HYDRODYNAMIC LINE BLANKETED ATMOSPHERES OF WOLF-RAYET STARS

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Abstract. In this paper I examine the acceleration of Wolf-Rayet winds in the optically thin part of the atmosphere. First, I investigate the radiative force using atmosphere models with specified velocity structures. It is found that "standard" model atmospheres that reproduce the observed spectra of Wolf-Rayet stars do not provide by a large factor ($\approx$ 10) the force needed to accelerate the adopted velocity structure. Second, using clumping in order to have a favorable luminosity to mass loss ratio, it was attempted to find a hydrodynamic solution of a WR wind. If large clumping factors of the order of 30 are assumed then solutions are possible. However, such models are very unlikely to be correct since they predict much stronger emission lines than observed in any WR star. Third, a modification of the non-LTE rate equations is investigated. It is assumed that a Bowen resonance-fluorescence mechanism removes a small fraction of photons from the radiation field of the helium Lyα resonance line. It turns out that the ionization equilibrium of winds where helium is recombining from He^{++} to He^{+} is extremely sensitive to a modification of the radiation field of this line. A removal of 1% of the photons is sufficient to initiate an abruptly changing ionization equilibrium. It is proposed that the key to understand the acceleration of WR winds is the correct calculation of the ionization structure. If this hypothesis is true then today's non-LTE atmospheres yield systematically wrong results. This would not only affect the radiative acceleration but also the observable helium lines that are used for the diagnostic of the stellar temperature. It would imply that the luminosities of WR stars are underestimated by the present atmosphere models.

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

1. Introduction

At the last symposium on Wolf-Rayet stars the term "standard model" was introduced to characterize hydrogen/helium non-LTE atmospheres (Hillier 1991; Schmutz 1991a). During the last years the model calculations have become more sophisticated by including complicated CNO model atoms (*e.g.*, Hamann *et al.* 1994; Crowther *et al.* 1994). But otherwise, the theory of WR atmospheres has made little progress. The most outstanding feature of WR stars, their strong mass loss, is still not understood, forcing the use of semi-empirical atmospheres with assumed velocity structures. So far it has been verified that there is basically no difference in predicted line spectra and derived stellar parameters if velocity structures with $\beta = 1$ or $\beta = 2$ are used (Hillier 1991; Schmutz 1992). However, it is possible to affect the resulting stellar parameters if structures are used that are different from the form given by the β-laws. Thus, the fact that the density structure cannot be calculated is one of the most important deficiencies of today's theory. In fact, non-LTE calculations and the resulting stellar parameters may be connected with the inability to find hydrodynamic solutions for WR winds.

K. A. van der Hucht and P. M. Williams (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, 127–137.
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https://doi.org/10.1017/S0074180900201782 Published online by Cambridge University Press

All but one previous attempt to explain WR winds by radiation pressure have flaws in their calculations that are evident. Either the adopted stellar parameters are not realistic in that the ratio of luminosity to mass loss is too high compared to what is thought to be correct for WR stars (*e.g.*, Pauldrach *et al.* 1985) or the force needed has simply been assumed to exist by a corresponding choice of the CAK parameters k and α (*e.g.*, Turolla *et al.* 1988; Springmann 1994). The only exception is the result of Lucy and Abbott (1993, hereafter LA). They showed that if a stratified ionization structure is assumed then enough force is obtained to drive a WR wind. However, all WR models have a stratified ionization structure and therefore, recombination in the wind is only a necessary condition but not a sufficient one. The reason for the success of the LA model is more subtle and will be discussed in Sect. 4. Section 5 then presents results of an apparently "easy way out" where the mass loss is assumed to be low and the observed wind features are produced by clumped material. Then in Sect. 6 a new mechanism is proposed that could be the key to WR winds.

2. Method

The calculation of a hydrodynamic WR atmosphere is obtained in three steps that are repeated and iterated to consistency. The first step is the calculation of a H/He non-LTE atmosphere. This calculation is performed with the Kiel code (Hamann & Schmutz 1987; Wessolowski *et al.* 1988) using the Λ-iteration technique of Hamann (1987). The next step is a formal solution of the radiation transfer with Monte Carlo simulation including tens of thousands of spectral lines. This code is a version of that of Abbott & Lucy (1985) modified to include the non-LTE ionization structure and opacities from the non-LTE atmosphere (see Schmutz 1991b). The third step is the solution of the equation of motion given the radiation force that is determined in the Monte Carlo radiation transfer (Castor *et al.* 1975). The full procedure is described in more details in Schaerer & Schmutz (1994). However, there is an important difference to the latter paper: Here, it is attempted only to solve for the *acceleration* of the WR wind. It is assumed that the mass loss is created and accelerated to something like half the terminal velocity by an unknown mechanism. The first part of the velocity law is therefore specified by a β-law and only the velocity structure of the outer part is calculated.

A new feature of the model calculations is that clumping is included, although only a very crude approximation is used. Only the high density part is treated by simply multiplying the mean density by the factor $C(v/v_\infty)^2$, where C is the clumping factor. The low density regions are assumed to be completely transparent and therefore they are neglected. This simple assumption is justified to first order by the results of Owocki *et al.* (1988)

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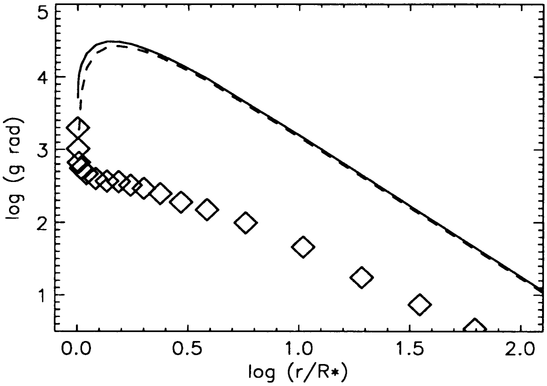

Fig. 1. Comparison of the calculated radiative acceleration with the acceleration needed to support the assumed velocity structure. The full drawn line gives the sum of the gravitation term and the kinematic structure, the dashed line is the contribution of the kinematic structure ($v dv/dr$). The diamonds denote the calculated radiative acceleration for the line blanketed WR model with the parameters $T_* = 45{,}000$ K, $R_* = 5$ $R_\odot$, $\log dM/dt = -4.0$, $\beta = 1$, and $v_\infty = 2500$ km s^{-1}. A line blanketed model with these parameter produces a spectrum of an early WN star with strong wind lines (Schmutz 1994).

who found a steep transition between low and high density regions and that the average density is dominated by the high density regions. In practice, this approximate treatment of clumping is realized by specifying a continuous density distribution that is enhanced from the mean density by the given factor and by reducing by the same factor all dimensions when used for radiation transfer calculations.

3. Radiation force of non-LTE WR models

Before I discuss hydrodynamic WR models I examine the radiation forces of non-LTE models that reproduce observed WR spectra. Puls & Pauldrach (1991) have investigated carefully the radiative forces obtained from such WR star models. They concluded that these models do not yield sufficient radiation to drive their winds. After including the effects of line blanketing Schmutz (1994) found that the situation is even worse: the line blanketing effects lower the deduced luminosities but the inferred mass loss rates are not reduced. In Fig. 1 the radiation force obtained with the line blanketed model that is discussed in detail by Schmutz (1994) is compared to the force needed to support the adopted atmosphere structure. The radiation force of this model is about a factor 10 too small to drive its wind.

4. Critique of the Lucy & Abbott model

The results presented in Sect. 3 are in striking contrast to the recent finding of Lucy & Abbott (1993, hereafter LA) who present WR type models that yield enough force to accelerate the wind. In order to compare the properties

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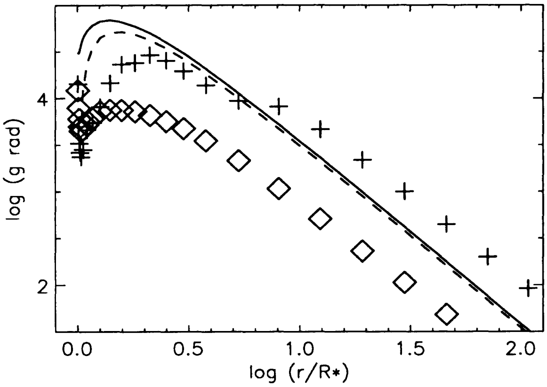

Fig. 2. The radiative acceleration (diamonds) obtained with a non-LTE model with the same stellar parameters as the model of Lucy & Abbott (1993). As in Fig. 1 the acceleration that is needed to support the assumed velocity structure is given by the full drawn line. The plus signs give the radiative acceleration of a recalculation of the LA model adopting their assumptions for the ionization and temperature structure.

of my model with that of LA, I have calculated a model with the same stellar parameters as LA, using the mass loss rate they obtain from their calculation: $T_* = 85{,}000$ K, $R_* = 2.5$ $R_\odot$, $\log(dM/dt\,/\,(M_\odot/yr)) = -4.7$, $\beta = 1$, and $v_\infty = 2500$ km s^{-1}. In Fig. 2 the resulting radiation force is compared to that implied by the adopted velocity structure. In contrast to LA's calculation (compare to Fig. 4 of LA) my model fails by a large factor to provide the force needed. Also shown in Fig. 2 is the resulting force if I adopt the temperature and ionization structure as used by LA. Basically, my recalculation of the LA model agrees with their result. Only close to the photosphere ($r < 5$ R_*) my model yields somewhat less force. I attribute this difference to a higher absorptive opacity (from excited He$^+$ levels) in my model. The recalculation of the LA model is a test to demonstrate that the discrepancy between the LA results and mine are physical and are not due to differences in the line list or other trivial reasons. Further, as noted by LA and confirmed by my calculations, the temperature structure can also be excluded as being of prime importance. This leaves the ionization structure as the reason for the differences of the radiation forces.

An inspection of the ionization structures reveals that in my non-LTE atmosphere helium remains completely ionized throughout the wind, whereas in the LA model the structure is recombining. The recombination properties of WR atmospheres are well studied and have been explained in detail in one of the first papers on WR analyses (Schmutz & Hamann 1986). All models for WR stars that reproduce the observed HeI *and* HeII lines have He^{++} recombining to He$^+$ in the wind. Thus, the fact that in the LA model the degree of ionization is decreasing outward is perfectly reasonable and agrees with the results of the atmosphere models (see *e.g.*, Fig. 2 of Hillier 1988).

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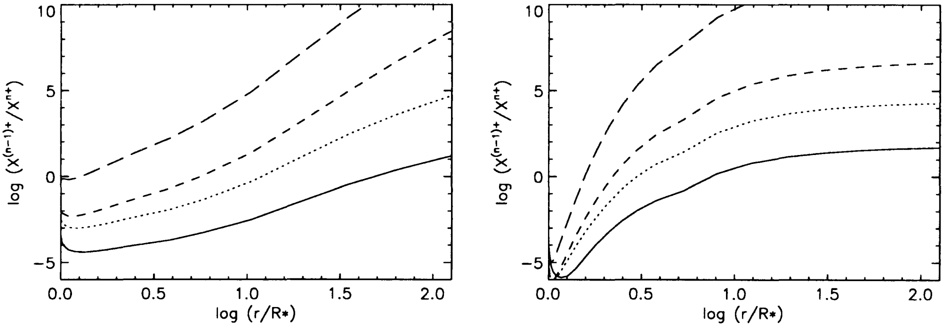

Fig. 3. Ionization structures of a non-LTE atmosphere (left) and of the LA model. The full drawn line shows the ratio of He^+/He^{++}, the dotted line the ratio C^{3+}/C^{4+}, the short dashed line N^{3+}/N^{4+}, and the long dashed line N^{3+}/N^{4+}. Left panel: The ionization structure of the line blanketed $T* = 45{,}000$ K model that yields the spectrum of a early type WN star with strong lines (see Schmutz 1994; see also Fig. 1). Right panel: The ionization structure of the LA model with $T* = 85{,}000$ K.

However, LA's choice of stellar parameters is such that their model has a too high luminosity for its mass loss. With the adopted stellar parameters the LA model falls into the region where atmosphere models predict helium to be fully ionized throughout the wind (see Fig. 1 of Schmutz *et al.* 1992).

But a high luminosity relative to the mass loss rate and a recombining atmosphere are still not sufficient to explain the high force that is found with the LA model. It turns out that for the radiative force the crucial property is *where* in the wind the recombination occurs. Figure 3 shows the the population ratios of a few ionization stages taken from the line blanketed WR atmosphere discussed in Sect. 3 and from the LA model. It can be seen that, despite a higher effective temperature, a higher luminosity, and a smaller mass loss rate, in the LA model helium recombines much closer to the photosphere. In contrast, there is a gradual slow recombination of helium in the non-LTE model that is typical for all non-LTE WR atmospheres independent of temperature and whether line blanketing is included or not.

Thus, the LA model contradicts the results of non-LTE calculations: the ionization structure has a strongly deviating radius dependence, the luminosity is too high, and the temperature structure differs. Unfortunately, there is no predicted line spectrum of the LA model in order to test against observations. However, from the point of view of today's non-LTE model atmospheres, it must be concluded that the LA model is inconsistent if not simply wrong (but see Sect. 6).

5. Models with large clumping factors

The investigations of Sect. 4 showed that a large luminosity to mass loss ratio and fast recombination of helium are favorable for hydrodynamic solutions of WR winds. Both these properties are supported by clumping. I have invested

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a lot of time and computer resources to search for a hydrodynamical solution of a WR atmosphere with the clumping factor as a free parameter. I was not able to find such a solution. The main problem that is encountered is that there is always a lack of force above the photosphere. There are ways to circumvent this difficulty. First, if it is assumed that the wind is coasting in this region, *i.e.*, the radiation force is insufficient to accelerate the material and the wind is decelerating, then the density structure is such that enormously strong emission lines are produced that are by a factor of ten or more stronger than ever observed in a WR star. Second, if the mass loss is assumed to be low enough that the material can be accelerated in the inner regions, *i.e.*, basically a solution similar to that of Pauldrach *et al.* (1985) except that clumping forces the wind to recombine, then the wind is accelerated to much too high a terminal velocity. Common to all these solutions is that an improbably large clumping factor of the order of 30 is needed (relative to the mean density). Although the fact that I could not find a solution is not a proof, I believe that it is unlikely that real WR star have low mass loss rates and mimic large rates with large clumping factors.

6. Modified non-LTE calculations

In Sect. 4 I concluded that, from the point of view of today's non-LTE atmospheres, the ionization structure of the LA model is wrong. However, it is not at all clear which model agrees better with reality. I believe that for the acceleration of the WR wind in the optically thin part there is no other realistic candidate than radiative force. It is certain that even the strongest WR winds are accelerated in the optically thin, *i.e.*, observable, part of the atmosphere. A correlation between ionization potential and line width was found long ago (Beals 1941; Smith & Aller 1971; Kuhi 1973) and confirmed by more recent investigations (Willis 1982; Koenigsberger 1990). Thus, since a fast recombining ionization structure turned out to be the essential property for a strong radiation force, I conclude that today's non-LTE atmospheres do not correctly model the ionization structures and therefore, that they predict systematically wrong results. The logical next step is to search for a possible reason for the failure of the non-LTE calculations.

Motivated by the observed "forest" of FeV and FeVI emission lines in the 1200 – 1500 Å region (see Koenigsberger & Auer 1985; Nugis & Sapar 1985) that are probably pumped by continuum fluorescence in the far UV, I suspect that one or several of the far UV Fe lines could influence the resonance transitions of HeII. A fraction of the line photons could get lost by exciting an iron level and escape via a branch of the numerous optically thin transitions to high iron levels. As a test for the influence of such a process I have assumed a loss of 1% of the line photons from the HeII Lyα line: In the rate equation I have replaced the line radiation field by $\bar{J}^{\mathrm{rate}} = 0.99\bar{J}^{\mathrm{line}}$. The

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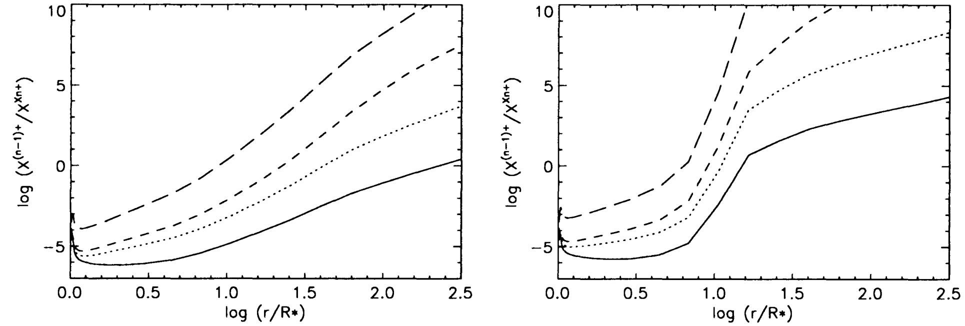

Fig. 4. Ionization structure of a model atmosphere with the stellar parameters $T_* = 85{,}000$ K, $R_* = 2.5$ $R_\odot$, $\log dM/dt = -4.7$, clumping with $C = 4$ (see Sect. 2), and a hydrodynamically calculated velocity structure that reaches $v_\infty = 1800$ km s^{-1} (see Fig. 5). the line styles mark ion ratios as in Fig. 3. Left panel: The ionization structure of the model calculation without photon loss from the HeII λ303.78 line. Right panel: the ionization structure of the model with a 1% photon loss from the HeII λ303.78 line.

result is that this small photon loss — which is in fact not small compared to the escape probability from the optically thick line, but it is small in absolute terms — has a very strong influence on the ionization structure.

Figure 4 shows the ionization structure of a model with similar stellar parameters as the LA model but with a hydrodynamically calculated outer velocity structure. The fast recombination that is obtained when photon loss is assumed does not look like the ionization structure assumed by LA but nevertheless, it also produces a strong enhancement of the radiation force close to the photosphere (Fig. 5).

Line lists contain many lines close in wavelength to HeII λ303.78. The best candidate line that could be of importance is FeVI λ303.70* that is separated by 80 km s^{-1}. Lucy *et al.* (1993) showed that a line even far out in the wings of an optically very thick line has a pronounced effect on the population of the upper level. But independently from the problem of identifying the correct process, the only important fact for the proposed mechanism is that some line photons are escaping.

7. Discussion

The test calculations presented in Sect. 6 assuming a 1% photon loss from the HeII Lyα resonance line showed that the ionization equilibrium of helium is fragile. If photons are lost, then the He^{++}/He^{+} ratio decreases much faster than in the case of no disturbance of the radiation field. Indirectly, via the radiation field, the degree of ionization of the metals also decreases quickly.

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* The transition probability is taken from Kurucz (1991) and the wavelength results from the FeVI term analyses of Ekberg (1975). Curiously, the proposed line is not in Ekberg's list of observed lines.

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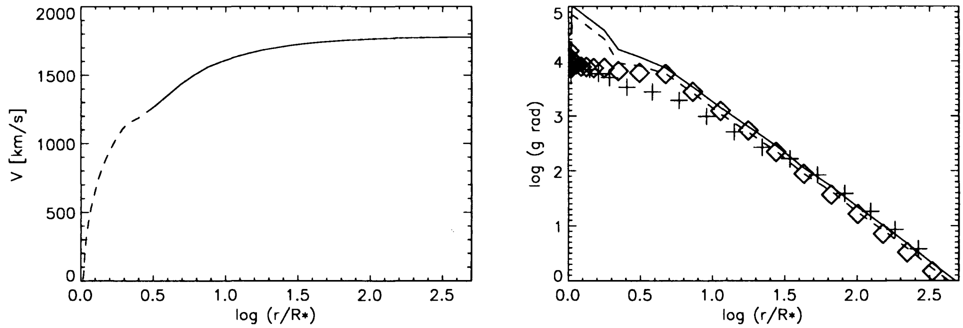

Fig. 5. Velocity structure and radiation force of the model of Fig. 4. Left panel: the full drawn line marks the part for which the velocity was obtained from the hydrodynamic calculation; the dashed line marks the region for which not sufficient force was available and a velocity law ($\beta = 0.5$) was adopted. Right panel: comparison between the calculated radiation force and the force needed to support the velocity structure. The meaning of the line styles is as in Fig. 1. The plus signs mark the calculated radiation force without photon loss; the diamonds denote the force obtained with a model with 1% photon loss from the He II λ303.78 line. Optical depth $\tau = 2/3$ is at $r = 4.6$ R_* ($\log(r/R_* = 0.66)$ and $\tau = 1$ at $r = 2.8$. Thus, the region for which no hydrodynamic velocity structure is obtained is not observable.

This change of ionization yields a replacement of the (photospheric) spectral lines by a new set of lines. This new line set intercepts the radiation at frequencies where the photosphere is more transparent and where most of the flux is emerging. LA pointed out the importance of the stratified ionization structure. This is certainly a necessary condition but it is not the important point, since a stratified ionization structure was always part of the model atmospheres. The investigations of Sect. 4 showed that the crucial property is how close to the photosphere a new line set is available. The closer to the photosphere the recombination sets in, the larger the amount of momentum that can be transfered to the wind. Although LA did not realize this aspect, it was nevertheless their calculation that demonstrated that there is a way to get the radiation force needed and therefore, LA deserve the credit to have discovered that WR winds can be accelerated by radiation pressure.

The model shown in Figs. 4 and 5 does support its velocity structure in the optically thin region, *i.e.*, the model yields about 1/3 of the total acceleration. Unfortunately, this model produces He II emission lines too strong by a factor of 2 and I have not yet been able to construct a fully consistent atmosphere. Thus, a hydrodynamic WR atmosphere has still to be calculated. Nevertheless, the test calculations are promising in that they showed a way how to increase the transfer of momentum from the radiation field to the wind. It could well be that photon loss from the He II Lyα resonance line is the key to understand the acceleration of WR winds.

If fast recombination is what happens in real WR winds, then this has more consequences than affecting the radiation force. It also changes the line

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strengths predicted by the models. Compared to the results of present non-LTE calculations the HeI lines will increase in strength and the models need to be hotter to produce the observed spectrum. If we are lucky this removes the systematic discrepancy between luminosities derived by spectroscopic analyses and those inferred from the mass using evolution models (Howarth & Schmutz 1992). Of course, an increase in deduced luminosity also eases the momentum problem of WR winds.

Acknowledgements

I thank Dr. Leon Lucy for discussions and valuable comments.

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DISCUSSION:

Nussbaumer: Could the classical Bowen mechanism which works via OIII transitions also help to take away a few HeII λ 304 photons? The beauty of this Schmutz-mechanism is that we do no longer need the enormous clumping factors which look too much like an artifact.

Schmutz: In the helium recombination zone O^{++} is not abundent enough that absorption by the OIII λ 303.8 line would produce the proposed mechanism.

Cassinelli: Several of us have observed with the Extreme UV Explorer (EUVE) the B2II star ϵ CMa. The brightest emission line in this spectrum is the HeII 304Å Lyman α line. The 2nd brightest line is the OIII line at 374Å. This is direct proof that the Bowen fluorescence mechanism does operate in the winds of hot stars. So your suggestion that it operates in WR stars is very plausible.

Owocki: I'm surprised that changes in the He ionization state should have such a dramatic affect on the radiative acceleration due to scattering in metal lines. Could you explain how this occurs.

Schmutz: First you have to keep in mind that the Fe ionization equilibrium is determined by that of He in that the latter determines the radiation field; thus the ionization temperature. Second, as long as you have the same main ionization stage of Fe as in the photosphere there is very little radiation pressure because the flux is flowing only in regions with low line density. You need a new line set, i.e. a new main ionization stage, to intercept the flux. The sooner this new set comes in, the more the WR wind can be accelerated.

Moffat: The more I listen to you theoreticians on your difficult modelling efforts, the more I am convinced that we observers should intensify our efforts to provide more rigorous constraints. One important way is to provide a yardstick to fix e.g. the ionization stratification directly from observation. Observing techniques are already available (e.g. high quality spectroscopic observations of WR binaries at crucial phases especially the geometrical eclipse when the O-star disk occults the inner wind regions in eclipsing binaries, or interferometry in lines of different ionization: e.g. γ Vel's wind should be resolvable right down to the WR core with SUSI in Australia at a resolution of 0".0005).

Conti: Would you care to say what would happen to a W-R spectrum if the iron abundance is a factor 10 lower (e.g. the SMC)?

Schmutz: What matters is the escape probability due to photon loss in the 303Å line. If the additional photon loss due to Fe is clearly larger than the Sobolev escape probability of the helium line then the effect saturates and the iron abundance has no influence. However, if the two processes are of the same magnitude then it could be that there is no difference between Galaxy and LMC but a much smaller influence in the SMC.

Cherepashchuk: The equivalent width of an emission line in a clumping model depends on the density jump, dimension of clumps, filling factor. Could you decrease equivalent width by changing of these parameters? Why do you reject the clumping model?

Schmutz: I do not reject clumpy models, I only said that I find it unlikely that a very high clumping ratio such as 25 or 30 is the solution of the WR wind problem. I need this high clumping ratio to get a recombining wind, but it implies that the line emissions are too strong.

Brown: When you speak of wind clumping factor, do you mean the ratio of maximum to minimum density or maximum to mean density? What do you assume about the temperature contrast between dense/tenuous components - e.g. equal pressures?

Schmutz: I mean the ratio of maximum to mean. In fact the clumped model simply assumes a vacuum between the compressed clumps, so pressure balance/distribution has not yet been considered.

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van Kerkwijk: What is your feeling about what the effect of this different ionization structure will be on the derived effective temperatures and radii for WR stars?

Schmutz: I do not think that there will be any significant effect for late type stars because for those the ionization equilibrium is very sensitive to small changes in effective temperature. Therefore a small correction will be sufficient. For early type (hot) stars it might be important and if we are lucky it will go in the right direction to increase the effective temperature and reduce the systematic difference between spectroscopically derived luminosities and that deduced from the theoretical mass-luminosity relation. (See Howarth & Schmutz 1992).

Usov, Cherepashchuk, Antokhin

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