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MODERN-ERA QUANTITATIVE SPECTROSCOPY OF OB STARS

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Abstract. In this review the stellar and wind properties of OB stars in the MW and the MCs derived by means of modern-era quantitative spectral analyses are summarised and briefly discussed with a particular emphases on the results inferred from optical observations.

1. INTRODUCTION

The evolution of the Universe is a central topic of the present-day astrophysical research. The main engines of this evolution are stars with $M_\star \geq 10\ M_\odot$ known as "massive stars". Though quite rare in the solar neiborhood, massive stars play a fundamental role in the present and the early Universe: they are important contributors to the chemical and dynamical evolution of galaxies; they dominate the integrated UV radiation in young galaxies and are key objects for studying and understanding exciting phenomena such as, e.g., the re-ionization of the early Universe, γ-ray bursters etc.

1. 1. QUANTITATIVE SPECTROSCOPY OF HOT MASSIVE STARS

Quantitative spectroscopy (i.e., the analysis of stellar spectra by means of atmospheric models) is the most powerful tool to get observational constrains on the physical properties of massive stars. However, modeling the atmosphere of a hot star is a considerable challenge, even for the present-day quantitative spectroscopy, for a number of very complicated physical processes have to be taken into account.

NLTE effecst. Due to the intense radiation fields and low densities, the physics of hot star atmospheres is dominated by radiative processes, i.e., departures from Local Thermodynamical Equilibrium (LTE) are important and have to be taken into account when calculating the occupation numbers of atomic levels (see Puls 2009 and references therein).

Stellar winds. Hot massive stars experience continuous mass-loss ("stellar winds") during all stages of their evolution. The process is very intensive[1] and is believed to be initiated and driven by radiation preassure in UV metal lines. Stellar winds have pronounced effects on the physics of hot star atmopsheres dominating the desity distribution and the radiative transfer, and modifying the chemical profile, surface

[1] Typical rates range from 10^{-5} to $10^{-7} M_\odot$ /yr against $10^{-14} M_\odot$ /yr for our Sun.

abundances and the spectral energy distribution. Excelent reviews on various aspects of line-driven winds can be found in Kudritzki and Puls (2000) and Puls, Vink and Najarro (2008).

Line blanketing. One of the most complicated process to be taken into account when calculating hot star model atmospheres is the effect of a vast number of overlapping metal absorption lines in the EUV, which act as a "blanket" above the photosphere. Two direct consequences of line blanketing are: the strong reduction of the EUV/UV flux in the outer atmosphere ("line-blocking") and the increased electronic temperatures and mean radiation field in the inner photosphere ("back-warming"). (For a more detailed consideration of the impact of line blanketing see Puls 2008 and references therein.)

The inclusion of the aforementioned processes into the model atmosphere calculations is not an easy task. Consequently, only wind-/metal-free models in LTE were calculated and used till recently. In the beginning of the new millenium, thanks to the enormous advancement of atomic physics and radiative transfer techniques, and thanks to the exponential growth of the computational power, a new generation of model atmosphere codes which properly account for non-LTE effects and the effects of stellar wind and metal line blocking/blanketing have become available. More information about the basic features of the codes can be found in Puls et al. (2005) and Puls, (2008) while here I will only mention that a specific feature of all these codes is that they make use of the so-called "standard" radiation-driven wind theory where the wind is assumend to be stationary, spherically symmetric and homogeneous (see Castor, Abbott and Klein, 1975). Deviations from the standard models, caused e.g., by stellar rotation, pulsations, magnetic fields and intrinsic instability of the radiative force, though actually present, are still not incorporated into the atmospheric models.

In the last decade, extensive surveys of OB-stars in our Galaxy and in the Local group have been performed using NLTE line blanketed model atmosphere codes, and a large number of very important new results were derived, which substentially improved our knowleadge about massive stars and their evolution. It is the goal of this contribution to provide a brief overview of the most important findings and conclusions obtained throughout these investogations with a particular emphases on the results originating from optical analyses.

2. FUNDAMENTAL PARAMETERS OF OB STARS

A hot star model atmosphere is described by seven parameters: effective temperature, $T_{\rm eff}$; surface gravity, $\log g$; stellar radius $R_\star$ at the Rosseland optical depth ($\tau_{ross} = 2/3$); elemental abundances, Z; mass-loss rate, $\dot{M}$; terminal wind velocity, v_∞ and the velocity exponent β. All these parameters (except $R_\star$) can be determined from spectral observations fitting strategic lines with model calculations.

In particular, $T_{\rm eff}$ can be determined from the best fit to lines of different ionization stages: in the optical, the ionization balance of Helium (for O and early-B stars) and Silicon (for B stars) is exploited while in the UV, the ionization equilibria of metal lines (e.g., Oxygen and Iron) are used instead; $\log g$ are estimated from the Stark broadened wings of Balmer lines (H_γ and H_δ) in parallel with $T_{\rm eff}$; $\dot{M}$ are inferred from unsaturated UV resonance/subordinate lines, from H_α or from Hydrogen and Helium lines in the IR, and finally, v_∞ and β can be constrained from saturated UV profiles or from H_α (for stronger winds).

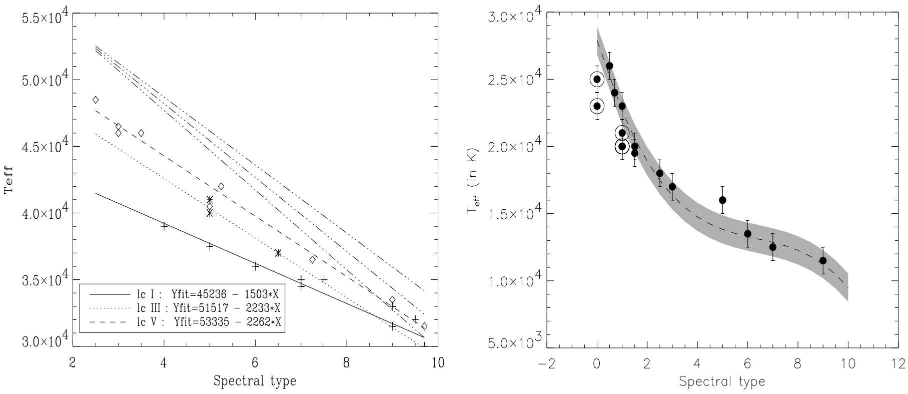

Figure 1: *Left*: The "blanketed" temperature scales for Galactic O-stars of different luminosity classes as suggested by Markova et al. (2004), based on original data from Repolust et al. 2004 and Martins et al. 2002. The dashed-dotted lines represent the "unblanketed wind-free" scale of Vacca et al. (1996). *Right*: The "blanketed" temperature scale for Galactic B-supergiants as deriveded by Markova and Puls (2008), using own data and data from Urbaneja (2004), Crowther et al. (2006), Przibila et al. (2006) and Lefever et al. (2008).

2. 1. EFFECTIVE TEMPERATURES

Exploiting optical and UV diagnostics, the "blanketed" temperatures of a large number of OB stars in the Milky Way (MW) and the Magelanic Coulds (MCs) have been determined and used to derive more realistic temperature calibrations for these stars. The obtained results can be summarized as follow.

i) The "blanketed" temperature scale for Galactic O-stars (supergiants=SGs, giants=Gs and dwarfs=DWs) derived by means of optical (Repolust et al. 2004, Markova et al. 2004, Martins et al. 2005a) and UV (Bianchi and Garcia 2002; Garcia and Bianchi 2004; Martins et al. 2004; Bouret et al. 2005) diagnostics is found to be significantly cooler than the plane-paralell "unblanketed" scale of Vacca et al. (1996), with largest differences (up to 8 000 K) measured for the hottest supergiants. For Galactic B-SGs, the corresponding reductions, measured with respect to the "unblanketed wind-free" scale of McEarlean et al. (1999), are smaller with actual values ranging from 4 000 K at the hotter to 500 K at the cooler temperature edge of the B-star domain (Markova and Puls, 2008 and references therein). An example for "blanketed" $T_{\rm eff}$ – spectral type calibrations for Galactic OB stars is given in Fig. 1.

ii) The $T_{\rm eff}$ reduction caused by line blanketing depends on metallicity. In particular, it turned out that for a given spectral type and luminosity class, OB stars in the MW are cooler than those in the LMC, which in turn are cooler than their SMC counterparts (Massey et al. 2004, 2005; Heap et al. 2006; Mokiem et al. 2006, 2007a for O stars, and Trundel et al. 2007; Hunter et al. 2007 for B stars). This finding is attributed to less blanketing and weaker winds caused by the lower metallicity. At least for O-dwarfs, it was shown that only part (25 to 30 %) of the established differences in $T_{\rm eff}$ can be explained by metallicity effects on the spectral type indicators, while the rest must be attributed to other more "physical" reasons (see Mokiem et al. 2004 and Markova et al. 2009).

iii) For many O stars, the "blanketed" $T_{\rm eff}$ - estimates based on UV diagnostics are significantly lower than those originating from the optical analysis. First steps to address this puzling result have been undertaken by Massey et al. (2009).

2. 2. SURFACE GRAVITY

Modern-era spectroscopic analysis of O-stars (e.g., Markova et al. 2004, Martins et al. 2004) indicate that for objects with weaker winds (DWs and Gs) the "blanketed" and "unblanketed" $\log g$ - estimates are practically equal (within the error) while for SGs (stronger winds) a systematic difference of up to 0.25 dex is observed. These results are fully consistent with theoretical predictions which show that the incorporation of line-blanketing and stellar winds into model calculations will lead to higher gravaity for O-type stars where the effect is governed by the strength of the wind while line blanketing does not seem to play any role (e.g., Puls et al. 1996).

2. 3. STELAR ROTATION

Rotation and Macroturbulence. It has been known for a relatively long time that absorption line spectra of hot massive stars exhibit a significant amount of broadening in excess to the rotational broadening ("macro-turbulence", $v_{\rm mac}$). Since axial rotation is a key parameter for stellar evolution calculation, it is particularly important to distinguish rotational effects from those of macro-turbulence.

To cure this problem a specific method, based on Fourier transform technics, has been developed (Simon Diaz et al. 2006) and applied (Dufton et al. 2006a, Simon Diaz and Herrero, 2007, Lefever et al. 2007, Markova and Puls 2008, Hunter et al. 2008a) to estimate $v \sin i$ and $v_{\rm mac}$ of a large number of OB-stars in the MW and the MCs. The main outcomes of these analyses show that: (i) $v_{\rm mac}$ is important in SGs and negligible in DWs; (ii) $v_{\rm mac}$ decreases with decreasing $T_{\rm eff}$ being highly supersonic within the whole OB-star domain; (iii) the $v_{\rm mac}$ broadening appears to be symmetric and consistent with a Gaussian distribution; (iv) the strength of $v_{\rm mac}$ does not seem to depend on metallicity.

The macro-turbulent phenomenon is difficult to interprete. An interesting possibility announced by Aerts et al. (2009) is that the need of macro-turbulence can be simply due to the omission of pulsational broadening in the present-day model atmosphere codes. A project to investigate this issue further is currently underway (Simon-Diaz et al. 2009).

Rotation and metallicity. Since stellar winds can reduce the angular momentum of a star significantly, and since the wind strength depends on metallicity, low metallicity stars are expected to rotate faster. To examine these predictions knowledge of the actual rotation speeds is required while due to the generally unknown value of the inclination of the rotation axes, the projected rotation velocities can only be derived from the observations. Fortunately, for statistically significant samples of stars a solution of this problem exists where the underlaying distribution of rotational velocities can be modeled assuming random angles of inclination. Following this approach the $v \sin i$ - distributions of a large number of OB-stars in the Galaxy (Dufton et al. 2006b) and the MCs (Mokiem et al. 2006, Hunter et al. 2008a) have been investigated. Consequently it was found that at least B-stars in the SMC rotate faster than their LMC counterparts.

Rotation and stellar evolution. Evolutionary tracks accounting for stellar rotation (Maeder and Meynet 2001) predict that during the core-hydrogen burning (CHB) the rotational speeds should remain relatively constant, showing only a slight decrease from the zero-age main sequence to the end of the hydrogen burning while after the CHB, they should decrease smoothly as the stars evolve to lower gravities. Due to the stronger winds, the rate of decrease is expected to be larger for more massive stars.

The behaviour of $v \sin i$ as a function of surface gravity for early B-type stars in the MW and the MCs was investigated by Hunter et al. (2008a) who found that:
i) the observed distributions are bi-modal with a border line at about 3.2 dex. Interpreted as the end of the CHB phase, this value implyes an extention of the predicted CHD lifetime (by 0.3 dex) to lower gravities.
ii) in agreement with the evolution theory, SGs ($\log g \leq 3.2$) rotate slower than DWs and Gs do. However, their spin velocities do not decrease smoothly as the star evolves to lower gravity, but instead stay almost constant with values being generally lower than those predicted.
iii) the number of low gravity objects is significantly higher than the expected one. Mass transfer binarity sistems or the blue loops rather than direct evolution from the main-sequence is suggested as a more likely explanation for the observed overpopulation of SGs.

Rotational mixing. Stellar evolution calculations with axial rotation for massive stars predict a surface He and N-enrichment during the main sequence evolution with an effect being stronger for stars at Z lower than solar (Maeder and Meynet 2001). Since photospheric mixing effects are more easy to detect at lower metallicities, the MCs have been intensively observed to investigate the efficiency of rotational mixing in OB stars (Trundle et al. 2007, Hunter et al. 2007, 2008a, 2008b, 2009). Concequently, an extensive base of precise estimates of the N-surface abundances and rotational speeds of more than 400 early B-type stars in the MCs, and about 50 such stars in the MW were obtained and subsequently compared to evolutionary models including overshuting and rotational mixing. The obtained results show that a signifcant part of the fast rotating CHB stars in the LMC do inded show surface N-enrichment and can therefore be considered as rotationally mixed single stars. On the other hand, two more populations of CHB stars have been identified which are incompetible with the models: the group of evolved stars which have high rotation speeds, but do not show N-enrichments, and the group of highly N-enriched stars which are intrinsic slow rotators. Binary effects and fossil magnetic fields may be the key to understand the 'peculiar' surface properties of these massive main-sequence stars (Hunter et al. 2008b). Concerning the first possibility, the element Boron seems to be an appropriate tool to distinguish between rotational mixing and the binary scenario (Brot et al. 2009).

Concerning B-SGs, in agreement with earlier findings (Trundle and Lennon, 2005 and references therein) a population of highly N-enriched slowly rotating objects was identified for which previous evolution trough a red supergiants phase rather than direct evolution from the main sequence seems more likely. Apart from this group, objects with relatively normal level of N-enrichment have been observed which might be considered as pre-red supergiant stars.

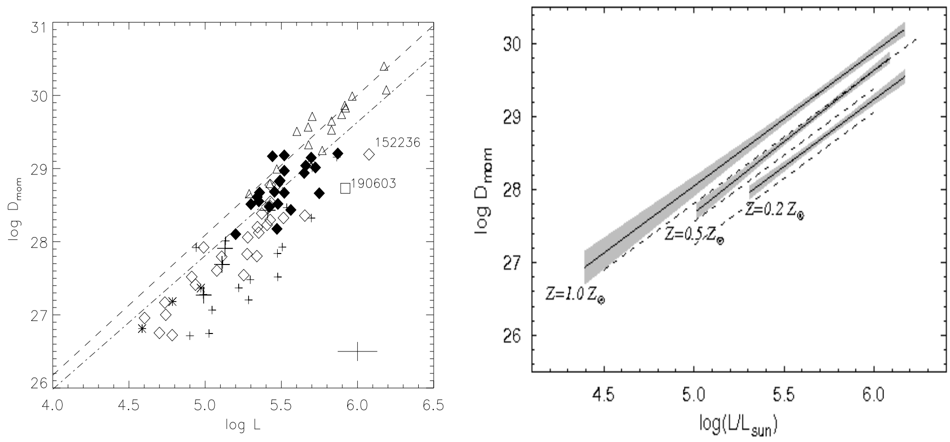

Figure 2: *Left*: The observed WLR for Galactic O-stars (triangles) and B-supergiants (diamonds and crosses) as derived by Markova and Puls (2008). The predictions of Vink et al. for O-stars (dashed-dotted) and B-SGs (dashed) are shown for comparison. *Right*: The observed WLRs for O-stars in the MW (Z=1.0 $Z_\odot$), the Large MC (Z=0.5 $Z_\odot$) and the Small MC (Z=0.2 $Z_\odot$) (adopted from Mokiem et al. 2006).

2. 4. STELLAR MASSES AND THE MASS DISCREPANCY PROBLEM

The most puzzling issue concerning stellar masses of single OB stars is the so-called *mass descrepancy problem* (the spectroscopically derived masses are lower than those estimated from evolutionary calculations) noted firstly by Herrero et al. (1992) and additionally confirmed by other investigators through moder-era model atmosphere analysis (e.g., Repolust et al. 2004; Markova and Puls, 2008; Crowther et al. 2006). What we know about mass-discreapncy at present is that: *first*, the problem does not seem to depend on metallicity since similar results have been obtained for O and early B-type stars in the MCs as well (see Trundel and Lennon, 2005; Heap et al. 2006; Hunter et al. 2008a; Massey et al. 2009) and *second*, at least for the case of He-enriched low luminosity O-stars, the problem might be related to efficient rotational mixing during the main-sequence phase (Mokiem et al. 2006, 2007a). For none He-enriched stars however an adequate interpretation is still missing.

3. WIND PROPERTIES

The Wind momentum Luminosity Relation. The standard radiation-driven wind theory predicts a power-law dependence between the "modified wind momentum rate", $D_{\rm mom}$, and stellar luminosity, L, (the so-called "Wind-momentum Luminosity Relation" (WLR):

$$logD_{\rm mom} = log\left(\cdot 10^{-6}{\rm M}_\odot/{\rm yr} v_\infty R_\star^{0.5}\right) = xlogL + logD_0(Z,SPT) + const \qquad (1)$$

where the slope x and the constant D_0 are expected to vary with spectral type and metallicity (Kudritzki et al. 1995, 1999; Vink et al. 2000; Puls et al. 2000).

While these predictions have been basically confirmed by observations of OB stars in the MW and the Local Group, a number of discrepancies were established when comparing the observed wind properties to those predicted by Vink et al. (2000). In particular,

(i) for weak-winded low luminosity ($\dot{M} \leq 10^{-8} M_{\odot}$, log $L \leq 5.2$) O-stars in the MW (Martins et al 2005a,b) and the SMC (Martins et al 2004; Bouret et al 2003), the observed values of $\dot{M}$ and v_{∞} (based on UV diagnostics!!) are significantly lower than those predicted by theory (the so-called "weak wind problem"). Various possibilities to explain these puzzling findings have been suggested and theoretically investigated (e.g., ineffective Coulomb-collisions due to decoupling of metals lines from the bulk plasma; shadowing of wind-driven lines; the crucial role of X-rays at low densities), but due to the lack of reliable $\dot{M}$ estimates at this wind regime, the actual physical mechanism(s) leading to the noted discrepancy is still not identified. Quantitative IR spectroscopy may provide the key to solve the weak wind problem (Puls, Vink and Najarro, 2009 and references theirin).

(ii) for O-stars with stronger winds, the observed values of $D_{\rm mom}$ are by a factor of 2 larger than those predicted by theory (e.g., Repolust et al. 2004; Markova et al. 2004; Crowther et al. 2006; Mokiem et al. 2005, 2006, 2007a). Small-scale wind inhomogenities (clumps) are beleived to be the physical reason for this discrepancy (Puls et al. 2008).

(iii) for low $T_{\rm eff}$ /low L B-type SGs in the MW, the observed values of $D_{\rm mom}$ are by about 0.3 dex lower than those predicted by Vink et al. (see Markova and Puls 2008). This result is interpreted as a direct consequence of the fact that the decrease in v_{∞} at the bi- stability jump (spectral class B1) is not *over-compensated* by an increase in $\dot{M}$, as predicted by theory, but instead $\dot{M}$ either decreases (by about a factor of 0.4), or slightly increases (by a factor of 2.5). The later finding in particular means that the low temperature predictions of Vink et al. suffer from unknown defects.

An example to illustrate the results outlined in the last two items above is given in Fig. 2 (left).

Metallicity effects. Since hot stars winds are initiated and accelerated by absorption of photospheric photons in UV metal lines, it is natural to expect that the wind properties will depend on stellar metallicity (Kudritzki et al. 1987). In particular, for stars with $T_{\rm eff} \geq 25\,000$ K theoretical calculations taking into account multiple scaterring of line photons predict that $\dot{M} \approx Z^{0.85+/-0.1}$ for metallicity 1/30 to 3 times solar (Vink et al. 2001). These predictions have been basically confirmed by the observations (Mokiem et al. 2006) which show that at a given luminosity, the wind momenta of LMC stars are intermediate to those in the MW and the SMC (Fig. 2, right). The dependence of wind strengths on metallicity is an important observational result with implications for stellar evolution calculations.

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