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The O stars in the VLT-FLAMES Tarantula Survey

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Abstract. The VLT-FLAMES Tarantula Survey (VFTS) has secured mid-resolution spectra of over 300 O-type stars in the 30 Doradus region of the Large Magellanic Cloud. A homogeneous analysis of such a large sample requires automated techniques, an approach that will also be needed for the upcoming analysis of the Gaia surveys of the Northern and Southern Hemisphere supplementing the Gaia measurements. We point out the importance of Gaia for the study of O stars, summarize the O star science case of VFTS and present a test of the automated modeling technique using synthetically generated data. This method employs a genetic algorithm based optimization technique in combination with FASTWIND model atmospheres. The method is found to be robust and able to recover the main photospheric parameters accurately. Precise wind parameters can be obtained as well, however, as expected, for dwarf stars the rate of acceleration of the flow is poorly constrained.

1. Introduction

It has been estimated that the disk of the Milky Way should contain about 100 open clusters as massive as R136 ($> 10^4 M_{\odot}$) in the 30 Doradus region in the Large Magellanic Cloud [1, 2], some eight of which have been found to date – Westerlund 1 being so far the most massive one

($\sim 5 \times 10^4 M_{\odot}$). Though searches for these massive clusters rely mostly on infrared imaging surveys, the Gaia mission may contribute to the identification of these objects as, for instance, current searches tend to be less sensitive for clusters with rather low stellar densities. Phase space correlations, for which Gaia has been designed, of all objects down to $V = 20$ mag may thus help to identify them.

Of the anticipated number of $\sim 10^4$ O-type stars in our Galaxy, so far only a small fraction has been found, though the census of O- (and early B-type) stars within the first 2.5 kpc is thought to be fairly complete ($\sim 85\%$, [3]). For the nearby O-star population, the main importance of Gaia therefore lies in *i*) the determination of distances accurate to within 1-2 percent; *ii*) the identification of spectroscopic and/or astrometric binary systems, *iii*) potentially the measurement of projected rotational velocities, and *iv*) identifying their cluster membership through phase space correlations. The latter item(s) may, for instance, reveal (spun-up) run-away sources [4]. At larger distances the discovery potential of new O stars and young open clusters will be larger, though *i*) through *iv*) remain fundamental objectives albeit the uncertainties involved will increase. All in all, some 150 000 O and B-type stars are expected in the Gaia sample [5], including peculiar objects such as B[e], Luminous Blue Variable, Of/WN, WNh and evolved Wolf-Rayet stars. The legacy of Gaia for these most massive stars will encompass break-throughs in our understanding of single and binary star evolution, cluster dynamics and evolution and the role of massive stars in the formation and evolution of the Milky Way galaxy.

The wavelength range of 847 to 874 nm covered by the medium-resolution Gaia Radial Velocity Spectrograph (RVS) may help to identify O stars, but is not sufficient to characterize their stellar and stellar wind properties [5, 6]. To achieve this, spectroscopy of the hot stars in the FLAMES/VLT Gaia-ESO Survey for the Southern Hemisphere (Blomme, this Volume) and the potential WEAVE/WHT Gaia-Survey for the Northern Hemisphere [7] will be vitally important. The large number of massive objects targeted in these projects warrants the development of automatic spectral analysis techniques. Here we report on one of the two automated approaches developed in the context of our VLT Large Programmes on massive stars [8, 9]. For a discussion of the second method we refer to Simón-Díaz (this Volume). In particular, we will discuss this method in the context of our on-going spectral census of ~ 800 O and early-B stars in and near the central cluster R136 using the Medusa/FLAMES instruments on the VLT, i.e. our VLT FLAMES Tarantula Survey (VFTS) program.

2. The FLAMES Tarantula Survey science rationale

The VFTS targets over 300 O-type stars, including 20 Of/WN and Wolf-Rayet emission line stars, and over 500 early B-type stars, covering the full luminosity range from dwarfs to bright supergiants. An overview of the project is given in [10]. The observational sample is presented by [9]. Early science results are reported in [11, 12]. An image showing the location of the O stars and Wolf-Rayet stars is presented in Figure 1.

Though a main focus of the project is to address outstanding questions in how massive stars evolve from the early main sequence to their deaths as core-collapse supernovae, the unprecedented sample size also allows to understand massive stars *as a population*. The latter includes the possibility to study evolutionary connections between the morphological sub-groups in the field, integrated cluster properties – important for understanding distant, unresolved star clusters, and cluster dynamics – valuable in the context of cluster formation and evolution. Here we focus on the science related to stellar evolution.

The evolution of massive stars is inextricably connected to the physics of mass loss, rotational mixing, core overshooting and binary interaction. Unfortunately, there are many gaps in our knowledge of these physical processes.

The VFTS permits a thorough investigation into how progression of increasing wind strength

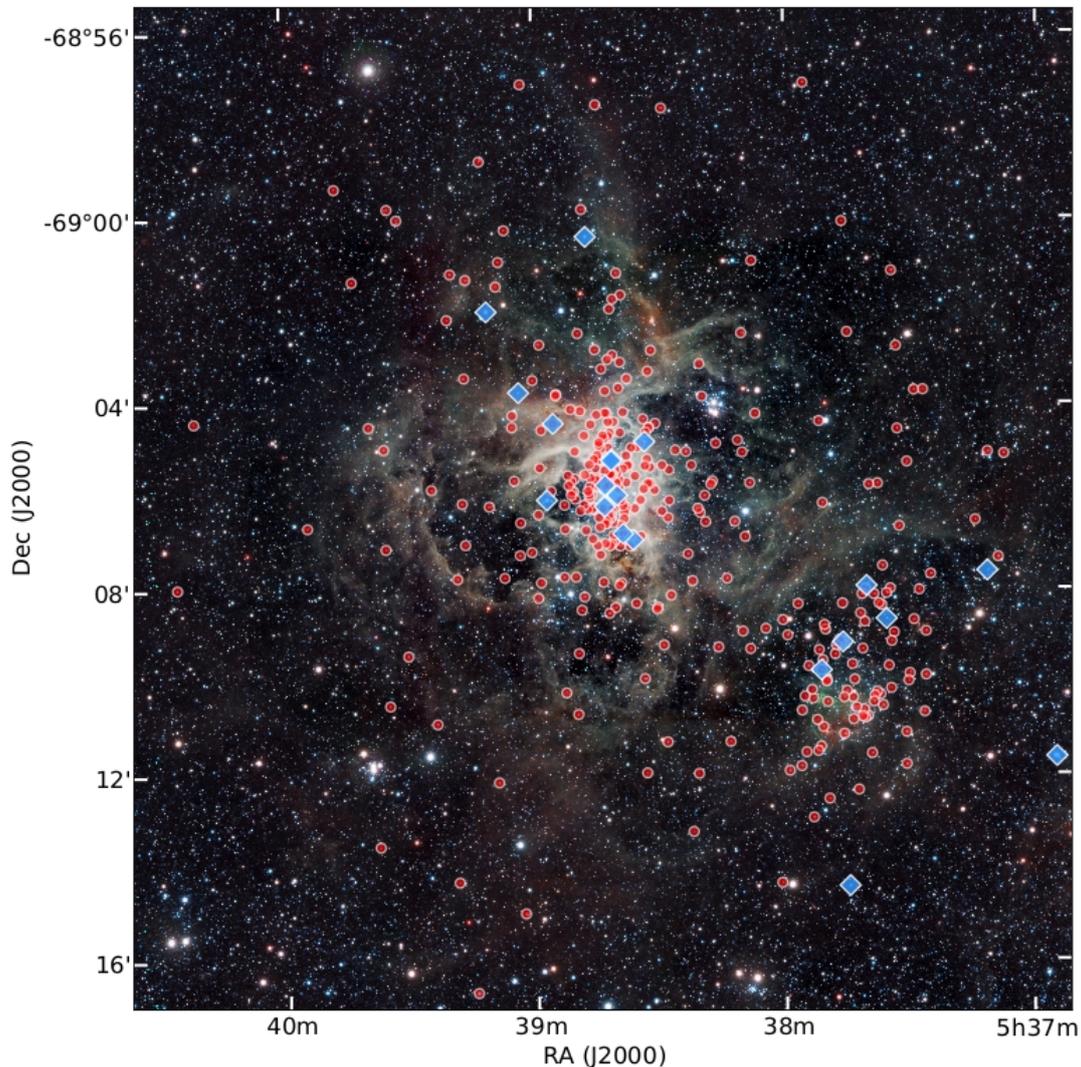


Figure 1. The 30 Doradus region in the Large Magellanic Cloud centered on its young (1–2 Myr; [13]) ionizing cluster R136. Overlaid on a $YJKs$ -band of the VISTA Magellanic Cloud Survey [14] the location of the O-type (red circles) and Wolf-Rayet stars (blue diamonds) observed by the VFTS are shown. From [10] with permission.

from O to Of to Of/WN to WN spectral type may be coupled to stellar evolution. Recent theoretical results [15–17] agree on the dominant role of the Eddington factor Γ for the mass loss properties of the most massive. By determining the mass-loss rates \dot{M} of a sizable number of Of, Of/WN, and WN objects, we aim to establish the empirical relation $\dot{M}(\Gamma)$ in the regime where it is most pronounced and most pivotal for stellar evolution, such that these predictions may be tested.

The first statistically significant test of rotationally-induced mixing in massive stars by [18, 19] showed that only some 60 percent of a sample of apparently single LMC B-type stars concurs with theoretical expectations. Two groups of stars appear in conflict with the predictions: a group of late-MS fast rotators with little mixing, and a group of slow rotators which show up to 0.7 dex increase in the surface nitrogen abundance. The former group may be populated by close

binaries, however, it is highly unlikely that binary effects may explain the second group [20]. The effects of mixing are expected to be more significant in O stars but, to date, abundance analyses have been limited by the models available. New theoretical developments [21] now provide the tools by which we can potentially investigate the effects of stellar rotation at the high-mass end of the Hertzsprung-Russell diagram, and establish whether the O star population also show groups similar to those identified among the B stars.

A long-standing and disquieting problem in massive star evolution is the large number of B supergiants [22, 23]. At present it is unclear what is the nature of these objects, i.e. whether they are core hydrogen or helium burning. A striking difference between O dwarfs and B supergiants is that while the former are the most rapid rotators known, the B supergiants rotate much more slowly ($v_R \sin i \lesssim 50 \text{ km s}^{-1}$). This has been ascribed to the expansion of the star after leaving the main sequence. [18, 24] showed that the preference for slow rotation occurs at gravities $g \lesssim 10^{3.2} \text{ cm s}^{-2}$ and suggested the B supergiants to be post main-sequence. [20] subsequently used this empirical finding to constrain the core overshooting in massive star models, that sensitively controls the position of the cool edge of the main-sequence band. [25] proposed an alternative explanation for the difference between the rotational properties of O V and B I stars, at least for stars initially more massive than $\sim 15 - 20 M_\odot$, suggesting this behavior to be related to a very substantial increase in the mass-loss rate once stars evolve to past spectral type B1 ([26]). If the overshooting is large enough for this to occur on the main-sequence, it may be the enhanced loss of angular momentum associated with the high mass loss that may spin the stars down. The Tarantula Survey aims to investigate the nature of B supergiants.

One of the key ingredients missing from current theories of both star formation and cluster evolution is an empirical relation for the binary fraction of massive stars [27], and the distribution of the mass ratios and periods of these systems (but see [28] for recent progress). The Tarantula Survey was therefore conceived as a multi-epoch program, with the aim of obtaining clear indications of binarity in the large majority of the targets. This adds a valuable parameter to the subsequent quantitative analysis and interpretation, enabling tests of the predictions of both single-star and binary evolution models that include all the relevant physical processes ([29]). This will provide important insights in our efforts to disentangle the roles of rotation and binarity for the first time, and to draw conclusions for the evolutionary end-points of O stars, including long-duration gamma-ray bursts and magnetars.

3. Spectral analysis by means of a genetic algorithm

VFTS observations were primarily done using the Medusa fibre-feed to the Giraffe spectrograph, yielding a spectral resolving power $R \sim 7000$ and 8500 in the LR02 (for a total of 6 epochs) and LR03 (3 epochs) settings. The region containing $\text{H}\alpha$ was observed in the HR15N setting (2 epochs), providing $R \sim 15000$. For five pointings of R136 and its direct surroundings the ARGUS integral field unit + Giraffe was used ($R \sim 10500$). In parallel to the ARGUS observations, red-arm UVES spectra were taken of a small sample of stars in the inner part of 30 Dor ($R \sim 53000$). This yields a grand total of 22000 spectra with typical signal-to-noise ratios of 70 – 100, reaching 500 for the brightest targets.

Here we discuss the spectral analysis technique of the O stars for which model atmospheres accounting for the outflow of gas are required. To assure a homogeneous approach capable of dealing with large samples, we build on the automatic fitting method developed by [30], based on a genetic algorithm (GA) utilizing the optimization routine PIKAIA by [31] and employing the stellar atmosphere code FASTWIND by [32, 33]. FASTWIND solves the radiative transfer equations for a medium in which the state of the gas is described by statistical equilibrium, subject to the constraint of radiative equilibrium. A radial stellar wind is assumed to stream out from the photosphere with a prescribed velocity structure $v(r) = v_\infty (1 - b \times r_\odot/r)^\beta$, where b is chosen such that at r_\odot the flow has a prescribed minimum velocity $v(r_\odot) = v_\circ$. The maximum or terminal

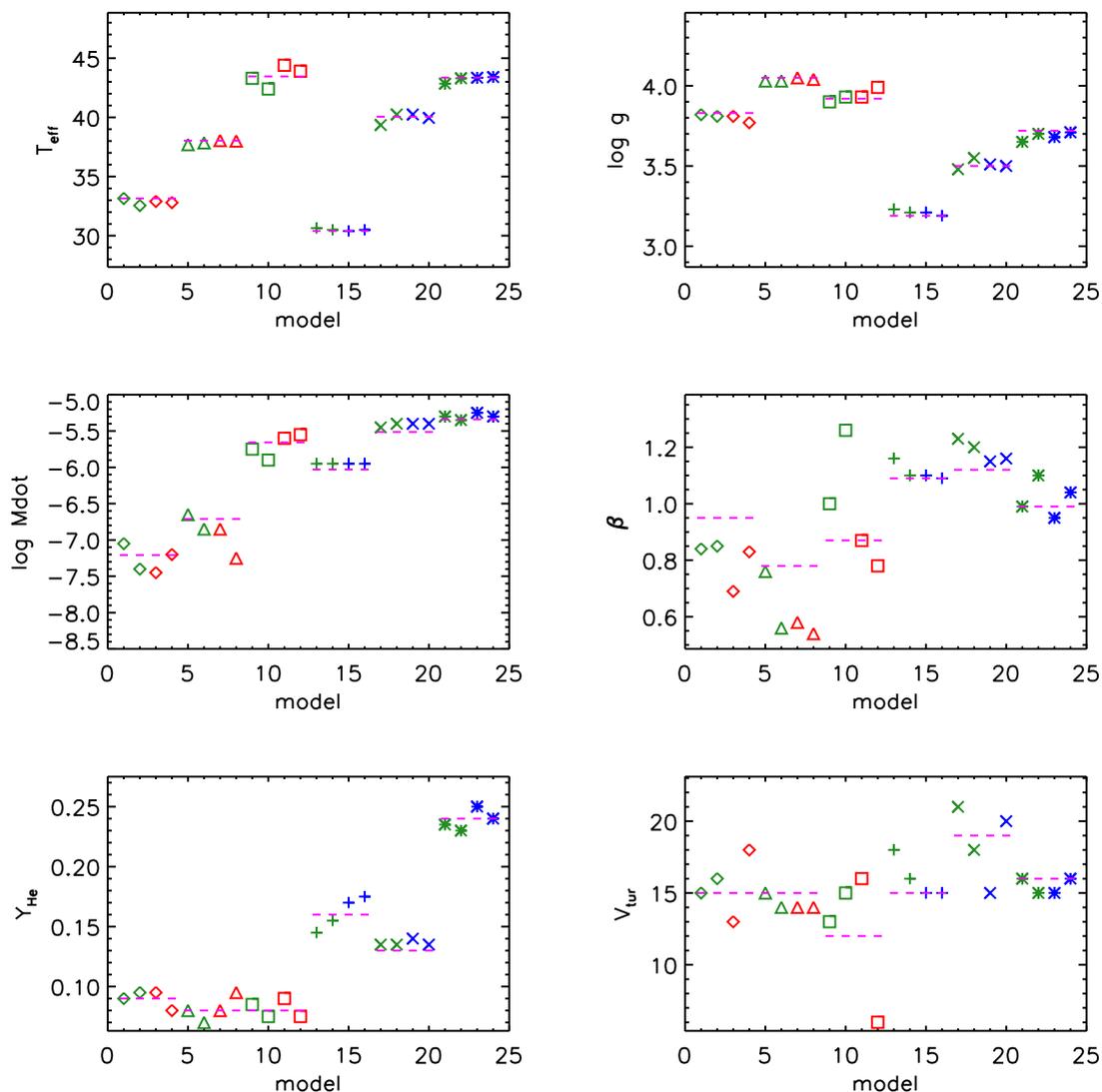


Figure 2. A comparison of the best fit results of the GA fitting method with simulated observations. The horizontal axis provides the model number with the first 12 models representing main sequence (MS) stars and the last 12 models supergiant (SG) stars. The meaning of the symbols is as follows: early-MS (\square); mid-MS (\triangle); late-MS (\diamond); early-SG (X); late-SG ($+$) and helium rich, high mass-loss SG ($*$). The magenta horizontal dashes indicate the correct model parameters. The fitting of the wind acceleration β is, as expected, poor for the mid- and late-MS stars. The mass-loss determinations for these objects suffer from this.

outflow velocity is v_{∞} and β describes the rate of acceleration of the outflow.

In the setup discussed here the method is used to constrain the effective temperature T_{eff} , gravity g , luminosity L , number fraction of helium over hydrogen Y_{He} , mean photospheric micro-turbulent velocity ξ_{micro} , mass-loss rate \dot{M} and measure of the rate of acceleration of the outflow β . Additional parameters can be added to the GA-method. These include the rotational velocity, radial velocity, photospheric macro-turbulent velocity and terminal flow velocity of the stellar

Table 1. The mean shift and mean dispersion of the fitting results (Fit) relative to the synthetic data (Syn), using all 24 test cases. The * superscript denotes values that are based on supergiant models only.

Parameter	Unit	<Fit–Syn>	Dispersion
T_{eff}	[kK]	–0.09	0.40
$\log g$	[cm s ^{–2}]	0.00	0.03
$\log \dot{M}^*$	[\dot{M} yr ^{–1}]	0.05	0.09
β^*		0.04	0.05
Y		0.00	0.01
ξ_{micro}	[km s ^{–1}]	0.0	2.2

wind. So far, no elements other than hydrogen and helium have been considered, however, we plan to include nitrogen for the analyses of VFTS objects building on the theoretical groundwork by [21].

To test our method we have performed a GA-analysis on a set of simulated stellar spectra. These have been computed using FASTWIND spectra broadened with a range of rotational velocities and degraded to the spectral resolution and typical S/N of our observations. Before we discuss the results it should be pointed out that in several respects this is an idealized test yielding error-bars that should be viewed as lower limits. First, the spectra were normalized to the actual continuum. This essentially implies that the stellar radius is known. Second, the models do not account for macro-turbulent broadening of the lines. Compared to rotational broadening this effect is usually negligible in O (and B) dwarfs but is typically substantial in supergiants [34], though see [35, 36]. Third, the rotational broadening is assumed to be known. This mimics the approach that will be taken in the VFTS analysis, as $v_{\text{rot}} \sin i$ values will be determined separately using techniques described by [34]. Fourth, the terminal velocity of the flow is adopted. Fifth, radial velocity shifts are non-existent. Sixth, the test implies that collisional broadening profiles are ‘known’. Seventh, the simulated spectra do not suffer from nebular contamination. Eighth, the stars are ‘known to be single’.

Figure 2 shows an overview of the results of the test. In six panels we compare the best fit parameters with their true values. The luminosity has been excluded from the comparison as constraining this parameter only requires to perform an absolute scaling of the spectra, using information on a photometric magnitude (for instance V or K) and interstellar extinction properties. The correct model parameters have been indicated using (magenta) horizontal dashed lines. Colors indicate different projected rotational velocities: $v_{\text{R}} \sin i = 50$ (blue), 100 (green) and 300 (red) km s^{–1}. The horizontal axis provides the model number of each of the 24 test models. Models 1–12 represent dwarf stars while 13–24 are supergiants. Different symbols denote early- (\square), mid- (\triangle) and late- (\diamond) O dwarfs; early- (X) and late- ($+$) O supergiants, and helium enriched, high mass-loss O supergiants (*).

The mean shift and mean dispersion of the fitting results relative to the actual values are given in Table 1. One can immediately conclude that the fitting method does not suffer from systematic sources of uncertainty and that the synthetic spectra are fitted (very) accurately. Several aspects of Figure 2, however, warrant discussion. The mass-loss rates are rather poorly constrained for late- and mid-O dwarfs and β for all O dwarfs. To constrain β one needs knowledge of how rapid the flow is accelerating, therefore one can only determine robust values for winds that are somewhat substantive. For supergiants relative to dwarfs the photospheric scale height is larger, implying the build-up of line optical depth starts further out in the flow.

For this reason, the β values of supergiant models for $\dot{M} \sim 10^{-6} M_{\odot} \text{yr}^{-1}$ can be constrained, while this is not the case for the dwarf models with similar mass loss. A mitigation strategy here is to adopt theoretical predictions of β for O dwarfs, for instance by [37]. These predictions seem relatively secure, therefore they will likely help to reduce the uncertainty in the mass-loss rates of mid- and late-O dwarfs.

The helium abundances are well reproduced. For the late-O supergiants (+ symbols), which have weak He II lines, the helium abundance appears to anti-correlate with ξ_{micro} . Though the uncertainties in the determination of the micro-turbulent velocity are quite modest in this test, fitting of this parameter in the real data is expected to result in substantially larger errorbars. This may have a negative effect on the error in Y of late supergiants.

4. Conclusions

We have presented a test of our automated genetic algorithm based fitting technique of O stars using synthetic observations. This method is one of two that is to be applied to analyze the spectra of ~ 300 O stars secured within the context of the VFTS project. An automated techniques is a prerequisite for the analysis of such a large dataset, to be surpassed even by the sub-set of O and early-B stars expected in the FLAMES/VLT and WEAVE/WHT surveys planned to support the Gaia observations themselves. The results are extremely promising, yielding only small error bars and no systematic offsets. The rate of acceleration of the outflow could not be measured accurately for mid- and late-O stars. This is expected when using optical spectra only, but can be remedied by adopting theoretical predictions.

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