{t} = R_* \left[\frac{v_\infty}{2500\,\mathrm{km\,s^{-1}}} \Big/ \frac{\sqrt{D}\dot{M}}{10^{-4}\,M_\odot\,\mathrm{yr^{-1}}} \right]^{2/3} \qquad (2)$$

and expect that models with same R_t exhibit the same line equivalent widths, irrespective of different combinations of D, $\dot{M}$, R_* and v_∞. For constant v_∞, the absolute spectra should only differ by a scaling with R_*^2.

Note that this scaling invariance holds only for the ρ^2 processes, i.e. for the main spectral features. The electron scattering opacity, however, scales linearly with density. Thus, in inhomogeneous models the enhanced clump density is already fully compensated by the volume filling factor; scaling down the mass-loss rate in order to keep the same R_t decreases the effective Thomson opacity. Hence, for a series of models with same R_t the extended line wings caused by frequency redistribution of electron-scattered line photons should become weaker with increasing D, while the main spectral feature remain unchanged. This is the reason why the too strong electron scattering wings predicted by the standard, non-clumped models are considered as evidence for inhomogeneities.

Among the manifold combinations of R_*, D and $\dot{M}$ which give the samed transformed radius R_t, one can restrict the subspace for which the processes *linear* in ρ are simultaneously invariant in the above sense, i.e. for which the electron scattering wings are expected to have the same strength. The condition that ρV also give fluxes that scale with R_*^2 yields $D \propto R_*$. In other words, if going to bigger stars with same transformed radius, one might increase the clump density enhancement $D \propto L^{1/2}$, and (despite of the constant factor R_*^2) the whole spectrum should remain invariant, the main line features as well as the electron scattering wings. Vice versa, this connection has an interesting consequence. If the degree of clumping (i.e. the parameter D) would turn out to be a universal or otherwise predictable property of WR type stellar winds, one could, in principal, estimate the stellar luminosity (and thus the distance etc.) from the spectrum alone. At least, one expects that less luminous stars have weaker electron-scattering wings than more luminous counterparts with otherwise similar spectra. By this one might, e.g., distinguish post-AGB stars with WR type spectra from Pop. I Wolf-Rayet stars.

4. Results from representative test calculations

A number of models with different clump density enhancement D have been calculated. The results confirm the approximate scaling properties anticipated in Sect. 3. In this section we present models which are typical for different subclasses of Wolf-Rayet stars and study the influence of the clumping parameter.

The Galactic Wolf-Rayet stars of the nitrogen sequence (WN) have been analyzed in previous papers (Schmutz et al. 1989, Hamann et al. 1993, 1995a) with homogeneous models. In the recent upgrade (Hamann & Koesterke 1998), grids of

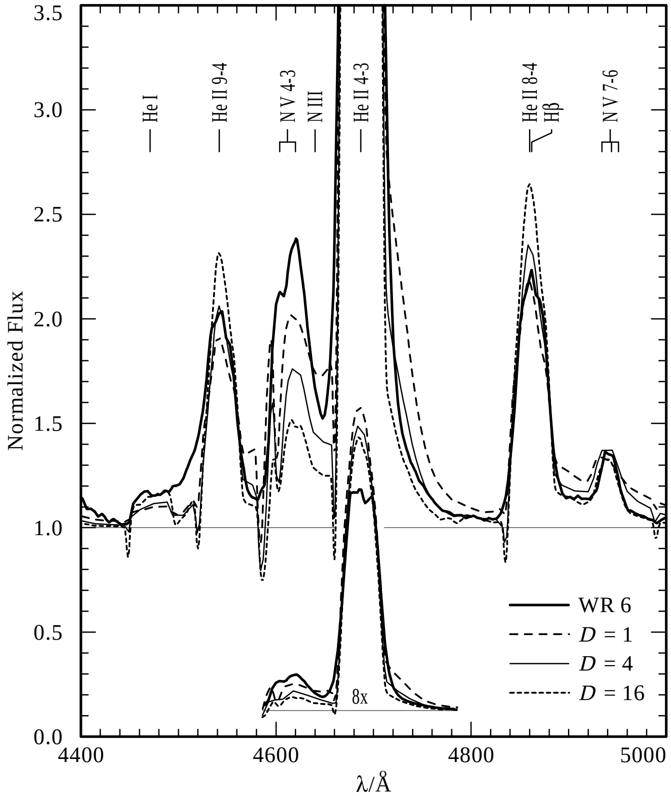

Fig. 1. Spectral region around He II 4686 for a series of models with different degree of clumping. Different drawing styles are applied for the model with density enhancement $D = 1$ (i.e. smooth), $D = 4$ and $D = 16$, respectively, as indicated in the inlet. The observed spectrum shown is from WR 6 (WN5-s). The model parameters for that early-subtype WN star with strong lines (WNE-s) are compiled in Table 1. Note that the mass-loss rate is changed such that the effect of clumping is compensated, while the other model parameters are kept constant.

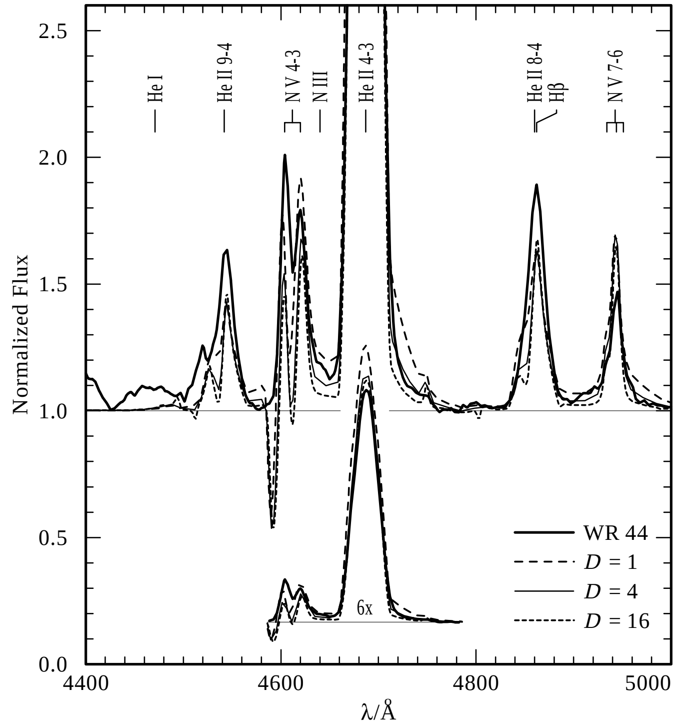

Fig. 2. Same as Fig. 1, but for an early-subtype WN star with weak lines (WNE-w). The observed spectrum shown is from WR 44 (WN4-w).The model parameters are compiled in Table 1.

helium-nitrogen models were compared to the observation. Now we select one example star from each spectral subclass and calculate appropriate models, setting the clump density enhancement to D=1 (i.e. no clumping), D=4 and D=16, respectively, while the transformed radius (Eq. 2) is kept constant. We compared the whole spectra and confirmed that the main features do not change by much. The only significant differences along a model series concerns the electron-scattering line wings, as expected. By comparison with observed spectra, a rough guess about the adequate value of D is obtained. The observations are taken from our atlas of WN spectra (Hamann et al. 1995b). The theoretical spectra are convolved with an appropriate gaussian for simulating the instrumental broadening.

For the early-type WN stars with strong lines (WNE-s), WR 6 (designation after van der Hucht et al. 1981; alias HD 50896) serves as our prototype. Taking the final parameters from Hamann & Koesterke (1998), we take the nearest grid model (which slightly differs from the best parameters) and recalculate a series with different degree of clumping. The model atmosphere is assumed to consist of helium and nitrogen. The model parameters are compiled in Table 1, while in Fig. 1 the region around the He II line at 4686 Å is displayed. This line is best-suited for our purpose, because the electron scattering wings are most pronounced at the red side of the strongest emissions. The comparison with the observation clearly reveals that the homogeneous model ($D = 1$) gives too strong electron-scattering wings, especially at the red flank of the He II 4686 line. The model with $D = 4$ fits much better, but higher values ($D = 16$) can not be safely excluded. Note that at these parameters the N V feature at 4604-4620 Å reacts very sensitive on the slightly different ionization structure of the models, thus violating the scaling invariance at constant R_t. Schmutz (1997) has studied the same star and derived a clumping factor of $D \approx 4$, in full agreement with our result.

Fig. 2 shows a model series together with the observation of WR 44, an early-type WN spectrum with weak lines (WNE-w). Although the electron-scattering wings are less pronounced than in the previous example, the homogeneous model ($D = 1$) is definitely ruled out by the comparison, while again $D = 4$ seems to fit best.

As the prototype for late-type WN stars we select WR 123 (alias HD 177230). In this case we calculate models with the adequate terminal velocity, because the fixed value of the available grid is too different. Moreover, the detailed comparison with the observation reveals that the even members of the He II Pickering series are systematically stronger than calculated, unless some hydrogen is put into the models. We find that a hydrogen mass fraction of 5% is adequate, which is quite usual for WNL stars, but in contrast to the zero hydrogen abundance given for

Table 1. Parameters of the test calculations

Figure	Fig. 1	Fig. 2	Fig. 3	Fig. 4
Comparison star	WR 6	WR 44	WR 123	Br 43
Spectral type	WN5-s	WN4-w	WN8	WC4
T_* / kK	100	70.8	35.5	141
log $R_t/R_\odot$	0.2	1.0	0.9	-0.13
v_∞ / (km/s)	1600	1600	1000	2800
log $L/L_\odot$	5.45	5.55	5.7	5.6
$R_*/R_\odot$	1.77	3.97	18.9	1.06
log $\dot{M}/(M_\odot \mathrm{yr}^{-1})$				
if $D = 1$	-4.12	-4.80	-3.84	-3.72
if $D = 4$	-4.42	-5.10	-4.14	-4.02
if $D = 16$	-4.72	-5.40	-4.44	-4.32
β_H	-	-	0.050	-
β_He	0.985	0.985	0.935	0.30
β_C	-	-	-	0.40
β_N	0.015	0.015	0.015	-
β_O	-	-	-	0.30

that star in our earlier papers. Again, the comparison with the observed spectrum reveals that the $D = 4$ model fits best. However, models in this parameter range have an extremely sensitive ionization structure, and the scaling invariance is not accurately fulfilled. Only a marginal fine-tuning of the other parameters would suffice to restore consistent fits at different D values.

WC star analyses are still in their infancy, and their parameters are not well established yet. WC spectra are crowded with blending lines, which hinders the study of the line wings. Earlier WC subtypes have less complex spectra than later subtypes. Therefore we select for the present purpose the WC4 star Br 43 in the Large Magellanic Cloud, for which we have a fit model at hand. We prefer here somewhat different parameters than we have given in Gräfener et al. (1998) for that star. The model shown here is numerically improved and was selected for an optimum fit of the 4686 Å emission. The true parameters of WC stars are still rather uncertain.

An observation is available from Torres & Massey (1987), and we convolve our synthetic spectra according to its relatively poor spectral resolution (10 Å). The spectra are rectified by division through the theoretical continuum.

Fig. 4 shows the spectral region around the C III/C IV/He II blend 4650–4686 Å, displaying the model series for different values of D together with the observation of Br 43. As in the case of the WN stars, the smooth model ($D = 1$) has too strong electron-scattering wings. But even the $D = 4$ model shows some scattered light at the flanks of the strong emission complex, filling the observed gaps to the neighboring lines. In contrast to the WN spectra, it is the $D = 16$ model which fits best. Although we should be careful when generalizing from one single object, this result might indicate that WC winds are even less homogeneous than the winds of WN stars.

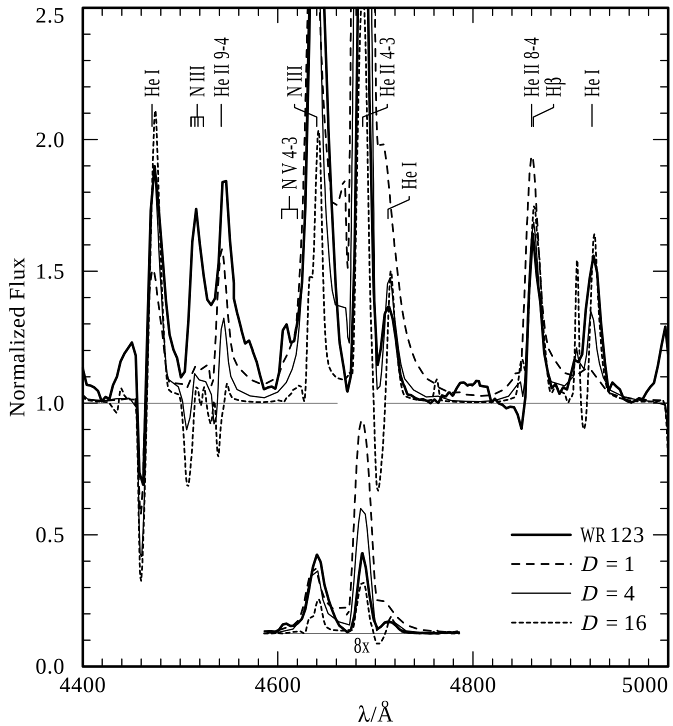

Fig. 3. Same as Fig. 1, but for a late-subtype WN star (WNL). The observed spectrum shown is from WR 123 (WN8). The model parameters are compiled in Table 1.

5. Summary and conclusions

In the previous sections, inhomogeneous Wolf-Rayet type stellar winds were modeled in a first-order approximation, assuming that small-scale clumps are distributed with a constant volume filling factor within a void interclump space. Model calculations as well as analytical considerations showed that the main spectral features, i.e. the strength of the emission lines, are invariant if the clumping parameter D (i.e. the density enhancement of the clumps compared to a homogeneous model with the same mass-loss rate) is compensated by scaling down the mass-loss rate with the factor $\sqrt{D}$. This holds in the same degree of approximation as the so-called transformation law for WR atmospheres and follows from the dominance of emission processes that depend on the square of the density.

Hence, to the first order the mass-loss rate is the only empirical parameter which is affected by the application of clumped models for spectral analyses. Note that the same clumping correction applies for empirical mass-loss rates derived from radio observations, as the free-free emission is a ρ^2-process as well. The good consistency between empirical mass-loss rates derived from the radio emission and the UV/optical/IR line spectrum, respectively, thus implies that the clump characteristics do not change very much from the line-forming regions close to the photosphere to the radio-emitting regions in hundreds of stellar radii.

When the clump density enhancement D is increased with a compensating decrease of the mass-loss rate (i.e. $\sqrt{D}\dot{M}$ = constant), the electron-scattering line wings become weaker. Along model series with same transformed radius but different combinations of mass-loss rate and radius (or luminosity), for which the main spectral features retain their strength approximately,

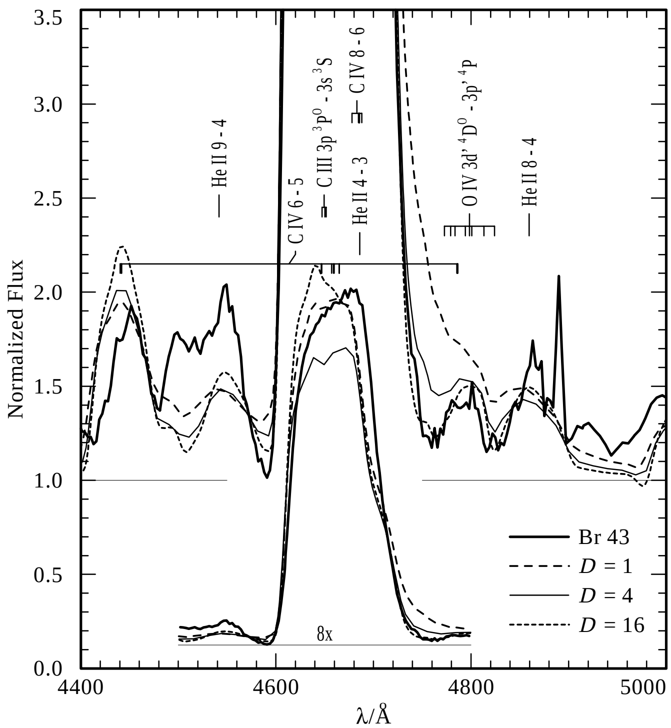

Fig. 4. Same as Fig. 1, but for a WC4 star. The observed spectrum shown is from Br 43 in the LMC. The model parameters are compiled in Table 1.

the bigger stars have stronger electron scattering wings if the same clumping parameter is chosen.

These electron scattering wings can be used, in principle, to determine the adequate value of the clump density enhancement D. We select Wolf-Rayet stars of different spectral subclasses and compare their spectra with adequate models, varying the density enhancement D. In all cases, the homogeneous model can be definitely ruled out because it predicts electron scattering wings that are significantly stronger than observed. For the three WN stars considered, the line wings are in reasonable agreement if $D = 4$, while for $D = 16$ they are possibly to shallow, but still compatible with the observation within the error margin. In case of the WC example star, $D = 16$ fits best.

Adopting that $D = 4$ is a typical value for the density enhancement, the empirical mass-loss rates become smaller by factor $\sqrt{D} = 2$ than obtained from the use of homogeneous models. This is in line with independent evidences. Moffat et al. (1994) performed wavelet analyses of emission line variations in WR spectra and derived a clump distribution which has the effect of $\sqrt{D} = 3$ in our notation (Moffat & Robert 1994). For the WN+O binary system V 444 Cyg, the radio emission gives about three times higher mass-loss than the change of the orbital period (cf. St-Louis et al. 1993). Thus clumping with $\sqrt{D} = 3$ would reduce the radio-derived rate to perfect agreement (although that close binary system might not be representative for single-star winds).

In Hamann & Koesterke (1998) we analyzed the nitrogen spectra of the Galactic WN stars. Now we claim that the resulting mass-loss rates have to be scaled down by at least 0.3 dex, while the other parameters are not affected. Adopting this factor of two, the average values of the "momentum ratio" $\dot{M} v_\infty c/L$ now become 4.5, 4.3 and 15 for the WNL, WNE-w and WNE-s spectral subclass, respectively. For our WC example (Br 43) with $D = 16$ the ratio is 17. These values are still above the single-scattering limit (i.e. unity), but no longer implausible for radiative acceleration with multiple-scattering effects (Lucy & Abbot 1993). Note that the non-radiative energy loss (Heger & Langer 1996) becomes less important when the mass-loss rates are smaller than previously thought. For the stellar evolution in the WR phase the consequences of smaller mass-loss should be examined.

References

Baum E., Hamann W.-R., Koesterke L., Wessolowski U., 1992, A&A 266, 402
Brown J.C., Richardson L.L., Antokhin I. et al., 1995, A&A 295, 725
Crowther P.A., Smith L.J., 1997, A&A 320, 500
Feldmeier A., 1995, A&A 299, 523
Gräfener G., Hamann W.-R., Hillier D.J., Koesterke L., 1998, A&A 329, 190
Hamann W.-R., 1994, Space Science Reviews 66, 237
Hamann W.-R., Koesterke L., 1998, A&A 333, 251
Hamann W.-R., Schmutz W., Wessolowski U., 1988, A&A 194, 190
Hamann W.-R., Leuenhagen U., Koesterke L., Wessolowski U., 1992, A&A 255, 200
Hamann W.-R., Koesterke L., Wessolowski U., 1993, A&A 274, 397
Hamann W.-R., Wessolowski U., Koesterke L., 1994, A&A 281, 184
Hamann W.-R., Koesterke L., Wessolowski U., 1995a, A&A 299, 151
Hamann W.-R., Koesterke L., Wessolowski U., 1995b, A&AS 113, 459
Heger A., Langer N., 1996, A&A 315, 421
Hillier D.J., 1984, ApJ 280, 744
Hillier D.J., 1987a, ApJ Suppl. 63, 947
Hillier D.J., 1987b, ApJ Suppl. 63, 965
Hillier D.J., 1988, ApJ 327, 822
Hillier D.J., 1991, A&A 247, 455
Hillier D.J., Miller D.L., 1998, ApJ 496, 407
Hummer D.G., 1962, MNRAS 125, 21
van der Hucht K.A., Conti P.S., Lundström I., Stenholm B., 1981, Space Sci. Rev. 28, 227
Koesterke L., Hamann W.-R., Kosmol P., 1992, A&A 255, 490
Lucy L.B., Abbott D.C., 1993, ApJ 405, 738
Moffat A.F.J., Robert C., 1994, ApJ 421, 310
Moffat A.F.J., Lépine S., Henriksen R.N., Robert C., 1994, Ap&SS 216, 55
Owocki S.P., 1994, Ap&SS 221, 3
Owocki S.P., Castor J.I., Rybicki G.B., 1988, ApJ 335, 914
Pollock A.M.T., Haberl F., Corcoran M.F., 1995, in: K.A. van der Hucht and P.M. Williams (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, Proc. IAU Symp No. 163, p. 512
Prinja R.K., Smith L.J., 1992, A&A 266, 377
Schmutz W., 1997, A&A 321, 268
Schmutz W., Hamann W.-R., Wessolowski U., 1989, A&A 210, 236
St-Louis N., Moffat A.F.J., Lapointe L. et al., 1993, ApJ 410, 342
Torres A.V., Massey P., 1987, ApJ Suppl. 65, 459
Wessolowski U., Schmutz W., Hamann W.-R., 1988, A&A 194, 160
Wessolowski U., Hamann W.-R., Koesterke L., Hillier D.J., Puls J., 1995, in: K.A. van der Hucht and P.M. Williams (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, Proc. IAU Symp No. 163, p. 174