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LETTER TO THE EDITOR

The IACOB project★

II. On the scatter of O-dwarf spectral type – effective temperature calibrations

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ABSTRACT

Context. We are now in an era of large spectroscopic surveys of OB-type stars. Quantitative spectroscopic analysis of these modern datasets is enabling us to review the physical properties of blue massive stars with robust samples, not only revisiting mean properties and general trends, but also incorporating information about the effects of second-order parameters.

Aims. We investigate the spectral type – effective temperature (SpT – $T_{\rm eff}$) calibration for O-type dwarfs and its claimed dependence on metallicity, using statistically meaningful samples of stars extracted from the IACOB and VFTS surveys.

Methods. We performed a homogeneous differential spectroscopic analysis of 33 Galactic and 53 LMC O dwarfs (spanning spectral types of O4 – O9.7) using the iacob-gbat package, a χ^2-fitting algorithm based on a large pre-computed grid of FASTWIND models, and standard techniques for the hydrogen/helium analysis of O-type stars. We compared the estimated effective temperatures and gravities as a function of (internally consistent) spectral classifications.

Results. While the general trend is that the temperature of a star increases with earlier spectral types and decreasing metallicity, we show that the wide range of gravities found for O-type dwarfs – spaning up to 0.45–0.50 dex in some spectral bins – plays a critical role on the dependence of the effective temperature calibrations as a function of spectral type and metallicity.

Conclusions. This result warns us about the use of SpT - $T_{\rm eff}$ calibrations for O dwarfs that ignore the effects of gravity, and highlights the risks of employing calibrations based on small samples. The effects of this scatter in gravities (evolutionary status) for O-type dwarfs should be included in future recipes that employ SpT - $T_{\rm eff}$ calibrations.

Key words. stars: early-type – stars: fundamental parameters

1. Introduction

An important deliverable that studies of massive stars must provide to the broader astrophysics community is a series of recipes in which the physical properties of OB-type stars (such as effective temperature, gravity, luminosity, radius, mass, wind momentum, and number of ionizing photons) are calibrated against more easily determined quantities (e.g., spectral type and luminosity class), or against the input parameters used in population synthesis models (mass and age). These recipes are expected to be applied to the study of different environments across the Universe, therefore characterizing the effect of metallicity (Z) on these calibrations is of key importance.

The spectral type – effective temperature (SpT – $T_{\rm eff}$) calibration for O-type stars has been extensively studied, across a range of metallicities, and using the most advanced codes available (see, for example, Vacca et al. 1996; Martins et al. 2002; Herrero et al. 2002; Bouret et al. 2003; Repolust et al. 2004; Massey et al. 2004, 2005, 2009; Martins et al. 2005; Heap et al. 2006; Mokiem et al. 2007; Rivero González et al. 2012; Garcia & Herrero 2013). These and previous studies have generally investigated the SpT – $T_{\rm eff}$ calibrations separated into three luminosity classes (LC): dwarfs (V), giants (III), and supergiants (I). The global picture is clear in terms of the dependence of $T_{\rm eff}$ on SpT and LC: early O-type stars are hotter than late-O stars and dwarfs are hotter than supergiants. The dependence on Z is less clear; while there are some hints that (as expected) stars are hotter at lower Z (for a given SpT), this is not always supported by the observations (Massey et al. 2004; Martins et al. 2005). In addition, there is another important factor that has not been sufficiently explored to date – the remarkable scatter found in $T_{\rm eff}$ for a given SpT + LC + Z combination.

Past studies have (necessarily) drawn their conclusions from relatively small samples of stars and, in some cases, from the comparison of results obtained using different codes and techniques. In this context, the efforts of the GOSSS, IACOB, and

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OWN projects (Maíz Apellániz et al. 2011; Simón-Díaz et al. 2011a; Barbá et al. 2010, respectively) in the Milky Way, and the VLT-FLAMES Tarantula Survey (VFTS, Evans et al. 2011) in the 30 Doradus region of the Large Magellanic Cloud provide us with an excellent opportunity to improve this situation. For the first time, large samples of O stars in two different metallicity environments are being investigated homogeneously using the same codes and techniques. This not only concerns the quantitative analysis, but also the spectral classification (Sota et al. 2011; Walborn et al. 2014).

Quantitative spectroscopic analysis of the IACOB, OWN, and VFTS O-type samples is on-going and will be published elsewhere (see, e.g., Sabín-Sanjulián et al. 2014; Bestenlehner et al. 2014). In this Letter we present first results on the investigation of the SpT $-T_{\rm eff}$ calibration in O dwarfs and its claimed dependence on Z using two carefully selected subsamples of stars from the IACOB database and the VFTS.

2. Observations and analysis

The Galactic sample is drawn from the class V stars observed by the IACOB project (see Simón-Díaz & Herrero 2014), excluding objects that were detected as double-lined or large-amplitude binaries. The final sample comprises 33 O-type dwarfs, spanning a range in SpT from O4 to O9.7. To investigate the effects of Z we considered O-type dwarfs from the VFTS (again omitting any target with indications of binarity or a composite spectrum, see Sana et al. 2013; Walborn et al. 2014; Sabín-Sanjulián et al. 2014). The Large Magellanic Cloud (LMC) sample comprises 53 O-type dwarfs[1], which are essentially those listed in Tables A.1 and A.2 from Sabín-Sanjulián et al. (2014), but without stars with uncertain SpTs, or indications of more than one target in the fibre.

Spectral types of the Galactic and LMC samples were taken from Sota et al. (2011) and Walborn et al. (2014), respectively. The stellar and wind parameters of these two samples were determined using the `iacob-gbat` package (Simón-Díaz et al. 2011b), based on a χ^2-fitting algorithm applied to a large precomputed grid of FASTWIND (Santolaya-Rey et al. 1997; Puls et al. 2005) models, and standard techniques for the hydrogen/helium analysis of O-type stars (see, e.g., Herrero et al. 1992; Repolust et al. 2004). The complete spectroscopic analysis of the IACOB sample will be presented in a forthcoming paper (Simón-Díaz et al., in prep.). Details of the `iacob-gbat` analysis of the VFTS O-dwarf sample were given by Sabín-Sanjulián et al. (2014). Estimates for the projected rotational velocities ($v \sin i$) used in the analyses are those given by Simón-Díaz & Herrero (2014, IACOB) and Ramírez-Agudelo et al. (2013, VFTS).

Before we discuss our results, we stress that we removed known binaries and composite spectra, we performed a homogeneous differential analysis of both samples, and the spectral classification of all the stars considered was (self-consistently) undertaken by the same team.

3. Results and discussion

The $T_{\rm eff}$ and $\log g_{\rm c}$ (gravity-corrected for centrifugal acceleration) estimates for the Galactic and LMC samples are shown as a function of SpT in Fig. 1; the SpT $-T_{\rm eff}$ and SpT $-\log g$ calibrations from linear fits to the data are overplotted as dashed lines. These results are also summarized in Table 1, in which we indicate the number of stars and the means and ranges of the $T_{\rm eff}$ and $\log g_{\rm c}$ estimates per SpT bin.

[1] To ensure that the range of SpTs is the same between the two samples, the O2-/O3-type stars observed by the VFTS were not considered.

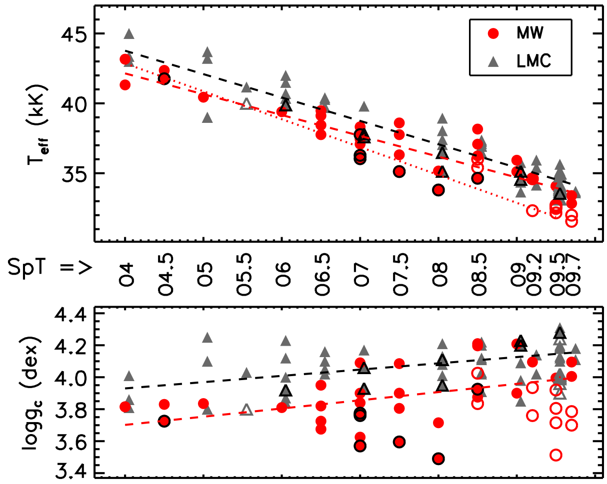

Fig. 1. $T_{\rm eff}$ and $\log g_{\rm c}$ estimates for the Galactic (red circles) and LMC (gray triangles) O-type dwarfs as a function of SpT; corresponding linear fits are overplotted with red and black dashed lines. Stars with $v \sin i > 250$ km s^{-1} are highlighted in black. Luminosity class IV stars are plotted as red and gray open symbols and were not used for the linear fits (see text). The widely used SpT $-T_{\rm eff}$ calibration by Martins et al. (2005) is also shown for reference (red dotted line).

The SpT $-T_{\rm eff}$ calibrations agree well with previous studies, in which LMC O-type dwarfs ($Z \sim 0.5\ Z_{\odot}$) are ~1000–2000 K hotter than Galactic stars (e.g., Mokiem et al. 2007; Rivero González et al. 2012). However, one important feature of our results (which is also present in other previous works dealing with SpT $-T_{\rm eff}$ calibrations, see, e.g., Vacca et al. 1996; Martins et al. 2005; Massey et al. 2009) is the non-negligible scatter of $T_{\rm eff}$ for most of the SpT bins. This dispersion – of up to ~3500 K in the more extreme cases – is higher than the estimated uncertainties from the quantitative spectroscopic analysis (typically ± 500–1500 K, depending on the specific example). As a consequence, we can find (1) stars with same metallicity, different SpTs, but the same $T_{\rm eff}$; (2) stars with different metallicities, the same SpT, but the same $T_{\rm eff}$; and (3) Galactic O stars with a higher $T_{\rm eff}$ than those in the LMC for a given SpT. Thus, the situation is more complex than simply comparing two linear SpT $-T_{\rm eff}$ calibrations resulting from samples with different metallicities.

This situation is easily understood when one also considers the gravities in the interpretation of the results. As illustrated by Fig. 1 and Table 1, there is also a broad scatter in the gravities associated with a given SpT bin (up to 0.45–0.50 dex in the most extreme cases). In particular, we note that the Galactic O-type dwarfs span a range of gravities of 4.2 to 3.5 dex[2], with a range of 4.3 to 3.8 dex for the LMC stars.

From our results it is clear that adopting a unique gravity for the O dwarfs is an oversimplified assumption. As a consequence, the dispersion found in the SpT $-T_{\rm eff}$ calibrations is to be expected and arises from the degeneracy between $T_{\rm eff}$ and $\log g$ to reproduce a similar He ionization equilibrium (i.e., SpT) for a given star. In this context, we note that there is a *rough*

[2] The slightly wider range in $\log g_{\rm c}$ found in the IACOB sample is due to a few mid O-type stars with $v \sin i$ above 250 km s^{-1}. In these cases both the spectral classification and the spectroscopic analysis is less accurate than for the rest of the sample.

Table 1. Summary of $T_{\rm eff}$ and $\log g$ results for the IACOB and VFTS O-dwarf (V) samples.

SpT	# Stars	$T_{\rm eff}$ [kK]		$\log g_{\rm c}$ [dex]		SpT	# Stars	$T_{\rm eff}$ [kK]		$\log g_{\rm c}$ [dex]	
MW (IACOB)		Mean	Range[1]	Mean	Range	30 Dor (VFTS)		Mean	Range	Mean	Range
O4	2	42.2	1.8	3.82	0.00	O4	3	43.8	2.0	3.89	0.20
O4.5	2	42.1	0.6	3.78	0.11	O4.5	0	–	–	–	–
O5	1	40.4	–	3.84	–	O5	4	41.2	4.7	3.99	0.45
O5.5	0	–	–	–	–	O5.5	1	41.2	–	4.03	–
O6	1	39.4	–	3.81	–	O6	6	40.8	2.1	4.00	0.39
O6.5	4	38.7	1.7	3.79	0.28	O6.5	4	40.0	0.7	4.08	0.14
O7	7	37.0	2.3	3.79	0.52	O7	3	38.4	2.2	4.05	0.24
O7.5	4	36.9	3.5	3.85	0.49	O7.5	0	–	–	–	–
O8	2	34.5	1.4	3.60	0.22	O8	6	37.2	3.8	4.08	0.26
O8.5	4	36.5	3.5	4.05	0.34	O8.5	7	36.9	0.9	4.09	0.31
O9	2	35.5	0.8	4.05	0.31	O9	5	34.7	2.1	4.07	0.38
O9.2	1	34.6	–	4.09	–	O9.2	3	35.2	1.8	4.10	0.12
O9.5	1	34.1	–	3.99	–	O9.5	9	34.5	2.4	4.19	0.21
O9.7	2	33.1	0.6	4.05	0.09	O9.7	2	33.7	0.1	4.14	0.07

Notes. Typical uncertainties in $T_{\rm eff}$ for the VFTS sample are in the range ±0.5−1.5 kK, while the formal errors in $\log g$ range between 0.07 and 0.15 dex (however, systematic errors make 0.10 dex a more reasonable lower limit in $\Delta\log g$, see Sabín-Sanjulián et al. 2014). Typical uncertainties in results for the IACOB sample are on the same order or slightly smaller in some cases. [(1)] Difference between the highest and lowest values.

correlation between the scatter found in $T_{\rm eff}$ and $\log g$, and between the low/high $T_{\rm eff}$ and low/high $\log g$ cases in each bin.

This effect is known and is the reason that the $T_{\rm eff}$ of a supergiant is lower than that of a dwarf with the same SpT. Indeed, it is also the reason why separate SpT – $T_{\rm eff}$ calibrations are normally given for different luminosity classes (e.g., Martins et al. 2005). However, given the wide range of gravities found for stars classified as O dwarfs, the most important insight from Fig. 1 is that assuming a unique (but metallicity-dependent) SpT – $T_{\rm eff}$ calibration for stars of this luminosity class is an oversimplified recipe. Indeed, the situation is even more complex when one also considers the effects that rotation and resolving power produce on the classification of O-type spectra (see Markova et al. 2011).

The location of the two samples in the $T_{\rm eff}$-$\log g$ diagram[3] is shown in Fig. 2 together with evolutionary tracks and isochrones from Brott et al. (2011) for $Z = Z_\odot$ and $\upsilon_{\rm rot,ini} = 220\,{\rm km\,s^{-1}}$ and the position of the zero-age main sequence (ZAMS) for $Z = 0.5\,Z_\odot$ (same physics and $\upsilon_{\rm rot,ini}$). For reference, the blue band indicates the approximate region where O7 V stars are located. As expected from the $T_{\rm eff}$ –$\log g$ degeneracy in reproducing a similar He ionization equilibrium, this band is tilted and not vertical, with a slope of about 750 K per 0.1 dex in $\log g$. The figure also shows the displacement of the ZAMS toward higher $T_{\rm eff}$ and $\log g$ with decreasing metallicity (see Mowlavi et al. 1998, for more details). This effect, combined with the effects of line blanketing (Martins et al. 2002, 2005; Repolust et al. 2004), leads to the SpT – $T_{\rm eff}$ and SpT –$\log g$ calibrations in the LMC to be different to those in the Galaxy. Fig. 1 shows that this is the observed trend when the analyzed samples are statistically meaningful; however, as we indicate in Sect. 4, one must handle this argument with care when dealing with an individual star or when extracting conclusions from the study of small samples.

In Figs. 1 and 2 we also included results for a small number of class IV (subgiant) stars. While the general trend is to find the O IV stars in the lower $T_{\rm eff}$ and lower $\log g$ envelope of the distribution, it is noteworthy that some of them are located in the same region as the O-type dwarfs. In many cases, particularly when the quality of the observations is poor, it can be difficult

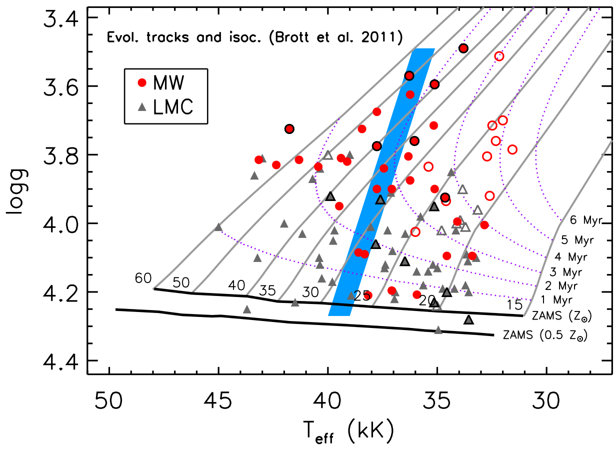

Fig. 2. Galactic and LMC O-dwarf results plotted in the $T_{\rm eff}$–$\log g$ diagram (same symbols as Fig. 1). Evolutionary tracks (solid grey lines, with initial masses as indicated at the ZAMS) and isochrones (dotted purple lines) are from Brott et al. (2011) for solar metallicity; the ZAMS for both $Z = Z_\odot$ and $0.5\,Z_\odot$ are indicated as black lines. The blue region indicates where the O7 V stars are located.

to morphologically separate O IV from O V stars . Moreover, it may also be difficult to distinguish the two classes from the results of the spectroscopic analysis because the estimated gravities for the O IV stars (which are normally concentrated amongst the late-O spectral types) are compatible with the lower end of the $\log g$ distribution found for mid- and early-O dwarfs. Hence, by misclassifying O IV stars as O dwarfs, or if one increases the statistics by combining stars from both luminosity classes, the scatter in the SpT – $T_{\rm eff}$ calibration due to gravity effects would become even larger.

4. Implications

In the following, we provide some important consequences (mainly warnings) implied by our results:

1. Given the significant scatter of $T_{\rm eff}$ associated with each SpT bin, one must be careful when drawing conclusions from the analysis of small samples (either for a given Z or when

[3] From here on, $\log g$ refers to the actual gravity, denoted previously by $\log g_{\rm c}$.

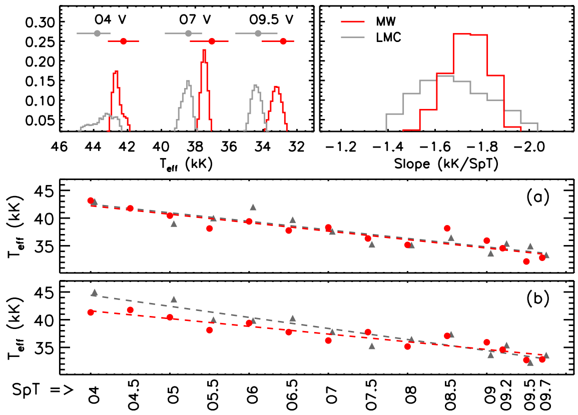

Fig. 3. *Upper panels*: results from a Monte-Carlo simulation where one star is drawn from the Galactic and LMC samples per SpT bin. Probability distributions for the $T_{\rm eff}$ of three representative SpT bins and for the overall slope of the calibration are shown in the *left-* and *right-hand panels*. *Lower two panels*: two possible SpT – $T_{\rm eff}$ relations arising from the simulations (employing the same symbols as in Fig. 1), highlighting the potential consequences of drawing conclusions from small samples.

comparing results across a range of environments). To illustrate this, we present a comparison of results from a Monte-Carlo simulation in Fig. 3 in which a smaller sample (just one star per SpT bin) is drawn from each global sample (including the O IV stars). The upper panels show the probability distributions for the $T_{\rm eff}$ associated with three SpT bins (left panel, in which the means and ranges, including the O IV stars, are also indicated), and for the derived slope of the calibrations (from linear fits to the data). The lower panels show two possible SpT – $T_{\rm eff}$ relations drawn from such simulations in which (a) the same calibrations would be obtained for the two metallicities; (b) a different slope is obtained, in which $\Delta T_{\rm eff} \sim 4000$ K is found for the hottest stars, but where similar temperatures are associated with the late-O stars.

2. We compare in Fig. 1 our linear SpT – $T_{\rm eff}$ calibration for Galactic O dwarfs with the one suggested by Martins et al. (2005, MSH05), which is widely used. Obviously, the agreement is far from being satisfactory in the late-O regime, but the discrepancy can be explained by taking into account (i) gravity and small-number statistics effects and (ii) the fact that MSH05 included a few O3–O3.5 V stars in their linear fit, while Rivero González et al. (2012) have indicated a change in slope at SpT around O4. Thus, the calibration by MSH05 might suggest too low $T_{\rm eff}$ values in the late O-dwarf regime.
3. MSH05 also proposed a characteristic constant gravity of 3.92 dex for all O dwarfs. We showed that this is a dangerous oversimplification. In fact, as we discuss in item 5, any possible attempt to provide a SpT – $\log g$ calibration will critically depend on the age and mass distribution (plus other effects such as the $v \sin i$ of the stars) of the analyzed O-star sample.
4. The broad range in gravities not only affects the $T_{\rm eff}$ associated with an O dwarf for a given SpT, but also the corresponding stellar mass and radius (and consequently other related quantities such as the number of ionizing photons). For example, Fig. 2 shows that a Galactic O7 V star may have a range in (evolutionary) mass of about 10 $M_{\odot}$. From simple calculations, the radius of an O7 V star with $\log g = 3.7$ will be roughly twice that of a star on the ZAMS ($\log g \sim 4.2$). In addition, an O7 V star close to the ZAMS will only emit roughly half as many ionizing photons as the star with a lower gravity. This is counterintuitive because the ZAMS star is hotter (by ~3,500 K), but the combined effect of $T_{\rm eff}$ and radius produces this result. Of course, these numbers are purely for illustration and are based on evolutionary calculations (and estimated for a unique initial $v \sin i$). A more thorough investigation of the scatter in stellar mass, radius, and number of ionizing photons, using actual luminosities derived from absolute magnitudes, is one direction for future work.
5. We highlighted the importance of gravity on the interpretation of the scatter seen in SpT – $T_{\rm eff}$ calibrations for O dwarfs, but our comments can be directly translated into any parameter affecting the evolutionary status (governed by mass, age, initial rotational velocity, mass-loss, etc.) of the individual stars in the considered sample. For example, in a sample drawn from a single-age starburst population, all stars with masses above 15 $M_{\odot}$ will only have the same gravity if it is younger than 1 Myr; as soon as the population evolves, the early-O dwarfs will have lower gravities than the late-O stars (as illustrated by the isochrones presented in Fig. 2). As a consequence, the SpT – $T_{\rm eff}$ calibration that should be employed in these two situations is different (both in terms of absolute values and slope): in general terms, an O dwarf with a given SpT will be hottest when it is on the ZAMS and will cool as it evolves during the following 3–4 Myr, during which time it would still be classified as an O dwarf.

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