

Atmospheres and Winds of PN Central Stars

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Abstract. The progress over the last years in modelling the atmospheres and winds of PN central stars is reviewed. We discuss the effect of the inclusion of the blanketing by millions of metal lines in NLTE on the diagnostics of photospheric and stellar wind lines, which can be used to determine stellar parameters such as effective temperature, gravity, radius, mass loss rate and distance. We also refer to recent work on the winds of massive O-type stars, which indicates that their winds are possibly inhomogeneous and clumped. We investigate implications from this work on the spectral diagnostics of PN central stars and introduce a method to determine wind clumping factors from the relative strengths of H α and He II 4686. Based on new results we discuss the wind properties of CSPN.

Keywords. stars: fundamental parameters; stars: winds, outflows

1. Introduction: a brief history

Since many decades model atmospheres have been a fundamental tool to understand the physical nature of PN Central Stars and the ionization and emission of their surrounding nebulae. After the pioneering work by Aller (1948), which revealed the importance and enormous potential of CSPN spectroscopy, and Heap (1979, and references therein), which provided the first quantitative spectral analyses based on model atmospheres, the field was advanced by Méndez *et al.* (1983), Kudritzki and Méndez (1989) and Méndez *et al.* (1988). In this work, high quality spectra obtained with new 4m-class telescopes and very efficient spectrographs and detectors were analyzed in detail using a new generation of hydrostatic, plane parallel NLTE model atmospheres to determine effective temperatures, gravities and helium abundances. This work demonstrated nicely that O-type CSPN form an evolutionary sequence in the ($\log g$, $\log T_{eff}$)-plane and that the gravities and temperatures determined spectroscopically could be used to estimate stellar masses, radii, luminosities and distances by comparison with the predictions of post-AGB evolution and the core mass - luminosity relationship.

While this new concept seemed compelling, there were clear indications of quantitative deficiencies. The masses determined seemed systematically larger than white dwarf masses and some of the objects (such as NGC 2392) had unrealistically high masses. The model atmospheres used, though in NLTE and certainly state-of-the art, did not include the opacities of metal lines and they also neglected the effects of stellar winds and spherical extension, which were suspected to be substantial, in particular for cooler objects, where the gravities are lower, and for more massive objects, which are closer to the Eddington limit.

Indeed, Perinotto (1989) and Kudritzki and Méndez (1989) stressed the importance of stellar winds not only for the evolution of CSPN but also for their diagnostics. With

a new generation of “unified model atmospheres”, which included the effects of stellar winds and spherical extension, many CSPN were re-analysed and, indeed, somewhat lower masses were found (Kudritzki and Méndez 1993, Kudritzki *et al.* 1997). In addition, the mechanical momenta of the stellar winds determined were in rough agreement with general scaling relations obtained from the theory of radiation driven winds and compared to the momenta of massive O-stars, however the scatter around this relationship was large.

The major remaining model atmosphere deficiency at this stage was the neglect of metal line opacity, which - if included - needed to be calculated in NLTE, certainly a formidable problem. This problem has been overcome in recent years and a wide variety of very efficient model atmosphere codes does exist now taking into account the effects of millions of metal lines in NLTE and the velocity fields of stellar winds together with spherical extension. These new codes allow for detailed studies of the UV spectra and a re-analysis of the optical spectrum now with the inclusion of line-blanketing. This is the subject of the review presented here. We will focus on low gravity, relatively cool O-type CSPN. WR-type objects and objects of higher gravity are discussed in other reviews in these proceedings.

2. UV spectroscopy of CSPNs

A significant number of good UV-spectra of CSPN obtained with IUE, HST, and recently with FUSE are available. Many of them show the signatures of stellar winds through broad P-Cygni profiles of resonance lines, which are frequently used to determine terminal velocities of the stellar winds and estimates of mass-loss rates. However, the latter are usually very uncertain, either because the wind lines are strongly saturated or because the ionization equilibria in the wind are uncertain and affected, for instance, by the presence of soft X-rays and EUV radiation emitted in stellar wind shocks.

On the other hand, there are also thousands of photospheric metal lines in the UV spectra of CSPN and their analysis provides independent means to determine effective temperatures through photospheric ionization equilibria such as Fe IV/v. They also allow for an accurate determination of stellar metallicity. Pauldrach *et al.* (2004) and Herald and Bianchi (2004a) have carried out such studies and determined temperatures and metallicities for a larger sample of CSPN. Compared to Méndez *et al.* (1988) and Kudritzki *et al.* (1997), this work generally confirms the effective temperatures derived from the optical line spectrum. This is important in the cases of those CSPN which have a much higher He II “Zanstra-temperature” (the standard example is NGC 2392). The UV work makes it clear that the high nebular ionization observed in these cases is not caused by a central star with an extremely high atmospheric temperature.

The downside of the “photospheric” UV-work is that it does not allow for a direct spectroscopic determination of stellar gravities. Thus, if not combined with optical spectroscopy, there is no direct spectroscopic way to determine masses, radii, and luminosities. This is only possible, if independent assumptions about the distance are made. A beautiful example is the work by Herald and Bianchi (2004b) of 7 LMC CSPN. Assuming a distance to the LMC, the determination of T_{eff} from the UV spectrum allows to determine radii, luminosities and, then, with post-AGB evolution, stellar masses. Very convincingly, the authors obtain stellar masses between 0.55 and 0.65 M_{\odot} .

Pauldrach *et al.* (2004) use a very interesting different approach. Realizing that the theory of radiation driven winds predicts a strong dependence of mass-loss rates and terminal velocities on stellar luminosity and stellar mass (see Kudritzki and Puls, 2000, and references therein), they use a concept first worked out by Kudritzki *et al.* (1992)

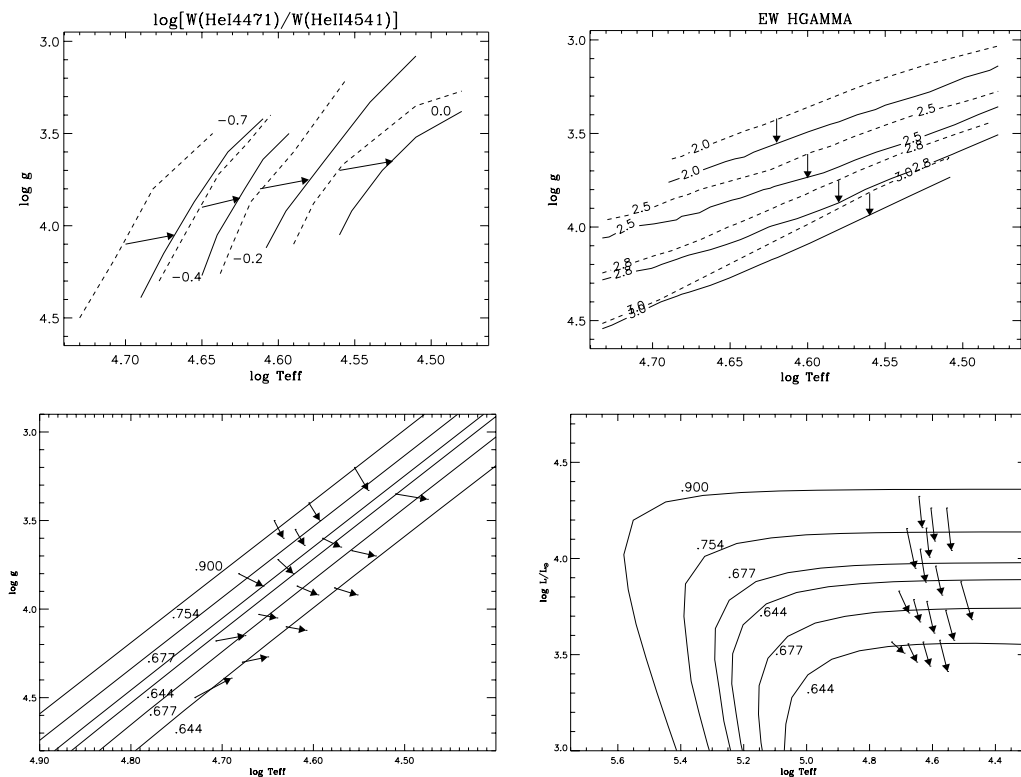


Figure 1. Upper part: isocontours of the logarithm of $\log [W_{\lambda}(\text{HeI}4471)/W_{\lambda}(\text{HeII}4542)]$ and $W_{\lambda}(\text{H}\gamma)$ in the $(\log g, \log T_{\text{eff}})$ - plane. Dashed isocontours are unblanketed models, solid are blanketed. Vectors indicate the shifts caused by the effects of NLTE metal line blanketing. The calculations were done with the NLTE code FASTWIND (Puls *et al.*, 2005). Lower part: Shifts in the $(\log g, \log T_{\text{eff}})$ - plane (left) and HRD (right) caused by the use of blanketed model atmospheres overplotted to post-AGB evolutionary tracks by Vassiliadis & Wood (1994). The tracks are labelled by their stellar masses.

to determine stellar masses and luminosities from the observed terminal velocities and the UV-mass-loss rates. They study the same CSPN sample as Kudritzki *et al.* (1997) and obtain very similar effective temperatures. But for many objects, the masses and luminosities are significantly different leading to the conclusion that either the stellar wind hydrodynamics or the core mass-luminosity relationship of post-AGB evolution, which was the basis for the work by Kudritzki *et al.* (1997), are not completely accurate.

The second conclusion, if true, would have enormous repercussions for the interpretation of post-AGB evolution. Looking critically at the results obtained by Pauldrach *et al.*, we note that only two of their nine objects have masses below $0.8 M_{\odot}$, five have masses between 1.3 and $1.4 M_{\odot}$ just below the Chandrasekhar limit, and two are in between. For a number of reasons, that seems to be in conflict with galactic evolution and dynamics (see Napiwotzki 2006). We also note that in their determination of mass-loss rates, Pauldrach *et al.* (as did Kudritzki *et al.*) assumed homogeneous, unclumped winds, an assumption which might not be justified, as we will discuss later. A re-analysis of the optical spectra of these CSPN, now using blanketed models, can perhaps help to clarify the situation. This will also be described later.

3. The effects of metal line blanketing

The inclusion of the opacity of millions of spectral lines in NLTE has two major effects. First, it changes the spectral energy distribution in the UV because of strong metal line absorption in the outer atmosphere (“line-blanketing”). However, about 50 percent of the photons absorbed are scattered back to the inner photosphere providing additional energy input and, thus, heating of the deeper photospheres. This second “backwarming” effect increases the continuum emission from the photosphere and modifies ionization equilibria such as He I/II, which are used for the determination of T_{eff} . Fig. 1 demonstrates how the He I/II ionization equilibrium is shifted towards lower T_{eff} because of the backwarming effect. At the same time, the pressure-broadened wings of the Balmer lines (the standard diagnostic for $\log g$) become weaker, because the millions of metal lines increase the radiative acceleration g_{rad} and decrease the effective gravity $g_{eff} = g - g_{rad}$. As a result higher gravities are needed to fit the Balmer lines (see Fig. 1) in addition to the lower temperatures obtained from the helium ionization equilibrium. In summary, the use of blanketed models leads to systematic shifts in the ($\log g$, $\log T_{eff}$) – plane, which if compared with post-AGB evolutionary tracks result in systematically lowering CSPN masses, radii, luminosities and distances. Note that the presence of dense stellar wind envelopes increases the effects of backwarming and introduce an additional dependence on mass-loss rates (see Sellmaier *et al.* 1993, Repolust *et al.* 2004).

The combined effects of line blanketing and backwarming affect also the ionizing fluxes. Amazingly, for the ionization of hydrogen the changes are very small as the effects of blanketing and backwarming balance each other. However, the ionization of ions with absorption edges shorter than the one for hydrogen is significantly affected (see Kudritzki 2002, Martins *et al.* 2005).

4. Detailed analysis of optical spectra and the effects of wind clumping

The significant effects caused by NLTE line-blanketing make it worthwhile to re-analyse the optical spectra of the sample studied by Kudritzki *et al.* (1997). This will also allow for a comparison with the UV-study carried out by Pauldrach *et al.* (2004) discussed above. For our analysis we use the NLTE code FASTWIND (Puls *et al.* 2005), which includes the effects of NLTE metal line opacities, stellar winds, and spherical extension. The strategy for the analysis is identical to Kudritzki *et al.* (1997) (see also Repolust *et al.* 2004, for more recent work). T_{eff} and helium abundance are obtained from a fit to the He I and He II lines, while the gravity is determined from the higher Balmer lines. H_{α} as the strongest optical hydrogen line is formed in the stellar wind and, thus, used to constrain the mass-loss rate. The terminal velocity follows from fits to the UV P-Cygni lines.

While H_{α} is, in principle, a perfect tool to measure mass-loss rates (see Kudritzki and Puls 2000, Kudritzki 2006, for discussion and references), the results might be affected by stellar wind clumping. It has long been known that line driven winds are intrinsically unstable (Owocki *et al.*, 1988, 2004). This might lead to inhomogeneous, clumped winds such as described by Owocki and Runacres (2002) with regions of enhanced density ρ_{cl} and regions, where the density is much lower. In a very simple description, introducing clumping factors f_{cl} similar as in PN diagnostics, the relationship between the average density of the stellar wind flow ρ_{av} and the density in the clumps is then given by $\rho_{cl} = \rho_{av} f_{cl}$. The same relationship holds for the occupation numbers n_i of ions.

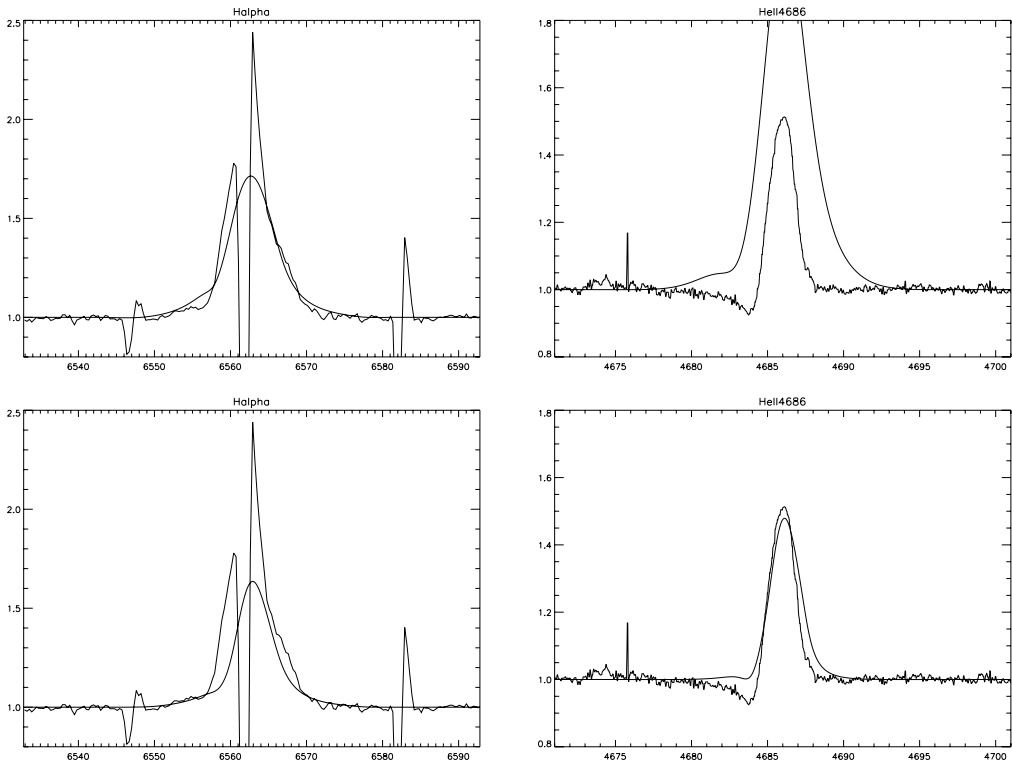


Figure 2. Diagnostics of the stellar wind emission lines H_α (left) and He II 4686 (right) of IC 418. In the top row $f_{cl} = 1$ is adopted and in the bottom we use $f_{cl} = 50$. Note that for H_α nebular lines have been (imperfectly) subtracted.

Line opacities κ depend on density through $\kappa \propto n_i \propto \rho^x$ and for very small, optically thin clumps the average optical line depth in the wind is given by $\tau_{av} \propto n_i^{av} \propto n_i^{cl} f^{-1} \propto \rho_{av}^x f^{x-1}$. For a dominant ionization stage we have $x = 1$ and the clumping along the line of sight cancels and does not affect the diagnostics. However, bound hydrogen is a minor ionization stage in hot stars, depending on recombination from ionized hydrogen with $n_i(H) \propto n_{ENP} \propto \rho^2$. Thus, if f_{cl} is significantly larger than one, the H_α mass-loss rate diagnostic is systematically affected and we have $\dot{M}(H_\alpha) = \dot{M}(true) f_{cl}^{1/2}$, following from the fact that $\dot{M}(true) \propto \rho_{av}$.

The spectral diagnostics of clumping in CSPNs is difficult. In principle, it requires the comparison of lines with different exponents x in the density dependence of their opacities. In WR-type CSPNs with very dense winds and very strong wind emission lines (see these proceedings or Hamann *et al.* 2003) incoherent electron scattering produces wide emission wings, the strength of which goes with $x \sim 1$. Clumping factors of the order of ten to twenty were found. This technique does not work for O-type CSPN, as their winds have much lower density. Also the UV P-Cygni lines of dominant ions provide usually little help, as these lines are mostly saturated and the ionization equilibria are uncertain. However, in most recent work on massive O-stars using FUSE and Copernicus spectra the P v resonance lines at 1118 and 1128 Å have been used as an indicator of clumping. The advantage of P v is the low cosmic abundance, so that the line is completely unsaturated even when in a dominant ionization stage. Substantial clumping

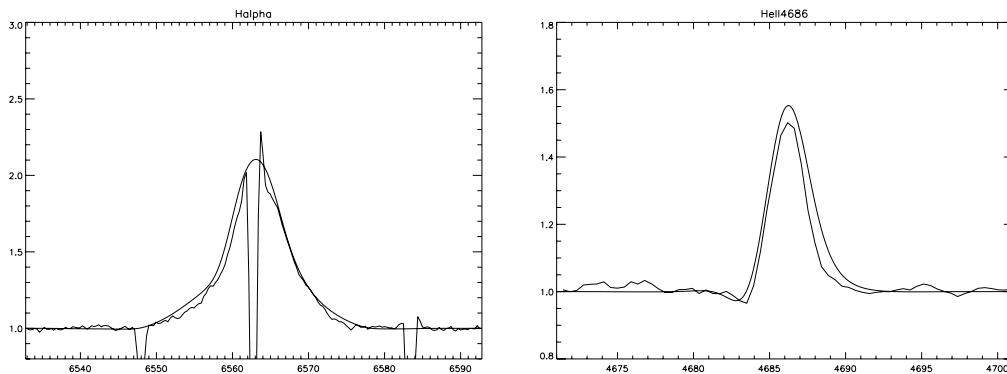


Figure 3. Diagnostics of the stellar wind emission lines H_{α} (left) and He II 4686 (right) of He 2-108. $f_{cl} = 1$ is adopted for the fit. Same as Fig 2 for the nebular lines.

Table 1. Stellar parameters of CSPN analyzed

object	T_{eff}	$\log g$	He ab.	R/R_{\odot}	$\log L/L_{\odot}$	M/M_{\odot}	d	\dot{M}	v_{∞}	f_{cl}	det.
	$10^3 K$	cgs					kpc	$\log M_{\odot}/yr$	km/s		
He 2-131	32	3.2	.33	3.5	4.07	.71	3.3	-6.88	400	8	y
Tc 1	34	3.2	.09	3.8	4.23	.81	4.4	-7.46	900	10	n
He 2-108	34	3.4	.09	2.6	3.92	.63	5.8	-6.85	700	1	y
IC 418	36	3.2	.17	4.0	4.38	.92	2.7	-7.43	700	50	y
IC 4593	40	3.6	.09	2.2	4.05	.70	3.5	-7.36	900	4	n
NGC 2392	44	3.6	.23	2.4	4.30	.86	2.8	-7.32	400	1	n
NGC 6826	46	3.8	.09	1.8	4.11	.74	2.6	-7.10	1200	4	n
IC 4637	52	4.2	.09	1.0	3.85	.62	1.3	-7.91	1500	4	n
NGC 3242	75	4.8	.09	0.5	3.89	.63	1.8	-8.08	2300	4	n

was found (Hillier *et al.* 2003, Bouret *et al.* 2005, Fullerton *et al.* 2006). Unfortunately, only a few useful FUSE spectra are available for our sample. We have, therefore, applied a different technique to constrain clumping, at least for a subset of our objects.

For cool O-type CSPN with $T_{eff} \leq 37,000$ K He II is a dominant ionization stage. That means for objects with strong winds and He II 4686 in emission and formed in the wind this line should have a density dependence close to $x = 1$. Its strength relative to H_{α} should allow one to constrain f_{cl} .

In the following we present the results of this new work. For lack of space we do not show typical examples of the fits of lines which constrain T_{eff} , $\log g$, and the helium abundance and refer to Kudritzki *et al.* (1997). Fig. 2 demonstrates in our most extreme case how f_{cl} is constrained. $f_{cl} = 1$ leads to far too strong emission of He II 4686 relative to H_{α} . A very large value of $f_{cl} = 50$, however, improves the fit significantly. Fig. 3 gives an example of the other extreme where a homogeneous wind with $f_{cl} = 1$ results in a very satisfactory fit. A summary of all results is given in Table 1. Note that the last column indicates the three cases where we were able to constrain f_{cl} . In the other cases, either nebular emission did not allow for a determination (Tc 1) or the objects were too hot for the method to be applicable.

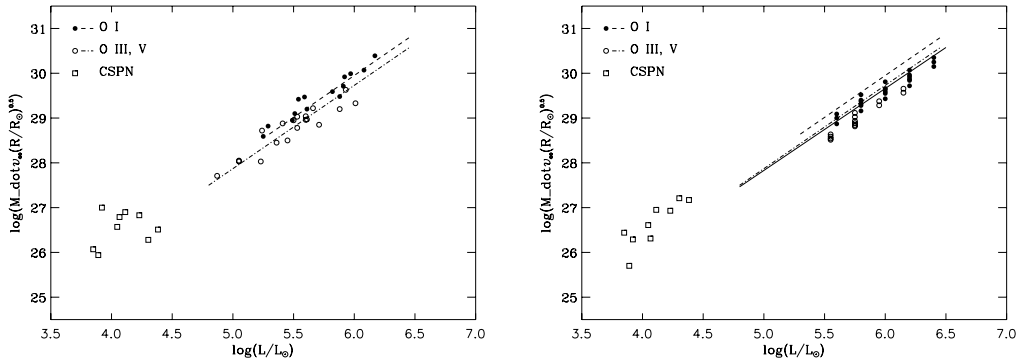


Figure 4. Left: Observed CSPN stellar wind momenta (this work) compared with those of massive O-stars (Repolust *et al.*, 2004, Markova *et al.*, 2004). Right: Calculated stellar wind momenta for the CSPN of this work and massive O-stars using the theory of line driven winds as developed by Kudritzki (2002). Symbols refer to model calculations. The dashed lines are the regression curves obtained from the observations of massive O-supergiants and dwarfs. The solid line represents the theoretical approach by Vink *et al.* (2000).

5. Discussion and future work

Comparing our results to Pauldrach *et al.* (2004) we find reasonable agreement for the effective temperatures for all cases (except He 2-108, which we find to be 17 percent cooler). This is very satisfying given the fact that different spectroscopic techniques were used for the determination of T_{eff} . However, in all but one case (He 2-131) the gravities obtained through our fitting of the Balmer lines are substantially lower. If one corrects for the temperature dependence of the Balmer lines (see Fig. 1) and the slightly different temperatures obtained, our gravities are on average 0.3 dex smaller. The reason is clearly the completely different approach used to determine gravities, as explained in section 2. Pauldrach *et al.* relied on the hydrodynamic simulation of stellar winds, whereas we have used the classical spectroscopic concept of Balmer line fitting. This will need further investigation.

For the determination of masses, radii, luminosities, and distances we have used again the classical approach of using the post-AGB core mass - luminosity relationship. Compared to Kudritzki *et al.* (1997) our masses are generally smaller in agreement with what we expect from section 3, however some of them (IC 418, NGC 2392) are still uncomfortably high.

The mass loss rates determined are uncertain because of the effects of stellar wind clumping. However, if we take into account that mass-loss rates determined with H_{α} scale with the stellar radius adopted as $\dot{M} \propto R^{3/2}$ (Kudritzki and Puls 2000) and compare with Pauldrach *et al.* we find agreement within a factor of two except for IC 418. Fig. 4 shows the CSPN wind momenta of our study compared to massive O-stars. There are two ways to interpret this plot. One is that CSPN form a convincing extension of the wind momentum - luminosity relationship of massive O-stars towards lower luminosities. Another one is that within the luminosity range of CSPN alone there is no clear relationship between wind momentum and luminosity (see also Tinkler and Lamers, 2002). Whether this is because of the uncertainties of mass-loss rate diagnostics or of the luminosity determinations, or both, will need further investigation.

It is interesting to compare this result with stellar wind models obtained with the theory of line driven winds. This is also done in Fig. 4, where we use the method by Kudritzki

(2002) to calculate wind momenta for the CSPN of Table 1. With a few exceptions the theoretical momenta are in the right ballpark.

Several steps need to be undertaken for future work. The first is to extend the work presented here and to re-analyse the UV-spectra of the sample and to compare in detail to see whether or not the results obtained from the two spectral windows are compatible, in this way addressing the original point made by Pauldrach *et al.* (2004). Taking into account the effects of clumping through the diagnostics of the P v and similar lines will be crucial.

A very important issue is the compatibility of stellar wind hydrodynamics with the stellar parameters derived by our method. While the wind momenta seem to agree within the observational errors, the terminal velocities calculated are too small in many cases for the parameters obtained by us. Whether this is a deficiency of stellar wind hydrodynamics or of the Balmer line diagnostics used, remains to be investigated. We note that one modification to be made in the wind hydrodynamics is the inclusion of clumping factors. It will be interesting to see whether this will help to resolve the discrepancy.

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