Massive stars in the UV

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September 25, 2008

Abstract

We emphasize in this paper the importance of the UV range for our knowledge of massive stars and the fundamental role played by past and present space-based UV capabilities (IUE, HST, FUSE and others). Based on a review of the work developed in the last years and the state of the art situation for quantitative spectroscopy of massive stars, we present crucial advances which could be addressed by hypothetical future space-based UV missions. Advantages and unique data that these missions could provide are explained in the context of our present knowledge and theories on massive stars in the Milky Way and nearby galaxies. It is argued that these studies are our key to a correct interpretation of observations of more distant objects.

1 Introduction

Massive stars and their descendants are important constituents of galaxies. Because of their high luminosities (up to $10^6\,\mathrm{L}_\odot$) and their massive winds ($\dot{\mathrm{M}}$= 10^{-8} to 10^{-4} $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, v_∞=100 to 2000 $\mathrm{km\,s}^{-1}$) they have an extremely important influence on the dynamics and energetics of the interstellar medium. They also enrich the interstellar medium in nuclear processed material. This

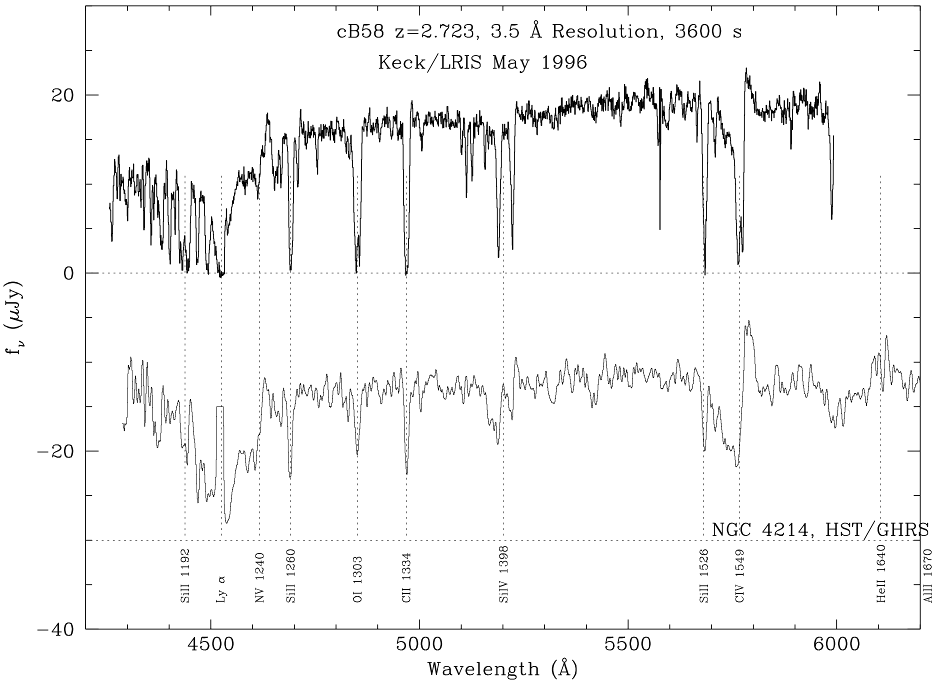

Figure 1: UV astronomy as key to understand high redshift galaxies. Optical spectrum of a galaxy at very high redshift (z=2.732) compared to a local starburst (adapted from Kudritzki, 1998)

enrichment occurs via mass loss (a massive star can lose 2/3 or more of its mass via a stellar wind) or during a SN explosion. They directly influence star formation by disrupting molecular clouds via SN explosions, or conversely they can initiate star formation through massive wind-blown bubbles and SN shells compressing nearby molecular clouds. Massive stars are also thought to be responsible for the reionization of the early Universe. More recently it has been proposed that the most massive stars are the progenitors of gamma-ray bursts.

Being crucial in many relevant aspects of astrophysics, detailed knowledge of massive stars have been hampered by the presence of strong stellar winds which dominate the resemblance of the atmospheres, the yields of ionizing radiation [**?**, **?**] and the evolution of these objects, leading to significant modifications in their observable spectra. Thus, we find stellar wind signatures at all wavelength ranges, from the UV ionized resonance transitions through the optical (H_α) to the Infrared and Radio.

Nevertheless, the correct interpretation of their wind lines in terms of radiation driven wind theory has provided the spectroscopist with a wonderfull tool to investigate the physics of galaxies. As they can be observed in medium resolution spectra as individual objects in galaxies out of the Local Group or as integrated spectra of starburst regions in galaxies with significant redshifts (see

Figure **??**), the correct knowledge of the physics of massive stars will yield information about the energy budget and chemical composition of galaxies along the cosmos history.

1.1 Importance of UV observations of Massive Stars

The UV constitutes an optimum spectral window as the spectral energy distributions of massive stars reach their maxima within this wavelength range. Appart from this efficient coincidence established by nature, massive stars decorate the UV spectral region with a number of key diagnostics to our understanding of the nature of these objects and their interaction with the surrounding media. The relevance of such diagnostics in the UV can be easily recognized since:

- The presence of P-Cygni profiles produced by the resonance transitions of C IV, N V, Si IV, O VI, etc, provides unique information about the stellar winds associated with massive stars.
- The bulk of blocking lines over several ionization stages from elements from the iron group enable to estimate metallicity and other stellar properties such as effective temperature.
- The unsaturated line profiles from ionized species trace very efficiently the mass-loss rate characterizing the stellar wind. Further, when combined with ρ^2 sensitive diagnostics at other wavelengths they may be used to calibrate the presence of inhomogeneities ("clumping") in the wind.
- They encompass enough number of X-Ray sensitive diagnostic lines such as O VI, C IV and N V.
- The optimized spatial resolution achieveval at UV wavelengths allows to resolve individual stars in starforming regions in external galaxies.

In this paper we review recent progress within the field of massive stars and discuss open problems which could be addressed by future UV missions.

2 Temperature Scale for massive OB stars

A calibration of the effective temperature of O supergiants is a key issue for the correct description of the radiation hardness in the EUV and UV spectral ranges and the corresponding ionizing photons released by the stars. This can have enormous consequences on the energy budget of their surroundings, as well as of starburst regions and galaxies whose UV spectra are characterized by these stars.

Since NLTE models are available, the temperature scale of massive OB stars has been determined using model atmospheres to fit a given ionization equilibrium. Helium, being the atom used to spectroscopically classify the earliest

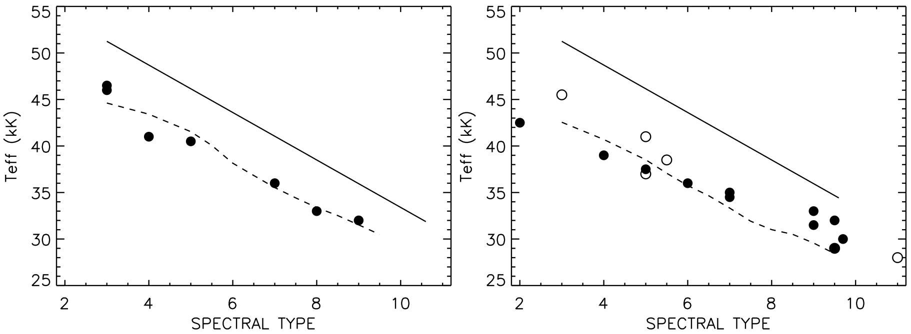

Figure 2: The temperature scale for Galactic O dwarfs (left) and supergiants (right). The solid lines are for the Vacca et al. (1996) scale, the dashed line for the scale defined by Martins et al. (2005) (the one the authors define as the theoretical scale), filled symbols are data from Repolust et al. (2004) and open symbols are data from Herrero et al. (2002).

stars, has become the traditional temperature indicator for these objects, although other ionization balances are formally possible. Of course, the resulting temperature scale is model dependent.

Very recently a number of calculations from different authors have strongly changed the temperature scale of massive OB stars. These calculations have been based on new families of model atmospheres that include sphericity, mass-loss and line -blanketing, in addition to NLTE. The combination of all these factors results in temperatures that are much cooler than those hitherto assumed.

vacca96 presented a compilation of the spectroscopic determinations of effective temperatures of massive OB stars. They gave preference to the most recent calculations, that at that time were mostly based on plane parallel, hydrostatic, unblanketed model atmospheres. Their temperature scale for dwarfs and supergiants can be seen in Fig. **??**

The first calculations pointing to a cooler temperature scale were those from martins02, who used CMFGEN [**?**], a code with all the improvements indicated above. These authors limited their calculations to OB dwarfs, so that the influence of mass-loss effects were negligible. Therefore, the main differences with vacca96 were clearly due to line-blanketing. These differences could reach up to 4 000 K for early types, and decreased towards O9 and B0 types, as can be appreciated in Fig. **??**

The work from martins02 was followed by a series of papers with similar results. h02 gave a temperature scale for supergiants in Cyg OB2 using FAST-WIND [**?**, **?**], another code with NLTE, sphericity, mass-loss and (in this case approximated) line-blanketing. They found differences up to 8 000 K. In this case both mass-loss and line-blanketing, played a role. These authors also showed

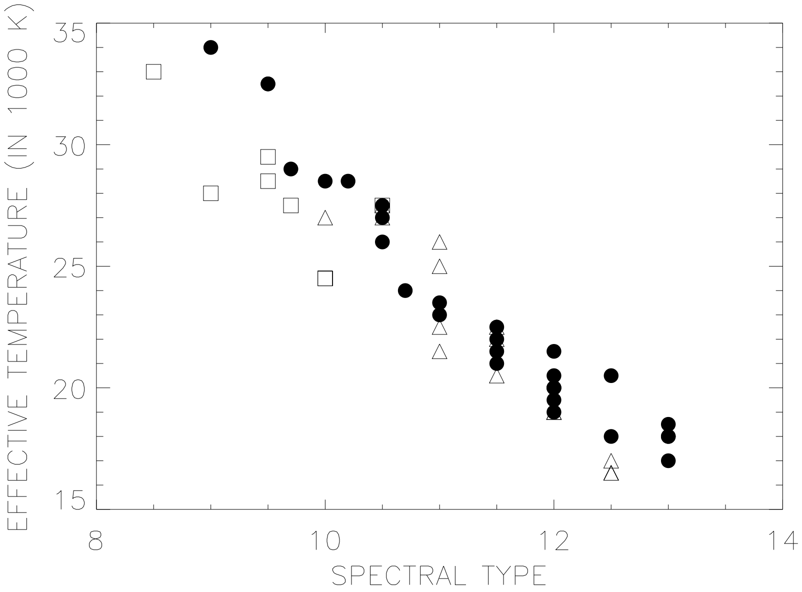

Figure 3: The temperature scale for early B supergiants in the Milky Way and the Magellanic Clouds. Spectral types are coded so that 9 means O9, 10 means B0 and so on. Solid circles are data by McErlean et al. (1999) for the Galaxy; triangles are data from Trundle et al.(2004) and Trundle et al. (2005) for the SMC; and squares are data from Evans et al. (2004) for the LMC

that two stars with the same spectral type and luminosity class may have different effective temperatures if their wind densities are different. While the results from h02 were based on analyses of only seven Cyg OB2 supergiants, repolust04 presented an analysis of 24 stars (17 giants and supergiants and 7 dwarfs), based on a slightly improved version of FASTWIND that confirmed the same trends. These same trends have also been confirmed by martins05 who have calculated models with CMFGEN and have given a new temperature scale for massive OB stars of different luminosity classes. These temperature scales agree quite well with those from repolust04, and confirm that new models result in effective temperatures that are several thousands Kelvin cooler for early and intermediate spectral types, decreasing towards late spectral types. The different temperature scales can be seen in Fig. **??**

OB stars in the Magellanic Clouds have been analyzed by massey04 massey04,massey05 using FASTWIND. Their results confirm that supergiants are 3000–4000 K cooler than dwarfs of the same spectral type at any metallicity. However, a clear trend of temperature with metallicity at a given spectral type and luminosity class is not seen: authors obtain that SMC dwarfs and supergiants are hotter than Milky Way counterparts, but while LMC dwarfs seem to extend the SMC scale, LMC supergiants seem to extend the Milky Way scale. In addition, SMC dwarfs of types O3-O4 do not fit into the relation indicated by the later O types in that galaxy, but have a temperature closer to their Milky Way analogues. When comparing to other authors we find further inconsistencies: O4-O5 SMC dwarfs analyzed by massey04 massey04,massey05 are hotter than Milky Way ones, but O4-O5 SMC dwarfs analyzed by bouret03 are cooler than similar objects in our Galaxy. While the analyses by massey04 massey04,massey05 constitute a major step forward to understand the metallicity dependence of the temperature scale of massive OB stars, the low number of objects and the large scatter in the relations indicate the necessity of further analyses, particularly because the scatter could be related to differences in wind density at a given spectral type.

We should finally mention the temperature scale obtained by bianchi02 and garcia04. These authors analyse stars by means of UV spectra (FUSE and IUE) using WM-basic [**?**]. The temperatures they find are much cooler than those from other authors. Wind clumping (see Sect. **??**) affecting their results is a plausible explanation still requiring investigation.

For types O9–B0 there is no clear difference between temperature scales from different authors or metallicities. It is then not strange that a comparison of temperatures scales for B supergiants results in no apparent difference between Galactic (from mcErlean99), LMC [**?**] and SMC analyses [**?**, **?**] (see Fig. **??**; the figure includes a few giants, but this does not change the conclusions that follow). We can see in Fig. **??** that the scatter at a given spectral type is very large. At spectral type B1, for example, we find a difference of 3 500 K between the hottest and coolest B1 supergiants (both from the SMC), and the difference increases to 4 500 K if we include the hottest object, a B1 III star. This large difference can be attributed to the different wind densities: the coolest B1 supergiant (AV78) has a mass-loss rate of $2.29 \pm 0.34 \times 10^{-6}$ $M_{\odot}$ yr^{-1}, while the

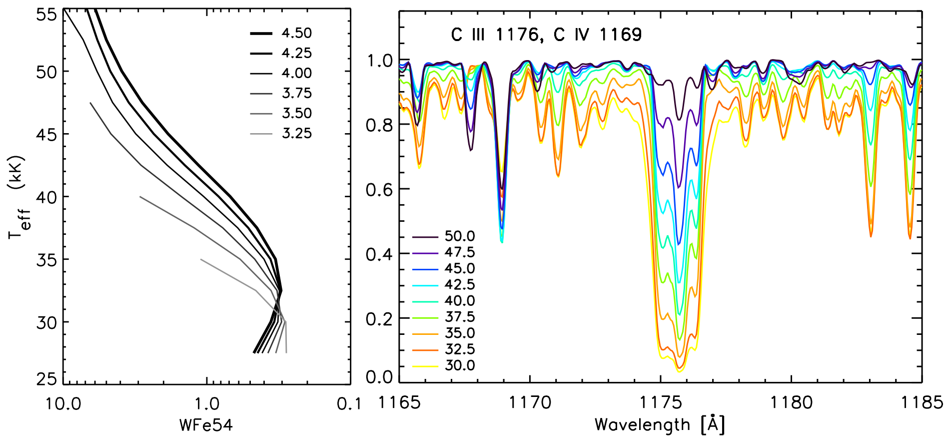

Figure 4: Temperature diagnostics in the UV for O dwarfs. **left** Fe v/Fe iv index as function of temperature and gravity.**right** C iii/C vi line sensitivity as a function of effective temperature (adapted from Heap et al. 2004)

hottest one (AV242) has $0.84\pm0.13\times10^{-6}$ M$_\odot$ yr^{-1}. The larger radius of the first star (79.0 versus 36.6 R$_\odot$) also contributes to a cooler temperature. For details of the analysis, see trundle04.

2.1 Potential of UV temperature diagnostics

We have seen above the impact of the new generation of atmospheric models on the temperature scale of massive OB stars. One of the immediate advantages of blanketed models is the simultaneous use of different ionization equilibria to determine the effective temperature of the star. Thus, appart from the "traditional" He i/He ii ionization balance, we may utilize unsaturated C ii- iv, N ii- v, O ii- v, Si iii- iv, etc diagnostic lines from which we, ideally, should obtain consistent values with the helium ionization equilibrium. Besides, the UV range encompasses a whole forest of iron group lines and enables to use the strength ratios of combined features of different ionization stages of the same ion to constrain the effective temperature of the star. Recently, several studies have been performed identifying key diagnostic lines to trace effective temperature of OB stars in the UV (heap04, bouret05 and references therein). Figure **??**-left shows the sensitivity of the so called WFE54 index to temperature and gravity [**?**], where WFE54 represents a weighted ratio of the equivalent widths of the the Fe v and Fe iv around $\lambda1370$ and $1620\mathring{A}$ respectively. We note that, although this index displays a relatively high sensitivity to stellar temperature, it also depends strongly on gravity. Therefore, if gravity is determined from other diagnostics (optical spectrum), this index constitutes an excellent temperature indicator for $T_{eff} \geq 35,000K$. On the other hand, the ratio of the carbon C iii1175- iv1169 line strengths (see Figure **??**-right) is essentially only dependent on the effective temperature [?]. The reader is referred to heap04 for a detailed identification of temperature UV diagnostics in O dwarfs.

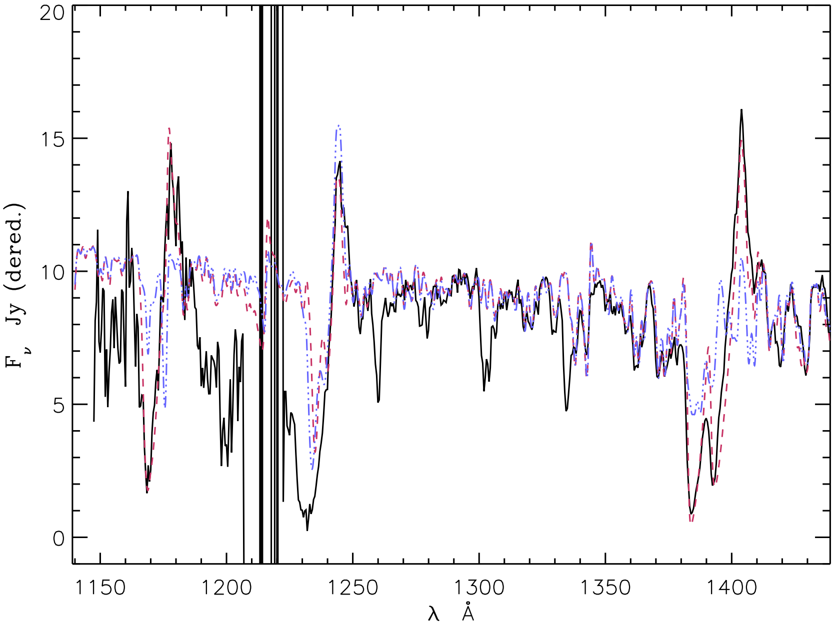

Figure 5: Temperature sensitivity of C III and Si IV in mid-type supergiants. HST-spectra of CygOB2#11 and model fits with $\Delta T = 1000K$.

For supergiants, the situation is very similar. However, the stellar wind may play a fundamental role. Thus, the sensitivity of some strategic UV lines to effective temperature will be shifted in the parameter domain compared to the O dwarfs case. Figure **??** shows how the C III1175 and Si IV1400 lines react considerably to changes of barely 1000 K in a mid type O supergiant.

We may then conclude that the new generation of blanketed models for massive stars provide powerfull diagnostics to obtain reliable effective temperatures for massive OB stars by means of ionization equilibria of metals other than H and He, allowing this way direct estimates of temperature from UV observations. This opens an important window to study massive stars in star forming regions in external galaxies using the unique spatial and spectral capabilities of future UV missions.

3 Abundances

With the advent of new blanketing codes, quantitative spectroscopic studies of the UV forest of metal lines has become reality. These codes allow to fit not only

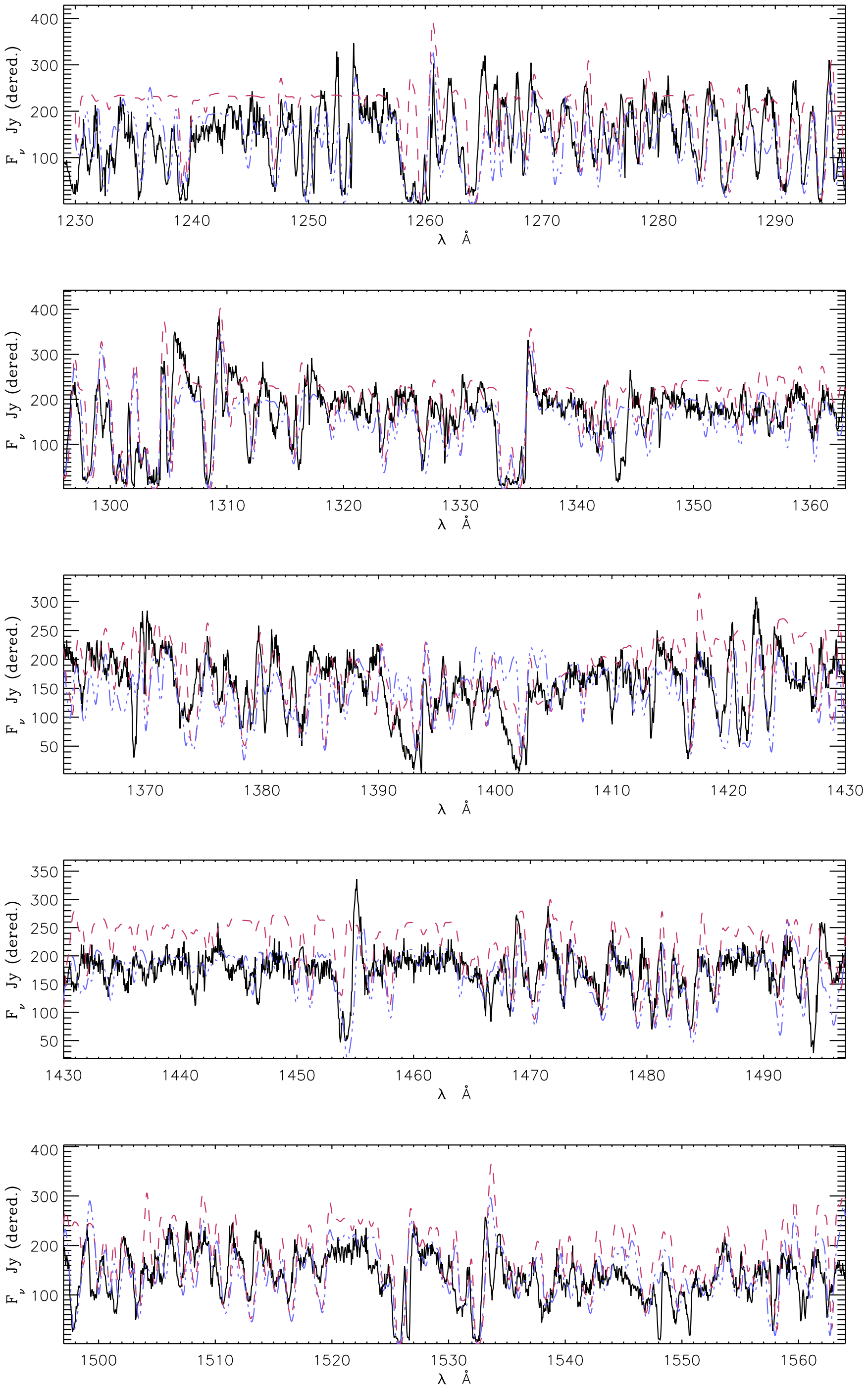

Figure 6: Comparison of the blanketed model (dashed) and the averaged observed (solid) UV IUE-SWP spectrum of P Cygni. A model including Nickel and Cobalt (dashed-dotted) is also displayed in the IUE-SWP region (adapted from Najarro, 2001)

the outshining UV saturated and unsaturated profiles from metal ions but also the underlying blanket of lines from iron group elements. Therefore, the new generation of models provides, for the first time, direct estimates for abundances of elements such as C, N, O, Si or S by fitting individual unsaturated lines while robust estimates of abundances of iron group elements may be obtained fitting integrated features in strategical UV wavelength regions. Of course, the analysis has to provide as well stellar parameters such as $T_{\rm eff}$, stellar mass, $\dot{\rm M}$, L_* and clumping.

Figure **??** displays the potential of new blanketed models to perform quantitative analyses of UV spectra for massive stars. It displays the excellent agreement for the Luminous Blue Variable (LBV) P Cygni between the model and the observed IUE SWP region [**?**]. Interestingly, we see from Fig. **??** that the main contributor to blanketing in this zone is Fe III. However, we can see as well that there are some regions (e.g. 1420–1500$\AA$, 1570–1730$\AA$) where the model clearly underestimates the blanketing. Before tentatively blaming it on the behavior of the extinction law, it is necessary to investigate the effects of other iron-group elements (Ni,Co,Cr) which are normally not included in many new models from computational saving reasons. Recomputing the same model but adding Ni and Co najarro01 found that, indeed, Ni III provides most of the missing blanketing as shown in Figure **??**. Further, Co III also contributes significantly in the 1750–1800$\AA$ region. When these two species are included, the agreement of the model with the observations is excellent throughout the whole IUE SWP range.

In O stars, the need of UV spectra to determine metal abundances becomes a must as the optical spectra no longer show the strong metal features present y B and A stars and we run out direct diagnostics to constrain the abundance of iron group elements. Figure **??** displays the potential of the UV to determine metal abundances in O type stars. We see from Fig. **??**-top the strong dependence with metallicity and spectral type of the UV C IV line, while Fig. **??**-bottom demonstrates the possibility to estimate the iron abundance in O stars.

We also see that as metallicity decreases (Fig. **??**-bottom) the strengths of metal features in the UV become weaker, and enhanced S/N is required to perform reliable metal abundance determinations. Future missions with enhanced UV sensitivity will play a key role in our ability to derive accurate abundances in low-metallicity environments.

4 X-rays

UV spectra of massive stars also trace the presence of X-rays in their stellar winds. X-ray emission in the wind alters significantly the wind ionization structure, enhancing the populations of the so called “superions” such as N V and O VI. In fact, X-rays were utilized more than ten years ago to explain the observed strength of O VIλ1036 in galactic and LMC O supergiants pauldrach94. For O and B dwarfs (low density winds) macfarlane94 showed that the effects of X-rays were enhanced when compared to supergiants (high density) as for lower wind densities we get significantly less recombinations to compensate the

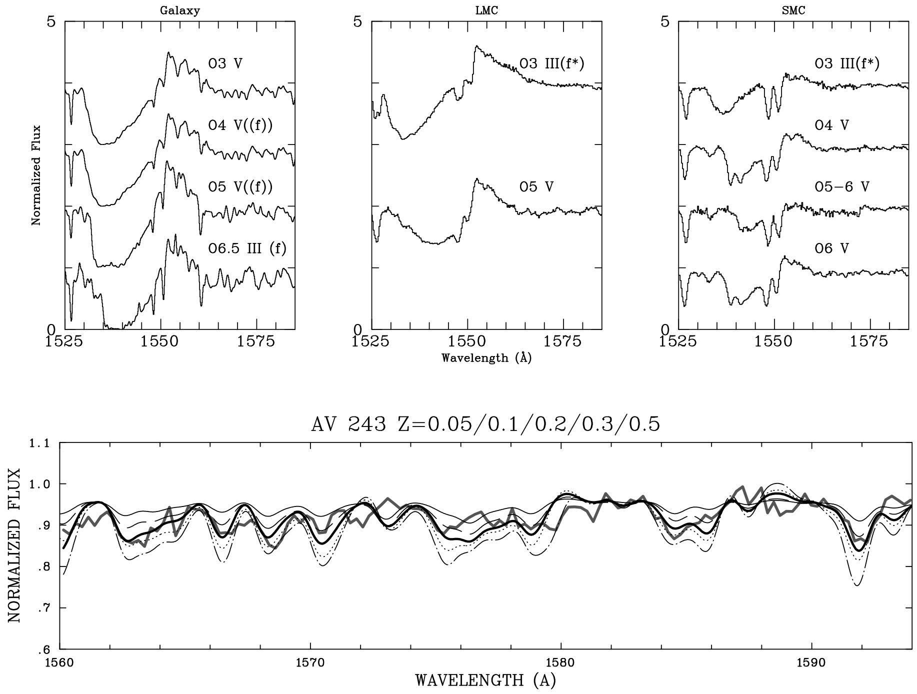

Figure 7: **Top)** Metallicity dependence of metal ions UV lines. Compilation of UV C IV stellar wind profiles of O dwarfs and giants in the Galaxy, LMC and SMC (adapted from Kudritzki 1998). **Bottom)** Model fits with different metallicities of the observed UV Fe IV spectrum of an O star in the SMC (adapted from Haser et al., 1998)

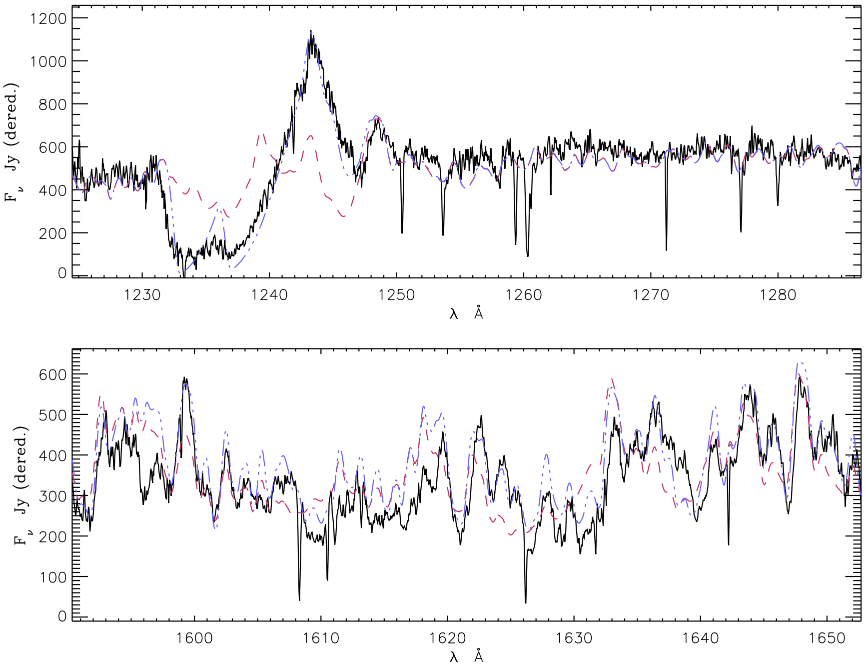

Figure 8: Effects of X-Rays in α-Cam O9If. The strong changes induced by including X-rays (dashed-dotted line) in the ionization structure of N and Fe in the wind are reflected in the observed N Vλ1240 and Fe IV lines around λ1640.

Auger ionization. They also found that these effects increased towards later spectral types. This effect is driven by the drop of the photospheric to X-ray flux ratio as the lower effective temperature for a later spectral type reduces drastically the bolometric stellar luminosity. Recent studies, confirming these findings have been carried out for a extended sample of O stars by bouret03 (bouret03,bouret05) and martins05b. Figure **??** displays the crucial effects of including X-rays on key diagnostic features such as N Vλ1240 and several Fe IV lines around λ1640 for αCam, a late O supergiant (Najarro et al in prep). Given the distance limited sample of massive stars from which current X-ray missions may provide direct measurements of X-rays, it is evident that future UV missions with enhanced sensitivity will constitute our ideal tools to probe the presence of X-rays in the winds of massive stars in external galaxies.

5 Clumping

Recent evidence indicates that currently accepted mass-loss rates may need to be revised downwards by as much as a factor of ten or more, because the most commonly used mass-loss diagnostics are severely affected by small-scale density inhomogeneities (*"clumps"*) in the wind, redistributing the matter into regions of enhanced and depleted, almost void density.The amount of clumping is quantified by the so-called clumping factor, $f_{\rm cl}$. Diagnostics sensitive to the *square* of the density, ρ^2, will tend to overestimate the mass-loss rate of a clumped wind by a factor $\sqrt{f_{\rm cl}}$. Considering that numerous stellar evolution calculations have found that changing the mass-loss rates of massive stars by even a factor of two has a dramatic effect on their evolution [**?**], it is clear that such revisions would have enormous implications.

Indeed, strong clumping has been claimed to be present in stellar winds of early type stars (e.g., eversberg98, lepine99, crowther02, hillier03 bouret03). h02, repolust04 and markova04 report that clumping may cause mass-loss rates for O-stars with H_α in emission to be overestimated by factors of 2.5. Detailed modelling of the UV and optical spectra of selected O stars by bouret05 indicates that not only are the winds strongly clumped, but that the clumping seems to begin very close to the wind base so that *all* mass-loss rates may need to be revised downwards, by factors of 7. prinja05 analyzed unsaturated wind lines in lower luminosity B supergiants and showed that their mass-loss rates may be factors of 10 or more less than theoretical expectations.

A compelling, independent indication for clumping has come from analyses of the Far-UV wind lines due to the P V$\lambda\lambda$1118, 1128 doublet (crowther02, hillier03, bouret05 massa03, fullerton06), which has only become widely accessible since the launch of *FUSE*. Because Phosphorus has a low cosmic abundance, this doublet never saturates, providing useful estimates of $\dot{M}$ for those cases where the ionization fraction is computed consistently (crowther02, hillier03, bouret05) or to $\dot{M}q$, where q is the ionization fraction of P V. At least for mid-O stars massa03 and fullerton06) have shown that P^{4+} is a *dominant* ion. Therefore, for these stars the P V$\lambda\lambda$1118, 1128 doublet constitutes a usefull constrain to

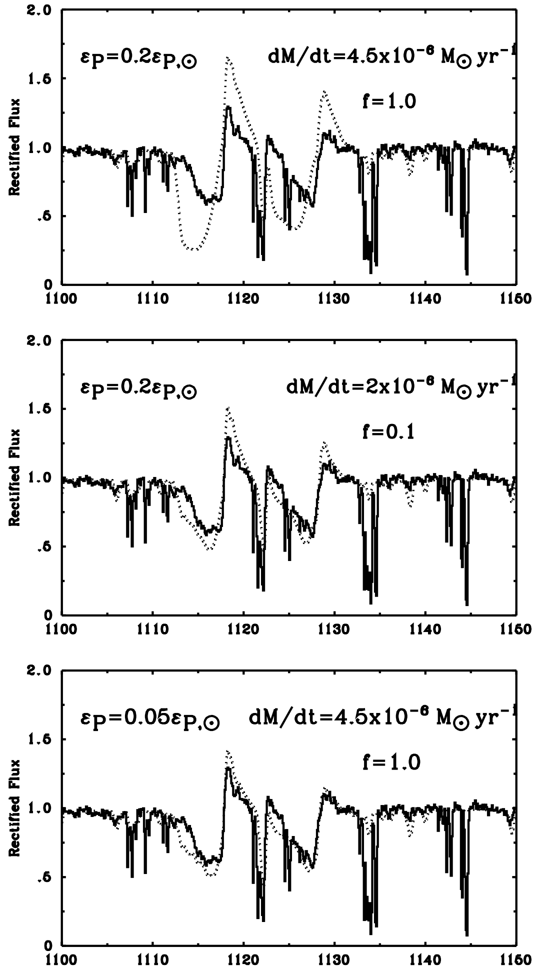

Figure 9: Clumping diagnostics in O stars. The P V$\lambda\lambda$1118, 1128 as tracer of low $\dot{\mathrm{M}}$ (adapted from Crowther et al., 2002)

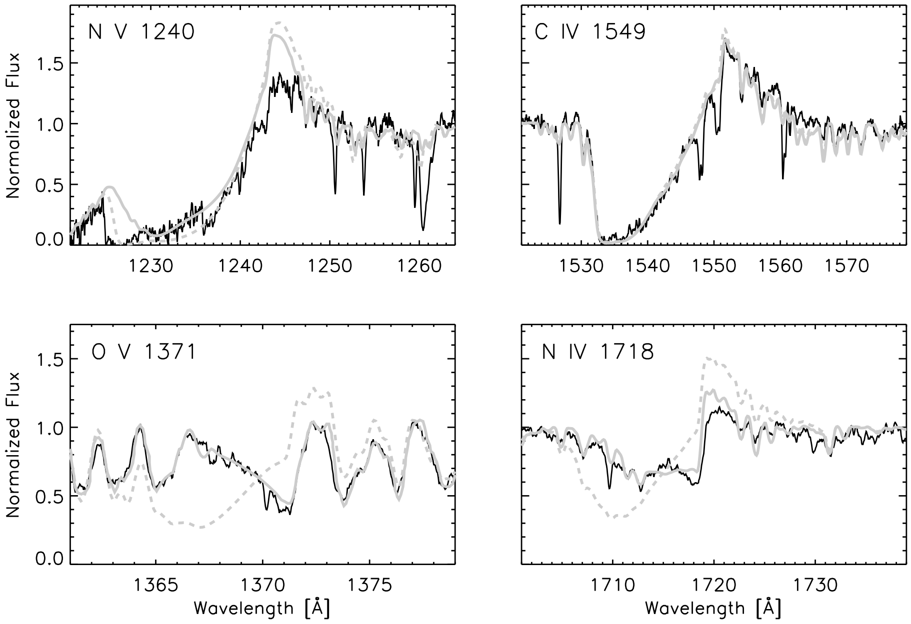

Figure 10: Unsaturated UV lines as tracers of clumping in O stars (adapted from Bouret et al., 2005)

determine $\dot{\mathrm{M}}$ itself. This is demonstrated in Figure **??** which displays model fits from crowther02 to a SMC O supergiant for different combinations of clumping, mass-loss rate and phosphorus abundance. Interestingly, the mass-loss rates derived by all these authors turned out to lie considerably below those inferred from other diagnostics.

The most reasonable way to resolve this discordance, unless nature does not like phosphorus to participate in massive stars, is to invoke extreme clumping in the wind. In a clumped wind, the continuum and H_α measurements (both sensitive to ρ^2) overestimate the actual $\dot{M}$, whereas the line strengths of Pv, being $\propto \rho$, are not directly affected by clumping. If the winds of OB stars are indeed substantially clumped, then the actual mass-loss rates are *much* lower than previously thought, by a factor of 10 or even more. Further, in cases of strong clumping the ionization structure of relevant species may be altered as well affecting key diagnostic lines at all wavelength ranges.

The downward mass-loss rate revisions suggested above would have dramatic consequences for the evolution of and feed-back from massive stars. Therefore, it is important to have robust and precise determinations of the mass-loss rates. All clumping diagnostics are subject to some degree of uncertainty which can be reduced by combining suitable diagnostics, scanning different portions of the wind, from close to the base (H_α) and near IR lines [**?**] over intermediate regions (Br_α, mid-/far-IR continua) to the outermost (radio) region. A *con-*

sistent analysis will severely constrain the *radial stratification* of the clumping, expressed in terms of the clumping-factor, $f_{\rm cl}(r)$. If used in combination with other diagnostics from (F)UV wind lines *and state-of-the-art model atmospheres* allowing for a decent description of the required ionization balance, the "true" mass-loss rates can be uniquely derived. Figure **??** shows that, appart from the P v$\lambda\lambda$1118, 1128 doublet there are other UV lines from different metals which can trace very efficiently the presence of clumping, especially for those regions of the parameter domain where the lines are unsaturated. Therefore, future UV missions with enhanced sensitivity will provide enough number of observations of OB stars over different spectral types and allow this way, to constrain the presence of clumping in these objects.

6 The Wind Momentum Luminosity Relation (WLR)

The winds of massive OB stars are driven by the absorption of photons from the radiation field by thousands of spectral lines from many atomic elements. These photons accelerate the atoms towards the empty surrounding space in such a way that the atom velocity increases with the distance to the stellar surface, until the material no longer absorbs them.

Since the winds of hot stars are driven by radiation, we expect a tight relationship between the mechanical momentum of the stellar wind and the photon momentum. Actually, the theory of radiative driven winds (Castor et al., 1975; Kudritzki et al., 1989) predicts that the "modified stellar wind momentum" depends directly on luminosity through the Wind Luminosity relation (**WLR**)

$$logD_{mom} = logD_0 + xlog(L/L_\odot) D_{mom} = \dot{\rm M} v_\infty (R_*/R_\odot)^{0.5} \qquad (1)$$

where the coefficients D_0 and x are a function of spectral type and luminosity class. Further, the coefficient controlling the dependence on luminosity, x, is determined by the statistics of the thousands of metal lines driving the wind, so a different WLR has to be established for each metallicity environment. The weak dependence on stellar radius arises from the competition of the accelerated stellar wind against the gravitational potential. We immediately see that, once calibrated on stars with known distance, the WLR may constitute a powerfull indicator of extragalactic distances (see Kudritzki & Puls, 2000, for a thoroughfull discussion). During the last decade an enormous effort has been made to calibrate the WLR as function both of spectral type and metallicity and compare the results with the predictions by theory (Puls et al., 2000; Vink et al., 2000, 2001).

Figure **??** shows the different relationships obtained by Kudritzki et al. (1999) for different spectral types in the galaxy. Of concern is the shift by more than one decade in modified momentum between the relation of early and mid B-supergiants. Though not totally, blanketing may provide the key to partially reduce the discrepancy between the observed WLR for O and early

B supergiants and that obtained for mid Bs. In fact, Urbaneja (2004) found a significant correction on the modified momenta of these stars with respect to the values derived by kud99 as shown in Fig.**??**-right.

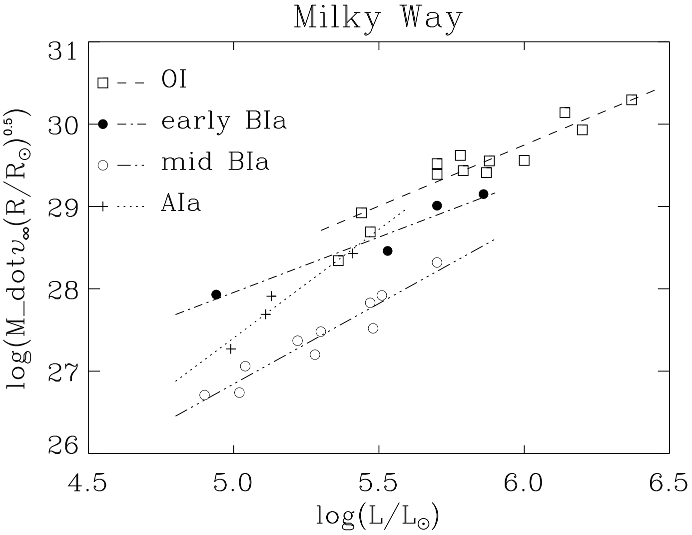

Figure 11: The WLR as a function of spectral type. Galactic WLR for O, B and A supergiants (Kudritzki et al., 1999). Note the considerable offset between the WLR for early and mid B supergiants.

Results on the metallicity dependence of the WLR for O stars and B supergiants and their comparison with theoretical predictions are displayed in Fig. **??**. From Fig. **??**-right we see how the modified momenta of galactic B-supergiants obtained with blanketed models [**?**] agree much better with theoretical predictions than those obtained with unblanketed models [**?**], although a significantly different slope is obtained. The whole worsens in the case of the SMC, where the WLR obtained from blanketed models [**?**] differs severely from theoretical predictions [**?**]. In the case of O stars, the situation is significantly improved. From Fig. **??**-left (see massey05, and references therein) we see how the theoretically predicted WLRs for O stars in the Galaxy, LMC and SMC are reasonably well reproduced by spectroscopic studies.

The WLR provides a strong test for the theory of radiatively driven winds, and the UV provides the best region to test the WLR, as it allows derivations of the mass loss rate, the terminal velocity and the metallicity. Stellar parameters can also be derived from the UV (Bianchi & Garcia, 2002; Garcia & Bianchi, 2004), although further work is needed for some of them (mainly gravity and radius). What we need here are observations of high resolution and high S/N at different metallicities. Inspection of figures **??** and **??** tell us that the number of observed stars is too low to provide a really constraining test of the theory.

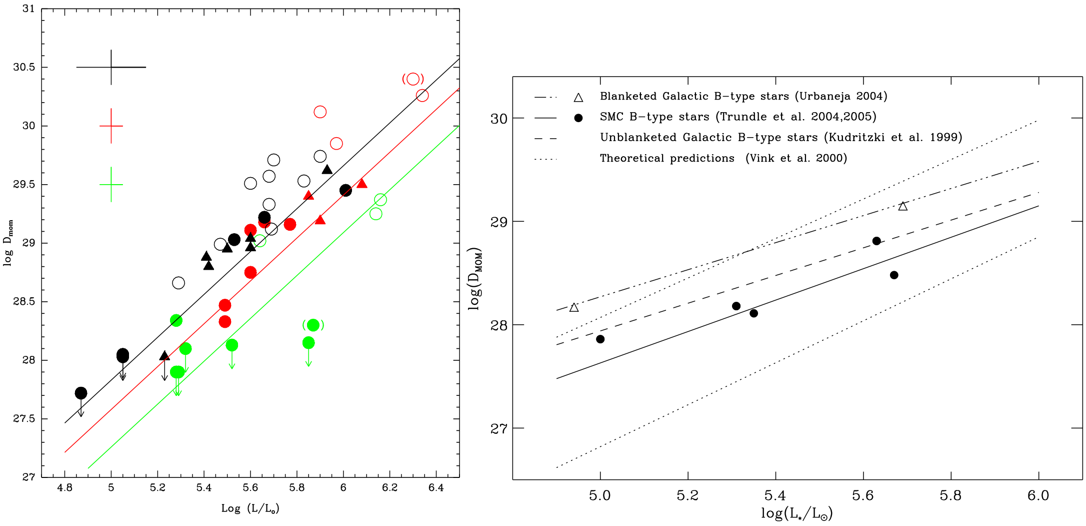

Figure 12: Metallicity scaling of the WLR for O and B supergiants. **(left)** Z scaling for O supergiants (adapted from Massey05). **(right)** Z scaling for B supergiants (Kudritzki et al., 1999; Urbaneja, 2004; Trundle & Lennon, 2005). (dash-dot): linear regression to galactic stars with blanketed models (Urbaneja, 2004); (dash-dot): unblanketed galactic (Kudritzki et al., 1999); (solid): blanketed SMC (Trundle & Lennon, 2005); (upper dotted) theoretical galactic predictions (Vink et al., 2000); (lower dotted) theoretical SMC predictions (Vink et al., 2001). Note the considerable correction to the modified wind momenta for B-supergiants due to line blanketing

The Magellanic Clouds, together with the Milky Way, provide a wide range in metallicity, and other galaxies in the Local Group offer additional opportunities. Thus, M31 may extend the observed metallicities towards supersolar values, Sex A or Leo A may extend them below SMC values and M33 offers a system with a strong metallicity gradient seen nearly face-on. The ability to get UV spectra for stars in all Local Group galaxies is the key to our correct understanding of the spectral type and metallicity dependence of the WLR. To that end, an UV telescope with more collecting power than HST is required.

6.1 The Thin Winds Problem

puls96 showed that the observed WLR for O-type dwarfs exhibited a severe curvature toward very low wind momenta for luminosities lower than $logL/L_\odot = 5.3$. kud00 reviewed three effects present in the physics of thin winds in dwarfs which may introduce deviations from the standard WLR. The first one is related to the decoupling of metal ions with the rest of the plasma. This will happen if the density falls bellow the range for which coulomb-collisions are able to

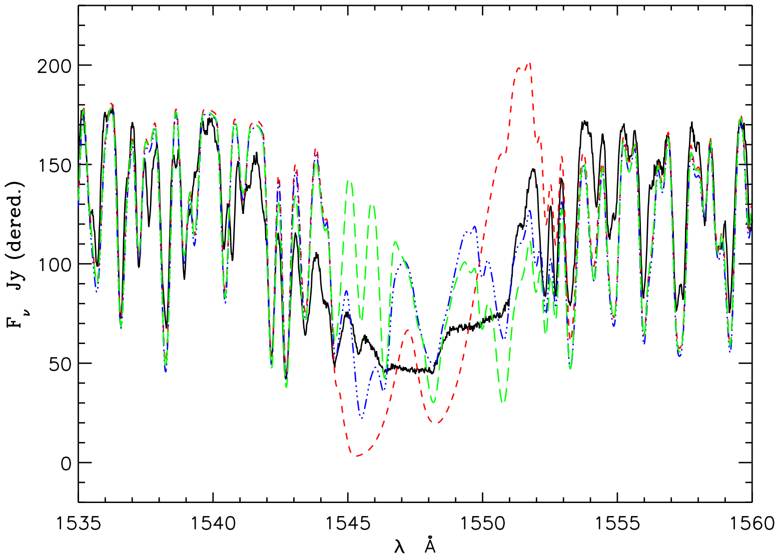

Figure 13: The weak wind problem in O dwarfs. Model fits with different mass-loss rates of the UV C IVλ1550 for the O9V star 10 Lac. $\dot{\mathrm{M}}$ values are 1,2 and $8\times10^{-10}\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

redistribute the photon momentum absorbed by the metal ions to the bulk of wind plasma [**?**, **?**]. The second one is caused by the shadowing of photospheric lines which considerably lower the line force, resulting on a net reduction of the mass-loss rate, especially in the case of B-dwarfs [**?**]. Finally, for low mass-loss rates where the continuum is thin throughout the transonic region, curvature terms of the velocity field may lead to line-accelerations much smaller than in the standard computations, resulting again on reduced mass-loss rates [**?**, **?**])

Recent spectroscopic analysis using unified models seem to confirm the presence of this turnover. h02 obtained a very low value for the mass-loss rate of the O9.5V star 10Lac. Their result, displayed in Figure **??** showed that in order to match the observed UV spectra of the star, the mass-loss rate hat to be reduced more than one order of magnitude bellow the theoretical prediction. It must be stressed that, although the presence of X-rays could introduce a significant uncertainty in the absolute $\dot{M}$ value, the upper limit is still well bellow the predictions from radiatively wind theory [**?**]. Recently bouret03 and martins05 martins04,martins05 have obtained similar results on analysis of O dwarfs in the SMC and the Galaxy (see Fig. **??**). One important conclusion from the above studies is that the discrepancy in the mass loss rates obtained seems not to be related to metallicity, as is present on both the Galactic and SMC stars.

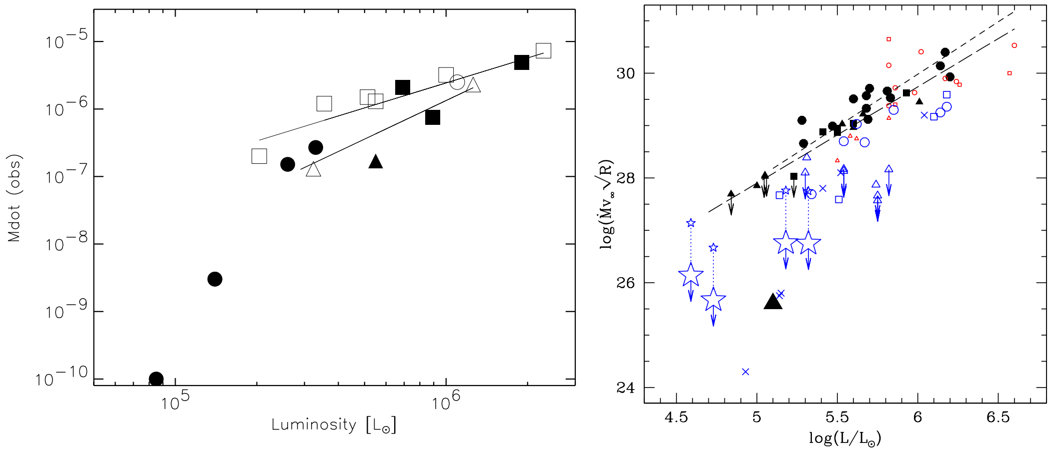

Figure 14: The problem of thin winds. **Left)** Mass loss rates derived for O dwarfs in NGC 346 (Bouret et al., 2003, LMC). **Right)** Modified wind momenta as a function of stellar luminosity for O stars (from Martins et al., 2005). Filled (open) symbols are Galactic (LMC, SMC) stars. Triangles and stars (squares, circles) correspond to luminosity class V (III,I). Note the low momenta of the SMC objects and the galactic star 10Lac (large triangle).

Figure **??** clearly shows a breakdown of the WLR for low luminosity O dwarfs. Although present results based on UV studies may suffer from effects such as X-rays, advection or adiabatic cooling, results from other indicators like H_α are not appropriate because of insensitivity to very low mass-loss rates. Moreover, other indicators in the IR and radio may be affected by clumping. Detecting this clumping in thin winds may be extremely difficult, and therefore high resolution, high S/N in the UV becomes the best (if not the only) way to derive the correct mass loss rate.

7 Wind terminal velocity

In the previous section we have seen that winds in massive OB stars are driven by photon absorption by numerous metal spectral lines. Atoms are accelerated until they cannot absorb photons anymore. From that moment on, atoms move freely into space asymptotically approaching a maximum velocity, which is formally reached at infinity. This is the so-called *wind terminal velocity,* v_∞. While the structure of the velocity field resulting from this process is very difficult to determine, the terminal velocity can be derived in a comparatively easy way.

Determination of the terminal velocity is one of the key aspects in studying the stellar wind. As explained in the introduction to this chapter it enters the expression for the modified Wind momentum- Luminosity Relationship (WLR), the product of the wind momentum times the square root of the radius, which is proportional to a power of the stellar luminosity. Therefore, reproducing the correct terminal velocity with models is crucial to obtain the correct mass-loss rate for a given luminosity, and to use the modified WLR as distance indicator. Moreover, one of the strong predictions of the theory of radiatively driven winds is the metallicity dependence of the terminal velocity. Therefore, a determination of v_∞ in regions of different metallicity constitutes a strong test for the theory.

Some of the spectral lines in the winds of OB stars are so optically thick, that they absorb photons even at large distances, when the terminal velocity has been reached and the wind density has fallen by orders of magnitude. We should note that these absorbed photons do not accelerate the wind significantly further, as their number and integrated momentum is very low compared to that of the whole wind. But leave their signature in the stellar spectrum, an thus we can derive the terminal velocity.

Atoms moving at a given velocity in the wind will absorb photons shifted to the blue with respect to their laboratory wavelength (at which they have been emitted at the stellar surface). Atoms moving at the largest velocity reached by the wind will absorb photons with the largest blueshift. Therefore, determining the maximum blueshift in an optically thick line we will obtain the wind terminal velocity. Of course, the number of absorbing atoms has to be large enough to absorb photons at the low densities present in the layers moving at the terminal velocity. Blue saturated P-Cygni profiles are therefore ideal to determine the wind terminal velocity as they fulfill this requirement. In addition, a number of effects that we describe below have to be taken into account.

While we could directly try to derive the terminal velocity from this maximum blueshift, the fitting of the whole P-Cygni profile formed in the wind gives us much more information. Fortunately, there is a simple method that allows us to calculate this profile in an approximated way, but precise enough to derive a number of interesting physical magnitudes, like the terminal velocity or the number of absorbing atoms. It is the *Sobolev plus Exact Integration* (SEI) method.

We use here the formulation as described by [**?**] (see also haser95, Lamers et al. (1999)). The velocity stratification is usually parameterized with a β-law,

$$w(x) = (1 - b/x)^{\beta} \tag{2}$$

with

$$w(x) = \frac{v(x)}{v_{\infty}}, \qquad x = r/R_{*}, \qquad b = (1 - w_{\min}^{1/\beta})$$

R_{*} being the stellar photospheric radius and $w_{\min}$ the ratio of the velocity at x=1 to the terminal velocity, fixed at a value of 0.01.

This is consistent with more exact hydrodynamical calculations. However, the indetermination in the exponent of the velocity field, β, produces an additional uncertainty in the terminal velocities.

When deriving wind terminal velocities, it is important to account for the velocity dispersion $v_{\rm turb}$ (usually termed as "turbulent velocity") present in those winds, to correctly reproduce the position of the emission peak, the blue through and the slope of the blue absorption, as originally proposed by Hamann (1981). Following [**?**] we adopt a parameterization of the form

$$v_{\rm turb} = a_t v(r) + b_t, \tag{3}$$

i.e., the turbulent velocity is assumed to be (roughly) proportional to the local wind-speed $v(r)$, and the coefficients are defined by

$$a_t = \frac{v_{ta} - v_{ti}}{1 - v_{\min}}; \qquad b_t = v_{ta} - a_t,$$

where $v_{ti} = v_{\rm turb}(v = v_{\min})$ is the minimum turbulent velocity (chosen to be of order sound-speed) and $v_{ta} = v_{\rm turb}(v = v_{\infty})$ the maximum one.

These parameters affect the overall appearance of all synthetic lines. Fig. **??** shows their effects on the synthetic profiles for a saturated case.

We also have to correct for the underlying photospheric components, which we do in an approximate way, by using IUE spectra of hot stars with weak winds and low projected rotational velocities as templates. Selection of photospheric template and continuum rectification has a big impact when fitting emission peaks, but has little effect in the determined terminal velocities. For Galactic stars a sample of Milky Way dwarfs with appropriate spectral types is usually selected (f.e., from the INES database). Of course, when working with extragalactic stars we have to use photospheric templates with the correct metallicity. Differences in metallicity may be a small source of error.

Because terminal velocities are derived from broad absorption features we can use modest resolution to obtain them. This allows us to look at relatively faint stars. These may be stars in other galaxies or Galactic stars that are optically bright but UV faint because of extinction in the Galactic plane. This extinction limits seriously our ability to observe massive stars in very young Galactic clusters.

Figures **??** and **??** give an example of profile fitting for Cyg OB2#10, an O9.5 I Galactic star, and M33-0900, a M33 B0.5-B1 Ia star. Both spectra have been observed with HST-STIS at an approximate resolution of 1200 during one and half hours, reaching the same S/N ratio (25). In both cases the wind terminal velocity was derived with an accuracy of 5%, although Cyg OB2#10 is a relatively bright star with V= 9.88 and M33-0900 has V= 17.3. This accuracy is of the order of that given by the radius term in the WLR expression (the total error is actually dominated by the mass-loss rate uncertainty).

These numbers therefore may be taken as a lower limit in terms of v_∞ observations, and indicate that most of the early OB stars in young Galactic star-forming (or recently star-formed) regions are hidden to us by dust obscuration in the UV. In Cyg OB2, for example, one of the richest Galactic OB associations, only six O stars have been observed in the UV with HST, and only another 3 might be observed under the same conditions.

The number of stars for which v_∞ has been determined is therefore small. For example, Howarth & Prinja (1989) list 203 Galactic O stars that were observed with IUE and for which they determined the wind terminal velocity. This work still constitutes the main source of data for Galactic v_∞, but only a few stars belong to a given cluster. More recently, prinja98 list terminal velocity determinations for 31 stars between O3 and B1 in the LMC (including six O3 stars in R136) and 9 stars in the SMC. More scarce are data for M31 and M33 stars. Bresolin et al. (2002) and Urbaneja et al. (2002) list six early B supergiants each, in M31 and M33 respectively.

While this allows us to study the behavior of the terminal velocity within our Galaxy, it is barely enough to study its behavior as a function of the spectral type and luminosity class for a given metallicity, or to study it within a single young cluster.

With a sensitivity 20 times larger, as expected for new UV missions we could see a qualitative change in the present situation. In our Galaxy we could gain a few magnitudes, depending on extinction conditions, reaching deeper in the dusty young clusters. However the real gain would be in the extragalactic stars. Even at the distance of M31 and M33 we could observe the O dwarfs and determine their terminal wind velocities. With modern ground-based optical telescopes we can secure their optical spectra and derive their stellar parameters. This would allow us to dissentangle the v_∞ – spectral type – metallicity relation, providing us with a very tight test for the theory of radiatively driven winds.

8 A-type Supergiants in the Ultraviolet

A-type Supergiants are evolved massive objects ($\sim 9 - 25 M_\odot$) located in a region of the H-R diagram where evolution is very rapid. Therefore, they are few in number: only about one hundred galactic stars are classified as such. Among these supergiants there is a clear gap between spectral types A5 and F0, which could be related to the evolution of these objects. The evolutionary stage of A-supergiants is still unclear. Although the most extensive work on their abundances suggests that these stars have evolved directly from the main sequence (Venn 1995a), the uncertainties in these studies are very high, due to the well recognized difficulty of modeling their atmospheres (Venn 1995b; Verdugo et al. 1999a). A recent work by Przybilla et al. (2005) analyses the various effects involved in the modelling of A-supergiants atmospheres (line blanketing, non-LTE, helium abundances, spherical extension, velocity fields, variability). In this work, accurate stellar parameters are determined from a hybrid non-LTE spectrum synthesis technique for four BA supergiants. From the abundances analysis these authors found that three of the stars studied appear to have evolved directly from the main sequence but for the AIb star, η Leo, a blue-loop scenario is derived.

A-type Supergiants are intrinsically the brightest stars at visual wavelengths, and therefore the best potential extragalactic distance indicators using the wind momentum-luminosity relation (Kudritzki et al. 1999). This relation is derived from the radiation-driven wind theory and mainly based on Balmer line fits.

Radiation pressure is adopted as the dominant driving mechanism for the mass loss of A-supergiants. Unified wind models, which include a solution of the spherical transfer equation in the comoving frame and a non-LTE treatment of hydrogen and helium, were developed by santo97. These models succeed in fitting a number of profiles of the Balmer series for the brightest A-supergiants [**?**], but cannot reproduce neither all the H_α profiles observed, nor their variability. An even more sophisticated model developed by aufdenberg00, which includes non-LTE line blanketing for several metallic lines, failed to fit a typical H_α P-Cygni profile for the brightest A-supergiant Deneb [**?**].

Stellar winds in A-type supergiants can be studied using the optical spectrum or/and the ultraviolet (UV) spectral range. In the optical all lines seem to be photospheric except H_α which shows a variety of very different profiles: symmetric absorption, P-Cygni, double-peaked or pure emission profiles [**?**]. It is in the UV range and particularly in the ultraviolet resonance lines where the presence of a stellar wind is cleanly traced. However, compared to the amount of work devoted to OB stars, the UV spectra of A-supergiants have scarcely been examined (e.g. Lamers et al. 1995, 1978; Praderie et al. 1980; Underhill & Doazan 1982; Hensberge et al. 1982). The most comprehensive studies of A supergiants in the ultraviolet range were performed by Talavera & Gómez de Castro (1987) and Verdugo, Talavera & Gómez de Castro (2006, 2003, 1997) from the observations taken by the International Ultraviolet Explorer (IUE) satellite.

The UV spectrum of A-supergiants is characterized by the presence of variable discrete absorption components (DACs; see some examples in Verdugo et al. 1999b) associated with the resonance lines of different ions, mainly Mg II, Al II, Si II, C II and Fe II. The appearance of these DACs is also related to the luminosity of the star. In Fig. **??** we show three typical observed Mg II[uv1] profiles: symmetric absorption profiles in Ib stars, profiles formed by several components, and a classical radiative-wind profile (without emission) in the Ia and Iab stars. The same behavior is observed in the other lines cited above as is also shown in Fig. **??** for the Fe II[uv1] lines.

It may therefore seem that the less luminous A-supergiants do not show any perceptible trace of mass motion in their spectrum, but a variability analysis showed the presence of DACs in the ultraviolet Mg II[uv1] lines of two Ib stars, which indicates that mass outflow exists. DACs in the UV spectrum of A-supergiants were initially found only in the brightest A-supergiants. The time scales of variability of these components are of the order of several months. However, a monitoring programme performed with the IUE satellite in two Ib A-supergiants revealed the appearance and evolution of a single blueshifted component in a much shorter time scale ($\sim$ 1 month; see Fig. **??**).

The DACs are stronger and more steady in luminous A-supergiants, whereas the Ib stars exhibit these features in a smoother but more variable way.

These two groups are also found from the analysis of the optical spectrum of A-supergiants (mainly from the H_α profile; Verdugo et al. 1999a, 2003).

The existence of these two groups must lie in a different extension, density and properties, in general, between the envelope of the AIa/Iab supergiants and the one of the AIb supergiants. These differences suggest a different evolution history of these stars. In fact, Przybilla et al. (2005) found from the abundance analysis of four A-type supergiants (one Ib star and three Ia/Iab stars), a blue-loop scenario for the only Ib star studied because of a first dredge up abundance ratios, while the other three objects appear to have evolved directly from the main sequence.

Another very interesting finding from the UV spectrum of A-supergiants which can also be linked with the evolution history of these stars is that there are some luminous stars which present a shortward shifted component at high velocity ($\sim$ -150 km s^{-1}) but there is not a component at zero velocity (except the interstellar components of the resonance lines) or this component is less intense than the high velocity one. Such behavior has been detected in the Fe II lines of some bright A-supergiants (see Fig. **??**). In principle, the absence of a component at 0 km s^{-1} could be due to the fact that the lines of Fe II are only formed in the wind, which would have a lower degree of ionization than the photosphere. However, this phenomenon is only detected in a few stars of our sample. Most of the A-supergiants show a zero velocity component for the lines of this ion. It is possible that this component at 0 km s^{-1} is formed also in the wind. In a low density envelope where shocks could be occurring, the spectra would present a pre-shock component (high velocity) and a post-shock component (low velocity). Therefore, the presence or not of such zero velocity component would be related to the density of the wind.

One of the main predictions of the radiatively driven wind theory is that the terminal velocity of the wind should increase with the escape velocity of the star. However, as shown in Fig. **??**, the opposite behavior is found in A-supergiants (Talavera & Gómez de Castro, 1987; Verdugo et al. 1997, 2003).

The terminal velocity, v_∞, is the mean velocity reached by wind material in regions far away from the star, where acceleration has effectively ceased but interaction with the interstellar medium has not yet become important. The terminal velocities of the winds of A-type supergiants can be measured directly from the UV P Cygni profiles.

Traditionally, the terminal velocity of a stellar wind has been observationally defined as the modulus of the largest negative velocity seen in absorption in the P Cygni profiles of UV resonance lines. For a P Cygni profile with a deep absorption (saturated profiles) through and a nearly vertical violet edge, the measured edge velocity ($v_{\rm edge}$) was considered the terminal velocity of the wind (Abbot 1978). However chaotic motions in the winds may extend and soften the vertical violet edge resulting in an overestimation of v_∞. The difference $v_{\rm edge}$ - v_∞ arising from a local velocity field, which has been parameterized as "microturbulence" by Hamann (1980, 1981) and Groenewegen et al. (1989). However, Howarth & Prinja (1989) demonstrate that for saturated ultraviolet line profiles the maximum velocity at which zero residual intensity is recorded ($v_{\rm black}$) provides an accurate measure of the wind terminal velocity. For stars without saturated profiles, but with identifiable discrete absorption components, the final central velocity reached by these components, $v_{\rm DAC}({\rm t} \rightarrow \infty)$, also provides a good indicator of v_∞ (e.g. Howarth & Prinja, 1989). However, estimating this quantity observationally requires frequent UV spectra taken over a sufficiently extensive period, and such a data are only available for a very few stars. Therefore from a single UV spectrum DACs only provide a lower limit to v_∞.

In order to determine terminal velocities of A-type supergiants is required to analyze several UV spectra taken over a large period. The wavelength or velocity, $v_{\rm edge}$, where the violet edge of the Mg II profiles reach the continuum provides an upper limit for the terminal velocities while in most cases the $v_{\rm DAC}$ is a lower limit.

Radiative winds are known to be unstable against small perturbations of the radiative force. However, such small perturbations in the wind cannot account for the aforementioned spectral features. The existence of magnetic fields is a more viable option and has been suggested by many different authors to explain the observations: (1) co-rotating interaction regions have been suggested to explain the presence of the UV DACs (Mullan 1984), (2) Co-rotating weak magnetic surface structures could explain the observed H_α variability (Kaufer et al. 1996), and (3) The existence of extended cool loops could account for another phenomenon observed in BA supergiants: High Velocity Absorptions (HVA; see Israelian et al. 1997). All these facts have motivated us to undertake a search for magnetic fields in the atmospheres of A-supergiants (Verdugo et al. 2005, 2003). Spectropolarimetric techniques has been drastically improved in the last few years allowing to detect weak magnetic fields (of a few hundred gauss) in massive stars. Magnetic fields have been discovered in 5 OB stars (see Henrichs et al. 2005 for a recent review). Specific behavior of variable stellar wind lines belongs to the well-known indirect indicators of a magnetic field in early-type stars. Typical cyclical variability of the DACs associated to UV lines are thought to be caused by magnetic fields at the base of the flow. Henceforth, analysis of the UV spectra variability is crucial to identify potential magnetic massive stars.

UV high resolution spectroscopy is therefore instrumental to make progress in the different open questions addressed above:

Is the radiation driven wind theory fully applicable to A-type supergiants? In addition, it seems to exist two different groups of A-type supergiants based on luminosity class but only a few UV spectra of luminosity class Ib stars are available. Therefore, high resolution spectra are needed to measure reliable wind parameters and to confirm the possible existence of two different types of A-supergiants. High resolution spectra are also needed to confirm the lack of UV Fe II resonance lines at rest in some of the brightest stars. Moreover, studies of UV variability are decisive to analyse the stellar winds properties, as well as the relevance of surface magnetic fields.

We would like to thank M. Urbaneja for providing some of the figures. F.N. acknowledges PNAYA2003-02785-E grant and the Ramon y Cajal program. This work has been partly supported by the Spanish MEC through PNAYA projects AYA2004-08271-C02-01 and 02.

References

[Aufdenberg2000] Aufdenberg, J.P. 2000, Ph.D. thesis, Arizona State Univ.

[Aufdenberg et al.2002] Aufdenberg, J.P., Hauschildt, P.H., Baron, E., et al., 2002, ApJ, 570, 344

[Babel1995] Babel, J., 1995 *Astronomy & Astrophysics*, 301, 823

[Babel1996] Babel, J., 1996 *Astronomy & Astrophysics*, 309, 867

[Bianchi & García2002] Bianchi, L. & García, M. The Effective Temperatures of Mid-O Stars *Astrophysical Journal*, 581, 610, 2002

[Bouret et al.2003] Bouret, J.C., Lanz, T., Hillier, D.J. et al., 2003 Quantitative Spectroscopy of O Stars at Low Metallicity: O Dwarfs in NGC 346 *Astrophysical Journal*, 595, 1182

[Bouret et al.2005] Bouret, J.-C., Lanz, T., & Hillier, D. J., 2005 Lower mass loss rates in O-type stars: Spectral signatures of dense clumps in the wind of two Galactic O4 stars *Astronomy & Astrophysics*, 438, 301

[Bresolin et al.2002] Bresolin, F., Kudritzki, R.P., Lennon, D.J. et al. Space Telescope Imaging Spectrograph Ultraviolet Spectroscopy of Early B Supergiants in M31, 2002 *Astrophysical Journal*, 580, 213

[Castor, Abbott & Klein1975] Castor, J. I., Abbott, D. C., & Klein, R. I., 1975 Radiation-driven winds in Of stars *Astrophysical Journal*, 195, 157

[Crowther et al.2002] Crowther, P. A., Hillier, D. J., Evans, C. J., et al. 2002 *Astrophysical Journal*, 579, 774

[Evans et al.2004] Evans, C.J., Crowther, P.A., Fullerton, A.W. & Hillier, D.J., 2004 *Astrophysical Journal*, 610, 1021,

[Eversberg et al.1998] Eversberg, T., Lépine, S., Moffat, A. F. J., 1998 *Astrophysical Journal*, 494, 799

[Fullerton et al.2006] Fullerton, A.W., Massa, D.L., Prinja, R.K., 2006, *Astrophysical Journal*, 637, 1025

[Gabler et al.1989] Gabler, R., Gabler, A., Kudritzki, R. P., Puls, J., & Pauldrach, A., 1989, Unified NLTE model atmospheres including spherical extension and stellar winds - Method and first results *Astronomy & Astrophysics*, 226, 162

[García & Bianchi2004] García, M. & Bianchi, L. The Effective Temperatures of Hot Stars. II. The Early-O Types *Astrophysical Journal*, 606, 497, 2004

[Groenewegen et al.1989] Groenewegen, M.A.T., Lamers, H.J.G.L.M., Pauldrach, A.W.A., 1989, *Astronomy & Astrophysics*, 221, 78

[Hamann1980] Hamann, W.-R., 1980, *Astronomy & Astrophysics*, 84, 342

[Hamann1981] Hamann, W.R. Line formation in expanding atmospheres - On the validity of the Sobolev approximation, *Astronomy & Astrophysics*, 93, 353, 1981.

[Haser et al.1998] Haser, S. M., Pauldrach, A. W. A., Lennon, D. J., Kudritzki, R.-P., Lennon, M., Puls, J., & Voels, S. A., 1998 Quantitative UV spectroscopy of early O stars in the Magellanic Clouds. The determination of the stellar metallicities, *Astronomy & Astrophysics*, 330, 285

[Haser1995] Haser, S. , *PhD Thesis, Munich*, 1995.

[Heap al.2004] Heap, R.S., Lanz, T., Hubeny, I. Fundamental properties of O Stars *astro-ph0412345* 2004

[Henrichs et al.2005] Henrichs, H. F.; Schnerr, R. S.; Ten Kulve, E., 2005, ASPC, 337, 114

[Hensberge et al.1982] Hensberge, H., Lamers, H.J.G.L., de Loore, C., Bruhweiler, F.C., 1982, *Astronomy & Astrophysics*, 106, 137

[Herrero et al.2001] Herrero, A., Puls, J., Corral, L.J., Kudritzki, R.P., Villamariz, M.R., An Analysis of HST UV Spectra of Cyg OB2 stars, *Astronomy & Astrophysics*, 366, 623, 2001.

[Herrero, Puls & Najarro2002] Herrero, A., Puls, J. & Najarro, F. Fundamental parameters of Galactic luminous OB stars VI. Temperatures, masses and WLR of Cyg OB2 supergiants *Astronomy & Astrophysics*, 396, 949, 2002

[Hillier et al.2003] Hillier, D.J., Lanz, T., Heap, S., et al., 2003 *Astrophysical Journal*, 588, 1039

[Hillier & Miller1998] Hillier, D.J. & Miller, D.L. *Astrophysical Journal*, 496, 407, 1998

[Howarth & Prinja1989] Howarth, I.D. & Prinja, R.K. The stellar winds of 203 Galactic O stars - A quantitative ultraviolet survey, *Astrophysical Journal Supplement*, 69, 527, 1989.

[Israelian et al.1997] Israelian, G., Chentsov, E., & Musaev, F., 1997, MNRAS, 290, 521

[Kaufer et al.1996] Kaufer, A., Stahl, O., Wolf, B., et al., 1996, *Astronomy & Astrophysics*, 305, 887

[Kudritzki et al.1989] Kudritzki, R. P., Pauldrach, A., Puls, J., & Abbott, D. C. Radiation-driven winds of hot stars. VI - Analytical solutions for wind models including the finite cone angle effect *Astronomy & Astrophysics*, 219, 205, 1989

[Kudritzki1998] Kudritzki, R.-P., 1998 Quantitative Spectroscopy of the Brightest Blue Supergiant Stars in Galaxies *Stellar astrophysics for the local group: VIII Canary Islands Winter School of Astrophysics*, 149

[Kudritki & Puls2000] Kudritzki, R.-P., & Puls, J. Winds from Hot Stars *Annual Review of Astronomy & Astrophysics*, 38, 613, 2000

[Kudritzki et al.1999] Kudritzki, R. P., Puls, J., Lennon, D. J., Venn, K. A., Reetz, J., Najarro, F., McCarthy, J. K., & Herrero, A. The wind momentum-luminosity relationship of galactic A- and B-supergiants *Astronomy & Astrophysics*, 350, 970, 1999

[Lamers et al.1999] Lamers, H.J.G.L.M., Haser, S., de Koter, A., Leitherer, C. The Ionization in the Winds of O Stars and the Determination of Mass-Loss Rates from Ultraviolet Lines, *Astrophysical Journal*, 516, 872, 1999.

[Lamers et al.1995] Lamers, H.J.G.L.M., Snow, T.P., Lindholm, D.M., 1995, ApJ, 455, 269

[Lamers et al.1978] Lamers, H.J.G.L.M., Stalio, R., Kondo, Y., 1978, ApJ, 223,207

[Lamers et al.1978] Lamers, H.J.G.L.M., Snow, T.P., 1978, ApJ, 219, 504

[Lépine et al.1999] Lépine, S., Moffat, A. F. J. *Astrophysical Journal*, 514, 909, 1999

[Macfarlane et al.1994] Macfarlane, J. J., Cohen, D. H., & Wang, P. X-ray induced ionization in the winds of near-main-sequence O and B stars *Astrophysical Journal*, 437, 351, 1994.

[Massa et al.2003] Massa, D., Fullerton, A.W., Sonneborn, G., et al., 2003 *Astronomy & Astrophysics*, 586, 996

[Markova et al.2004] Markova, N., Puls, J., Repolust, T., et al., *Astronomy & Astrophysics*, 413, 693, 2004

[Martins et al.2002] Martins, F., Schaerer, D., Hillier, D.J. *Astronomy & Astrophysics*, 382, 999, 2002

[Martins et al.2004] Martins, F., Schaerer, D., Hillier, D. J., & Heydari-Malayeri, M. Puzzling wind properties of young massive stars in SMC-N81 *Astronomy & Astrophysics*, 420, 1087, 2004

[Martins, Schaerer & Hillier2005] Martins, F., Schaerer, D., Hillier, D.J. 2005, *Astronomy & Astrophysics*, 436, 1049

[Martins et al.2005] Martins, F., Schaerer, D., Hillier, J., Meynadier, F., Heydari-Malayeri, M., & Walborn, N. O stars with weak winds: the Galactic case *Astronomy & Astrophysics*, 441, 735, 2005

[Massey et al.2004] Massey, P., Bresolin, F., Kudritzki, R.P., Puls, J. & Pauldrach, A.W.A. *Astrophysical Journal*, 608, 1001, 2004

[Massey et al.2005] Massey, P., Puls, J., Pauldrach, A.W.A. et al. The Physical Properties and Effective Temperature Scale of O-Type Stars as a Function of Metallicity. II. Analysis of 20 More Magellanic Cloud Stars and Results from the Complete Sample *Astrophysical Journal*, 627, 477, 2005

[McErlean, Lennon & Dufton1999] McErlean, N.D., Lennon, D.J. & Dufton, P.L. *Astronomy & Astrophysics*, 349, 553, 1999

[Meynet et al.1994] Meynet, G., Maeder, A., Schaller, G., et al., 1994, *Astronomy & Astrophysics*, 103, 97

[Najarro et al.1996] Najarro, F., Kudritzki, R. P., Cassinelli, J. P., Stahl, O., & Hillier, D. J. 1996, Stellar winds and the EUV continuum excess of early B-giants. *Astronomy & Astrophysics*, 306, 892

[Najarro2001] Najarro, F., 2001, Spectroscopy of P Cygni *ASP Conf. Ser. 233: P Cygni 2000: 400 Years of Progress*, p 133

[Najarro et al.2004] Najarro, F., Figer, D. F., Hillier, D. J., Kudritzki, R. P., 2004 Metallicity in the Galactic Center: The Arches Cluster *Astrophysical Journal Letters*, 611, L105

[Owocki & Puls1999] Owocki, S.P. Puls, J., *Astrophysical Journal*, 510, 355, 1999.

[Pauldrach et al.1994] Pauldrach, A. W. A., Kudritzki, R. P., Puls, J., Butler, K., & Hunsinger, J. Radiation-driven winds of hot luminous stars. 12: A first step towards detailed UV-line diagnostics of O-stars *Astronomy & Astrophysics*, 283, 525, 1994

[Pauldrach , Hoffmann & Lennon2001] Pauldrach, A.W.A., Hoffmann, T.L. & Lennon, M. *Astronomy & Astrophysics*, 375, 161, 2001

[Praderie et al.1980] Praderie, F., Talavera, A., Lamers, H.J.G.L.M., 1980, *Astronomy & Astrophysics*, 86, 271

[Prinja et al.2005] Prinja, R.K., Massa, D., Searle, S.C., *Astronomy & Astrophysics*, 430, L41 2005

[Prinja & Crowther1998] Prinja, R.K. & Crowther, P.A. HSTUV measurements of wind structure and velocities in Local Group OB stars, *Monthly Notices of the Royal Astronomical Society*, 300, 828, 1998.

[Przybilla et al.2005] Przybilla, N., Butler, K., Becker, S.R., Kudritzki, R.P., 2005, *Astronomy & Astrophysics*, in press

[Puls et al.1996] Puls, J., Kudritzki, R.P., Herrero, A. et al. , 1996 O-star mass-loss and wind momentum rates in the Galaxy and the Magellanic Clouds Observations and theoretical predictions *Astronomy & Astrophysics*, 305, 171

[Puls et al.1998] Puls, J., Kudritzki, R.P., Santolaya-Rey, A.E., Herrero, A., Owocki, S.P. *Proc. 2nd Boulder-Munich Workshop*, 1998, *PASP*, 131, 245

[Puls et al.2000] Puls, J., Springmann, U., & Lennon, M., 2000, Radiation driven winds of hot luminous stars. XIV. Line statistics and radiative driving *Astronomy & Astrophysics Supplement Series*, 141, 23

[Puls et al.2005] Puls, J., Urbaneja, M.A., Venero, R., et al., 2005, *Astronomy & Astrophysics*, 435, 669

[Repolust, Puls & Herrero2004] Repolust, T., Puls, J., Herrero, A. 2004, *Astronomy & Astrophysics*, 415, 349

[Santolaya et al.1997] Santolaya-Rey, A.E., Puls, J., & Herrero, A. 1997, *Astronomy & Astrophysics*, 323, 488

[Springmann & Pauldrach1992] Springmann, U.W.E., Pauldrach, A.W.A., 1992 *Astronomy & Astrophysics*, 262, 515

[Talavera et al.1987] Talavera, A. & Gómez de Castro, A.I., 1987, *Astronomy & Astrophysics*, 181,300

[Trundle et al.2004] Trundle, C., Lennon, D.J., Puls, J. & Dufton, P.L. *Astronomy & Astrophysics*, 417, 217, 2004

[Trundle & Lennon2005] Trundle, C. & Lennon, D.J. Understanding B-type supergiants in the low metallicity environment of the SMC II *Astronomy & Astrophysics*, 434, 677, 2005