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Properties of O dwarf stars in 30 Doradus

Carolina Sabín-Sanjulián[1,2] and the VFTS collaboration

[1]Departamento de Física y Astronomía, Universidad de La Serena, Av. Cisternas 1200 Norte, La Serena, Chile
[2] Instituto de Investigación Multidisciplinar en Ciencia y Tecnología, Universidad de La Serena, Raúl Bitrán 1305, La Serena, Chile
email: cssj@dfuls.cl

Abstract. We perform a quantitative spectroscopic analysis of 105 presumably single O dwarf stars in 30 Doradus, located within the Large Magellanic Cloud. We use mid-to-high resolution multi-epoch optical spectroscopic data obtained within the VLT-FLAMES Tarantula Survey. Stellar and wind parameters are derived by means of the automatic tool IACOB-GBAT, which is based on a large grid of FASTWIND models. We also benefit from the Bayesian tool BONNSAI to estimate evolutionary masses. We provide a spectral calibration for the effective temperature of O dwarf stars in the LMC, deal with the mass discrepancy problem and investigate the wind properties of the sample.

Keywords. Galaxies: Magellanic Clouds Stars: atmospheres Stars: early-type Stars: fundamental parameters

1. Introduction

The VLT-FLAMES Tarantula Survey (VFTS, Evans *et al.* 2011) is an ESO large programme that has obtained mid-to-high resolution multi-epoch optical spectra of hundreds of O-type stars in 30 Doradus, the largest H II region in the Local Group, located in the Large Magellanic Cloud. VFTS was developed aiming at the study of rotation, binarity and wind properties of an unprecedented number of massive stars within the same star-forming region. Within this project, a huge effort has been made in the study of O-type stars, including the analysis of multiplicity (Sana *et al.* 2013), spectral classifications (Walborn *et al.* 2014) and the distribution of rotational velocities (Ramírez-Agudelo *et al.* 2013, 2015). These studies are essential for the estimation of stellar parameters and chemical abundances of the complete O-type sample, which will allow to investigate fundamental questions in stellar and cluster evolution. To date, the quantitative study of the O-type sample is about to be complete (see Sabín-Sanjulián *et al.* 2014, 2017; Ramírez-Agudelo *et al.* 2017), as well as the determination of nitrogen abundances (Grin *et al.* 2017, Simón-Díaz *et al.* 2017.)

In this work, we study the properties of a sample of O stars close to the ZAMS, those with luminosity classes IV and V.

2. Observations and data sample

We have used spectroscopic data obtained by means of the Medusa mode of the FLAMES spectrograph at the VLT (Paranal, Chile). In addition, *I*-band images obtained with the *HST* (GO12499, P. I.: D. J. Lennon) were utilized to evaluate possible contamination in the Medusa fibres.

We have selected a sample of 105 likely single and unevolved O stars based on the multiplicity properties derived by Sana *et al.* (2013) and the spectral classifications by

Walborn *et al.* (2014). Our sample includes O stars with luminosity classes V and IV, as well as Vz, V-III (uncertain classification) and III-IV (interpolation between III and IV).

3. Quantitative spectroscopic analysis

The quantitative analysis of the spectroscopic data for our sample of O dwarfs was performed by means of the IACOB Grid-Based Automatic Tool (IACOB-GBAT, see Simón-Díaz *et al.* 2011, Sabín-Sanjulián *et al.* 2014). IACOB-GBAT is based on a grid of ∼190 000 precomputed FASTWIND stellar atmosphere models (Santolaya-Rey et al. 1997, Puls *et al.* 2005) and a χ^2 algorithm that compares observed and synthetic H and He line profiles.

Absolute magnitudes in the V-band calculated by Maíz-Apellániz *et al.* (2014) and projected rotational velocities by Ramírez-Agudelo *et al.* (2013) were used.

We estimated mean values and uncertainties for effective temperature $T_{\rm eff}$, surface gravity g, helium abundance $Y(He)$, stellar radius R, luminosity L, spectroscopic mass $M_{\rm sp}$ and wind-strength Q-parameter (defined as $Q = \dot{M}(R\,v_\infty)^{-3/2}$, where $\dot{M}$ is the mass-loss rate and v_∞ the wind terminal velocity). Evolutionary masses ($M_{\rm ev}$) were obtained by means of the Bayesian tool BONNSAI (Schneider *et al.* 2014), which used evolutionary models by Brott *et al.* (2011) and Köhler *et al.* (2015).

Most of the stars in our sample showed strong nebular contamination, but only 11 critical cases had to be analyzed using nitrogen lines (HHeN). This diagnostic was also used for 9 cases with too weak or inexistent He I lines. We could only provide upper limits for $\log Q$ for about 70% of the sample due to thin winds. In addition, possible/confirmed contamination in fibre was present in several stars, which could have altered the determination of physical parameters. A few cases were found with too low helium abundances and too high gravities, a possible indication of undetected binarity.

4. Spectral calibration

Figure 1 represents our $T_{\rm eff}$ scale as a function of spectral types. We perform a linear fit to the points excluding O2 stars, since they show indications of undetected binarity and/or contamination in fibre. When comparing with the most recent and complete spectral calibration for O dwarfs in the LMC before this work (Rivero-González *et al.* 2012a,b, who used HHeN diagnostics to analyse optical spectra of 25 stars, including 16 dwarfs), we found that there is an excellent agreement between both scales for spectral types later than O4. In the earliest regime, Rivero-González *et al.* utilized a quadratic fit obtaining hotter temperatures than ours, although the estimates for our O2 stars agree with their calibration. However, we cannot reach a firm conclusion about the necessity of changing the slope in the O2-O4 regime due to the small number of observed stars and their very likely binarity/multiplicity. A larger sample of O-type stars earlier than O4, as well as information on their possible composite nature are necessary.

5. Mass discrepancy

The mass discrepancy problem consists on a lack of agreement between spectroscopic and evolutionary masses. Since its identification by Herrero *et al.* (1992), several explanations have been proposed but it remains unresolved due to the diversity of results in different environments.

We compare our derived spectroscopic and evolutionary masses in Figure 2. We find a certain trend in the distribution: for masses below 20 $M_\odot$, we can only find stars with $M_{\rm ev} > M_{\rm sp}$, i.e., a positive discrepancy, while for higher masses both positive and negative

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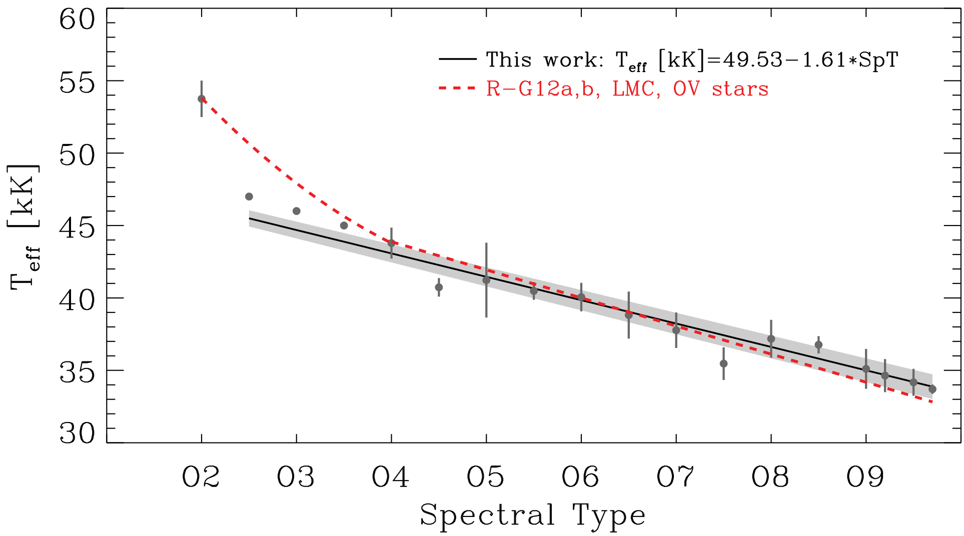

Figure 1. Effective temperature calibration compared to that derived by Rivero-González *et al.* (2012a,b). For each spectral type, the dark grey circles and bars represent the mean value and standard deviation of our $T_{\rm eff}$ estimates. Our linear fit is represented by the black line, and the grey zones indicate the associated uncertainties. O2 stars have been excluded from the fit due to their possible contamination in fibre and/or undetected binarity.

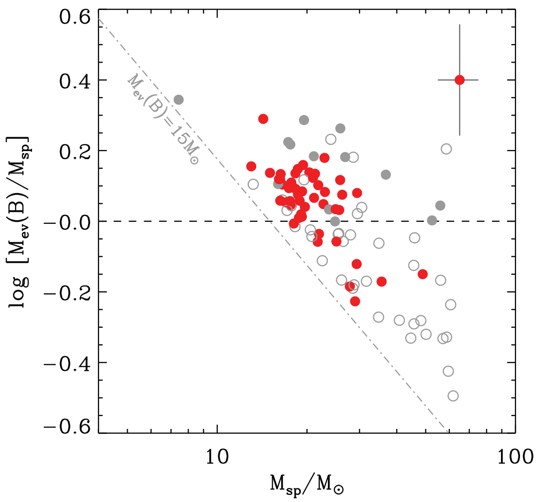

Figure 2. Logarithmic ratio of evolutionary masses from BONNSAI ($M_{\rm ev}(B)$) to spectroscopic masses ($M_{\rm sp}$). Grey filled symbols correspond to stars analyzed with nitrogen lines and no indications of binarity or contamination in fibre. Open symbols are those stars with possible undetected binarity or contamination in fibre. Typical error bars are given in the upper-right corner. The dashed line indicates points where $M_{\rm ev}\,({\rm B}) = 15\,{\rm M}_{\odot}$. O2 stars are excluded.

discrepancies are present. Nevertheless, this trend could be explained by a selection bias in our sample. All the O dwarfs in this work have masses systematically above 15 $M_{\odot}$ (see indication in Fig. 2). As a consequence, all stars with a negative mass discrepancy and masses below 15 $M_{\odot}$ are not present. To investigate this effect and reach a clearer conclusion about the mass discrepancy in the VFTS sample, results from the ongoing quantitative analysis of the early B-dwarfs should be included.

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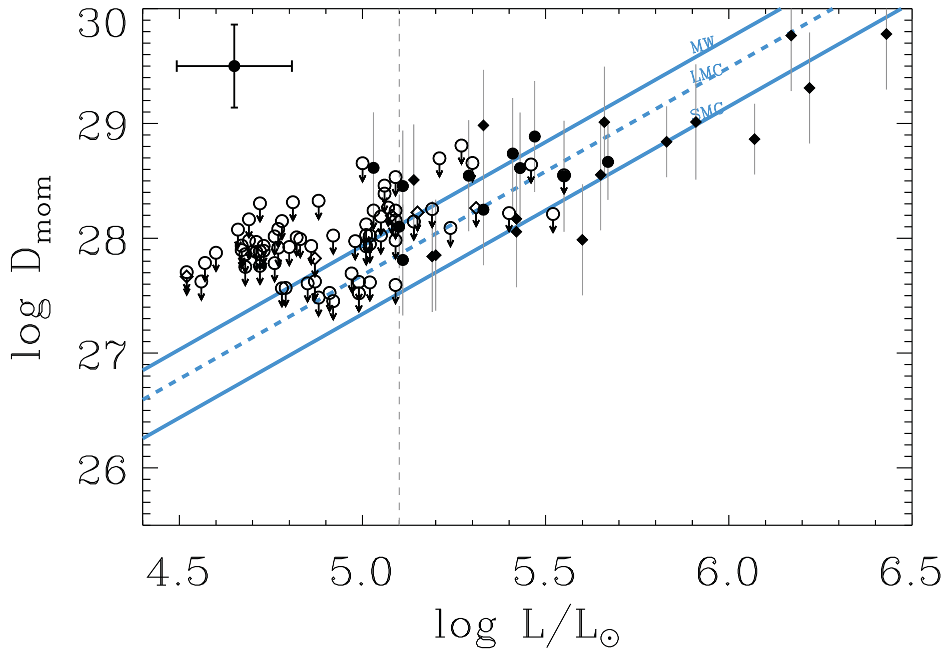

Figure 3. Wind-momentum – Luminosity Relationship (WLR) for our sample compared with theoretical predictions from Vink *et al.* (2001) for the metallicities of the Milky Way and the Magellanic Clouds. Open symbols represent stars with upper limits on $\log Q$ (hence $D_{\rm mom}$). Diamonds correspond to stars analyzed using nitrogen lines. Typical uncertainties are shown in the upper-left corner, and the vertical dashed line indicates $\log L/L_\odot = 5.1$.

6. Wind properties

In this study, we estimated the logarithm of the wind-strength Q-parameter (see Sect. 3) of the sample stars. If terminal velocities were available, $\log Q$ could be used to estimate mass-loss rates. Nevertheless, we lack UV spectroscopic data to derive directly terminal velocities. For this reason, we have followed the approach used by Mokiem *et al.* (2007a,b) to estimate the escape velocity $v_{esc} = 2gR(1-\Gamma)^{1/2}$ and the terminal velocity $v_\infty/v_{esc} = 2.65\,Z^{0.13}$, where Γ is the Eddington factor and Z the metallicity corresponding to the LMC. The wind momentum was calculated via $D_{\rm mom} = \dot{M} v_\infty R^{1/2}$, and is represented in Figure 3 as a function of stellar luminosity. Two different behaviours are present in the distribution:

• At luminosities higher than $\log L/L_\odot \sim 5.1$, winds were constrained for most of the stars. Most of them show consistency with the linear trend predicted by Vink *et al.* (2001) within the error bars. However, a large dispersion is found, showing some stars above the theoretical WLR for Galactic metallicity and some others below the prediction for the SMC. The first case could be explained by unclumped wind models and large uncertainties on the estimated terminal velocities, but no suitable explanation can be found for the second one.

• At luminosities lower than $\log L/L_\odot \sim 5.1$, only upper limits could be given for $\log Q$ and therefore $D_{\rm mom}$. To constrain such thin winds, UV spectroscopy is necessary.

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