A Massive Star Odyssey, from Main Sequence to Supernova
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Advances in radiatively driven wind models

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Abstract. We report on a re-analysis of the Galactic O-star sample presented by Puls et al. (1996) by means of NLTE-atmospheres including line-blocking/blanketing. In particular, we concentrate on the question concerning the dependence of the wind-momentum luminosity relation (WLR) on luminosity class. Owing to the line-blanketing, the derived effective temperatures become significantly lower when compared to previous results, whereas the so-called "modified wind-momentum rates" remain roughly at their former values. Therefore, we obtain a new WLR for O-stars. By comparing these "observational" results with new theoretical predictions and simulations, we conclude that the H_α forming region for objects with H_α in emission might be considerably clumped and thus a larger mass-loss rate than actually present is mimicked. We suggest that the previously found dependence of the WLR on luminosity class is an artefact.

1. Introduction

One of the major results from the analyses of radiation driven hot star winds is the empirical finding that their (modified) wind momentum rate can be expressed as a simple function of stellar luminosity,

$$\log \dot{M} v_\infty R_*^{0.5} \approx x \log L + D. \tag{1}$$

In terms of theory, the slope of this relation corresponds to the inverse exponent of the so-called line-strength distribution function (modified for ionization effects), i.e., $x = 1/\alpha'$. The vertical offset D is controlled by the effective number of lines driving the wind. Both parameters depend on spectral type and metallicity (for details, see Kudritzki & Puls 2000 and references therein).

Once having been carefully calibrated, the wind momentum luminosity relation (WLR) will allow for an independent determination of extragalactic distances on intermediate scales (up to Virgo/Fornax cluster distances), utilizing spectra of A-type supergiants taken with 10m-class telescopes.

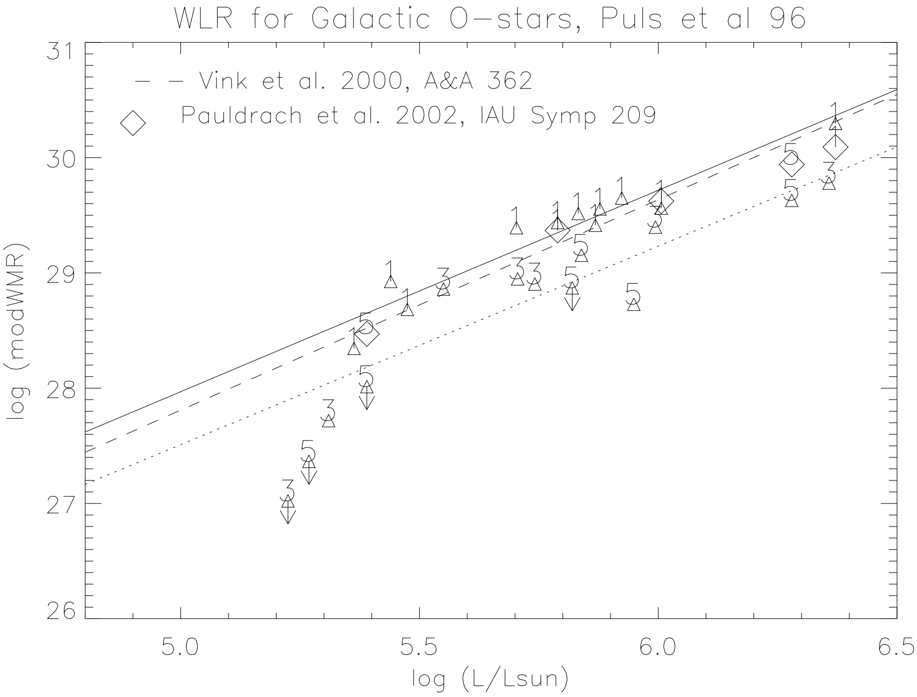

Figure 1. WLR for Galactic O-stars (cf. Puls et al. 1996), in comparison with recent theoretical predictions (dashed: Vink et al; diamonds: simulations by Pauldrach et al., for the same stellar parameters as derived by observations). Numbers correspond to luminosity class, arrows indicate upper limits for the modified wind-momentum rate (mWMR), and the lines result from linear regression to l.c. I and III/V objects, respectively.

While considerable progress, with respect to such a calibration, has been obtained in recent years, a number of questions became evident which so far prohibit a deeper understanding of some of the empirical findings. As an important example, we like to mention the problem of a much lower wind-momentum rate of mid-type B-supergiants compared to other spectral types (cf. Kudritzki et al. 1999).

In order to clarify these questions and to allow for an updated view of the present status quo, we have begun a re-investigation of already published data, with respect to both the "observed" values and the theoretical predictions, on basis of up-to-date model atmosphere codes including *line-blocking and blanketing.* In the following, we will report on first results from these investigations.

2. The WLR for Galactic O-stars: observations and theory

In Fig. 1, we display the starting point of all follow-up investigations, namely the WLR for Galactic O-stars, as presented by Puls et al. (1996). Interestingly, no unique relation had been found; instead, a clear separation between luminosity class I objects and the rest (here: III and V) seems to be apparent. The

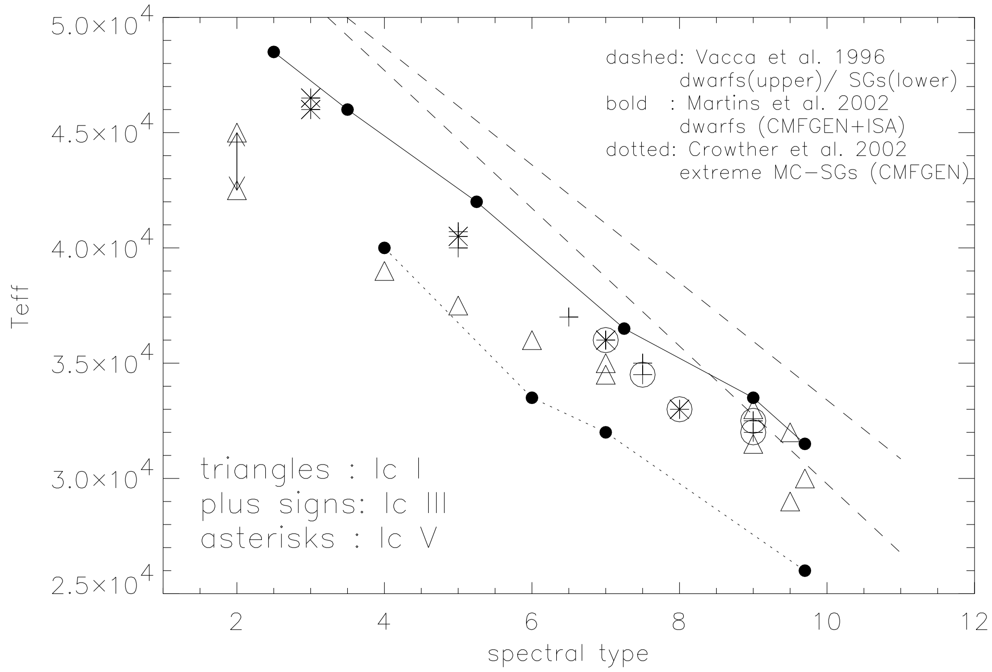

Figure 2. $T_{\rm eff}$ vs. spectral type for Galactic O-stars (line-blanketed models, this analysis), compared to similar investigations and results from unblanketed models. The entries at O2 correspond to HD93129A (recently detected binarity status, with $\Delta m \approx 0.5$, E. Nelan & N. Walborn, priv. comm.), displaying upper and lower limits for $T_{\rm eff}$. Cirles enclose extremely fast rotators with $v_{\rm rot} \sin i \geq 300$ km/s.

most obvious interpretation would be that the effective number of driving lines is a function of luminosity class. A comparison with recent theoretical predictions, however, indicates that this is not probable. While originating from completely different approaches, the simulations by both Vink, de Koter, & Lamers (2000, Monte-Carlo simulation, with $\dot{M}$ resulting from global energy conservation) and Pauldrach, Hoffmann, & Méndez (2002, self-consistent, line-blanketed wind models) predict a unique relation which is located in between the two "observed" ones. Actually, this uniqueness had previously been found in more simplified theoretical calculations, cf. Puls et al. (1996).

One has to keep in mind that the stellar/wind parameters entering Fig. 1 had been derived from pure H/He models, and that an influence of line-blanketing effects is more than likely. In order to exclude this potential source of uncertainty from further argumentation about "observed" relation(s) (nevertheless, dependent on the underlying physical assumptions) and possible contradictions with theory, we have begun to re-investigate the situation by means of line-blanketed models which have recently become available.

For this purpose we have used FASTWIND (Santolaya-Rey, Puls, & Herrero 1996) which has been updated for an approximative treatment of line-

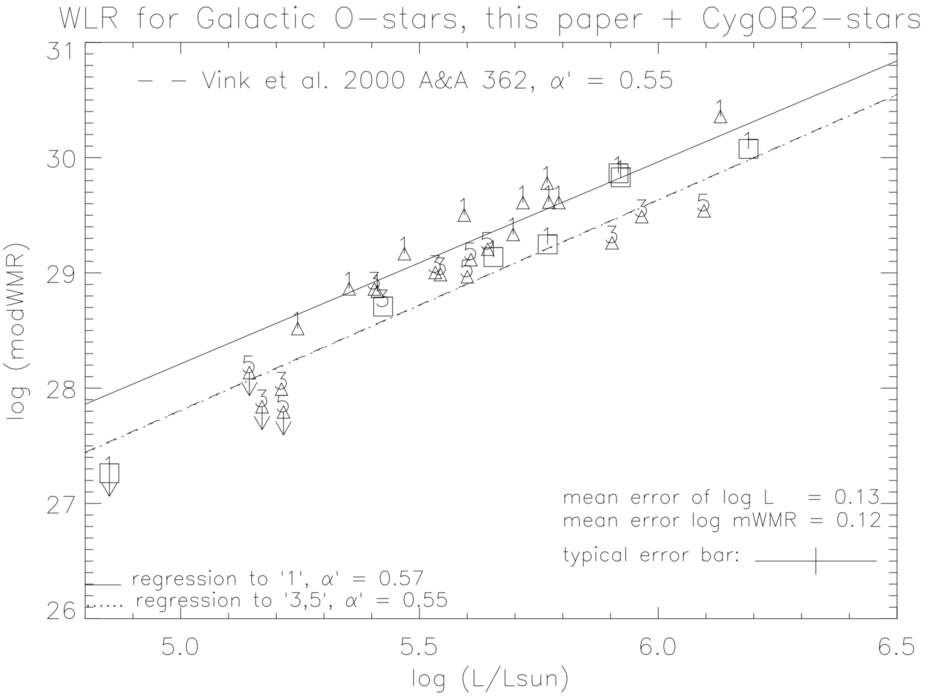

Figure 3. WLR for Galactic O-stars, using line-blanketed models, including results from Herrero et al. (2002) for CygOB2 stars (squares).

blocking/blanketing by us (for a brief description and first applications, cf. Herrero, Puls, & Najarro 2002). This code follows the philosophy of performing appropriate physical approximations allowing for a very fast computational time. Note that even the re-analysis of our first Galactic O-star sample required the calculation of 350 models.

The code has been carefully tested, by comparison with results from alternative, fully blanketed codes presently available (e.g., with CMFGEN (Hillier & Miller 1998), TLUSTY (Hubeny & Lanz 1995) and WM-basic (Pauldrach, Hoffmann, & Lennon 2001)). Part of these tests have already been discussed by Herrero et al. (2002), and additional material will be published elsewhere.

For our re-analysis, we have used the spectra described in Herrero et al. (1992) and Puls et al. (1996) and performed detailed line fits to the Hydrogen Balmer lines (α to ϵ), HeI and HeII, including λ 4686 (strongly wind-contaminated) and those He-lines neighbouring H_α. Details will be presented in Repolust et al. (2002, in prep.).

In Fig. 2, we display our new spectral type vs. $T_{\rm eff}$ relation. For dwarfs, the influence of line-blanketing is slightly larger than found by Martins, Schaerer, & Hillier (2002) in a comparable investigation (utilizing model-grids), whereas our effective temperatures of supergiants are somewhat hotter than derived by Crowther et al. (2002) for *extreme* MC objects. (Extreme objects are rare in our sample.) Note that the entry at O4 corresponds to ζ Pup, for which we have derived the same value (39,000 K) as indicated by Crowther et al. Compared to

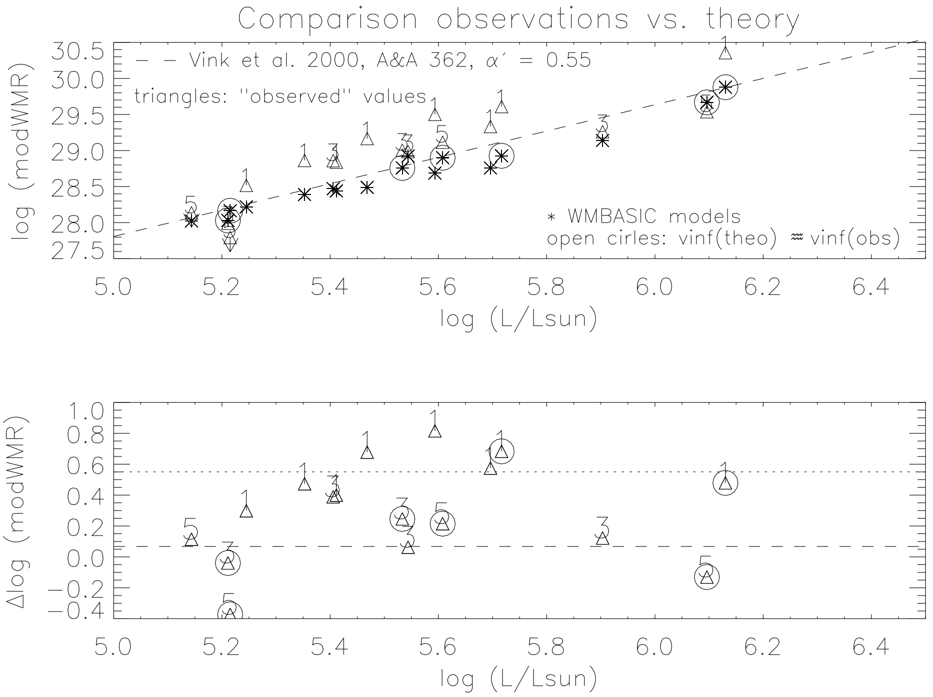

Figure 4. Comparison of observed and theoretical wind momenta. Upper panel: absolute values; lower panel: difference of logarithmic wind momenta. Lines indicate the mean difference with respect to l.c. I and for the rest, corresponding to (average) factors of 3.5 and 1.1, respectively (see text).

the latest calibration by Vacca, Garmany, & Shull (1996), utilizing pure H/He atmospheres, the differences are of the order of 4,000 to 8,000 K in the earliest types and become minor around B0.

Whereas the effective temperatures decrease significantly, the influence of line-blanketing on the derived stellar radius and $\dot{M}$ is marginal, since the optical fluxes (used by us to determine R_*) are similar to those from unblanketed models at their "older", higher $T_{\rm eff}$ (flux-conservation!) and since the influence of the reduced electron temperature on H_α is weak. Thus, compared to results from unblanketed models, the luminosities of the earliest types become significantly reduced and remain roughly constant around O9, whereas the "old" modified wind momentum rates are preserved. The resulting WLR is displayed in Fig. 3 (triangles only). Compared to Fig. 1, two points become apparent. First, the separation between l.c. I objects and the rest is still present. Second, the vertical offset is much larger (equal momenta at lower L), so that the "theoretical" WLR from Vink et al. is now consistent with the "observed" WLR for non-supergiants.

For most of the analyzed objects, we have additionally calculated self-consistent wind models by means of WM-basic. This was done for the stellar parameters derived in this study and without fine-tuning, i.e., without X-rays and leaving all metals at solar abundance. The results, compared to both the WLR by Vink et al. and the "observed" wind momenta, is shown in Fig. 4. On the one hand, the similarity between the two theoretical predictions is striking. On the other hand, theory agrees quite well with observations for non-supergiants, whereas for supergiants an average factor of 3.5 seems to be missing. A closer inspection (possible only for self-consistent hydrodynamical models) shows that just a part of the models (indicated by circles) is able to reproduce the observed terminal velocity, whereas the rest reveals a mismatch of the order of a factor of two (theory too low). The reason for this mismatch is still unclear, particularly since the (effective) gravities can be derived with rather narrow error bars of order ±0.1…0.15 dex.

Corresponding UV-spectra have been calculated for all models, for both the "observed" and the self-consistent wind-parameters, in order to obtain an additional constraint on the wind-density by comparing them to the observed (IUE) spectra. Although we have not undertaken a detailed analysis so far, some preliminary conclusions are already possible. Considering the global ionization balance, we find no contradiction with our "new" temperature scale. On the other hand, without inclusion of X-rays, CIV is almost always saturated, thus prohibiting any further conclusions. NV in "cooler" stars (below 35,000 K) is much too weak without X-rays, and PV reacts very sensitively to variations of $\dot{M}$ (cf. also Crowther et al. 2002) which is also true (and well known) for SiIV. Considering in particular the subset of models where the self-consistent terminal velocity agrees with the observed one, we find an interesting behaviour: For those objects where the observed and the theoretical mass-loss rates do not agree, SiIV favours the "observed" one, whereas the lines formed close to the photosphere (mainly Fe, Ni) seem to be consistent with a lower value.

In order to gain insight into whether the apparent problems are related to our spectroscopic analysis or to the theoretical simulations, the observed WLR for CygOB2 stars (which should be free of errors related to relative distances) has been included in Fig. 3. Note that this WLR has been derived with the same code as applied in the present investigation (cf. Herrero et al. 2002 and this volume). Although this sample consists almost exclusively of supergiants, the clear separation as a function of luminosity class, which we have confirmed for objects from our sample, is no longer visibile. On the contrary, only two objects, namely the most extreme supergiants in the CygOB2 sample, follow the "upper" WLR, whereas the derived values for all other objects are consistent with our WLR for l.c. III/V stars.

Guided by this perception, we have replotted our data (including the Cyg OB2 stars) in a slightly different manner, as shown in Fig. 5. In this plot, we have reclassified our sample in terms of the observed H_α profile: Class 1 comprises those objects with H_α in emission, class 3 designates objects with an absorption profile partly refilled by wind emission, and class 5 comprises objects with almost purely photospheric H_α profiles. Classified in this way, a unique trend, now also for the CygOB2 stars, becomes visible: *Stars with H_α in emission and those with refilled absorption profiles form two distinct WLRs.*

3. Conclusions: Clumping?

The difference between the new class 1 and 3 objects is, of course, given by the different contribution of wind-emission to the total profile. In class 3 objects,

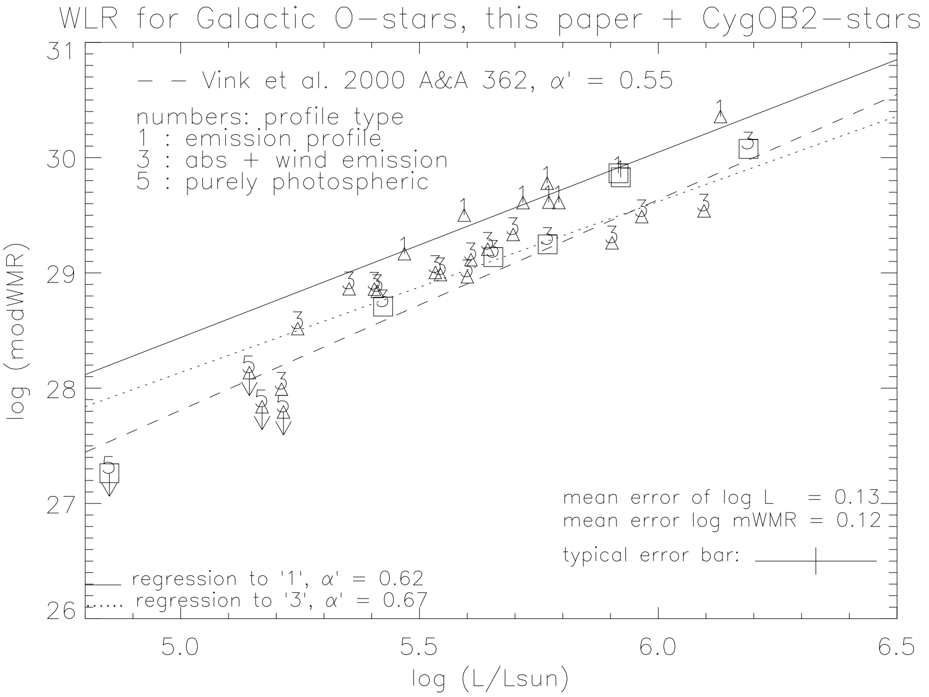

Figure 5. As Fig. 3, however classified as function of H_α profile type (see figure and text.

only contributions from the lowermost wind can be seen, whereas in class 1 objects the emission is due to a significant volume of the wind, out to 1.5 R_* in extreme cases (cf. Puls et al. 1996). Thus, there is the possibility that for these objects we *see* the effects of a *clumped* wind, which would mimic a higher mass-loss rate, as is most probably the case for Wolf-Rayet winds. Note that we do not exclude the presence of clumping in the intermediate/outer wind for class 3 objects, but owing to the low optical depth we simply cannot see it, in contrast to the case of class 1 objects where we observe the emission from a larger volume.

Actually, the principal presence of clumping has never been ruled out for O-star winds; however, there was simply no indication that *the H_α forming region* was considerably clumped (see the discussion in Puls et al.). Our new perspective is the result of a re-analysis of old data with improved models. In addition, recent theoretical considerations (e.g., Owocki & Puls 1999 and references therein; Feldmeier, Puls, & Pauldrach 1997) do not prohibit such a relatively deep-seated clumped region. Interestingly, time-series analyses of HeII 4686 from ζ Pup by Eversberg, Lepine, & Moffat (1998) have revealed "outward moving inhomogeneities", from regions near the photosphere out to 2 R_*.

Our hypothesis of seeing the effects of clumping at work is supported by three further facts. First, our hypothesis is consistent with the behaviour of the synthetic SiIV line described above, since this line reacts similarly to H_α (being a ρ^2 dependent line in O-stars). Second, for five out of the seven "class 1" objects from our sample, those synthetic Balmer lines formed in or close to the photosphere (H_γ and H_δ) show too much wind emission in their cores, and would require at least a factor of 1.5 less mass-loss in order to be consistent with observations (cf. also Herrero et al. 2002). Third, if we reduce the mass-loss rates of our class 1 objects by a factor of 0.42, these objects would perfectly fit the WLR for class 3, in accordance with theoretical expectations. Such a factor would correspond to an average clumping factor of 5.7, which is not too different from the values found in the case of Wolf-Rayet stars. Note also that a recent simulation for the atmosphere of ζ Pup by G. Gräfener (priv. comm.), including clumping, was able to simultaneously reproduce the UV and optical spectrum, for a mass-loss rate of *half* the value derived from our unclumped models. This finding is perfectly consistent with our conclusions stated above.

In summary, there are strong indications that mass-loss analyses of (at least) O-star winds utilizing H_α tend to overestimate the resulting values, unless clumping is accounted for or the winds are comparatively thin. Of course, we also have to be open to other possibilities which might explain the discrepancies found here. A combined multi-spectral analysis (UV, optical and IR) based on clumped wind-models and applied to large samples of stars of different spectral type should clarify these questions. Taking the recent advances in radiation driven wind models into account, this task has now become feasible.

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References

Crowther P.A., Hillier D.J., Evans C.J., et al. 2002, ApJ, submitted

Feldmeier, A., Puls, J., Pauldrach, A.W.A. 1997, A&A 322, 878

Eversberg, T., Lepine, S., Moffat, A.F.J. 1998, ApJ 494, 799

Herrero A., Kudritzki R.-P., Vílchez J.M., et al. 1992, A&A 261, 209

Herrero, A., Puls, J., Najarro, F. 2002, A&A, in press

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

Hubeny I., Lanz T. 1995, ApJ 439, 875

Kudritzki, R.-P., Puls, J. 2000, ARA&A 38, 613

Kudritzki, R.-P., Puls, J., Lennon, D.J., et al. 1999, A&A 350, 970

Martins F., Schaerer D., Hillier D.J. 2002, A&A 382, 999

Owocki, S.P., Puls, J. 1999, ApJ 510, 355

Pauldrach A.W.A., Hoffmann T.L., Lennon M. 2001, A&A 375, 161

Pauldrach, A.W.A., Hoffmann, T.L., Méndez, R.H. 2002, in: S. Kwok & M. Dopita (eds.), Proc IAU Symp. No. 209, in press

Puls, J., Kudritzki, R.-P., Herrero, A., et al. 1996, A&A 305, 171

Santolaya-Rey, A.E., Puls, J., Herrero, A. 1997, A&A 323, 488

Vacca W.D., Garmany C.D., Shull J.M. 1996, ApJ 460, 914

Vink, J.S., de Koter, A., Lamers, H.J.G.L.M. 2000, A&A 362, 295