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A VLT/UVES spectroscopy study of O2 stars in the LMC

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Abstract: We have analysed VLT/UVES spectra of six O2 stars within the Large Magellanic Cloud using the non-LTE atmospheric code CMFGEN. A range of physical properties was determined by employing a temperature calibration based upon N IV-N V diagnostics. Wind properties were also obtained from the Hα line, while CNO surface abundances were supplied through various diagnostics. Our results reveal effective temperatures in excess of $T_{\rm eff}$ ∼50 kK in all cases. We also addressed their evolutionary status and favour a mass dependent division. For lower masses $\leq$100 $M_\odot$, an O2 star follows the classical sequence, evolving from dwarf on to giant, through to supergiant. At higher masses, the dwarf phase may be circumvented and instead O2 stars begin their lives as giants or supergiants, evolving to the H-rich WN stage within ∼1.5 Myr.

1 Introduction

The O2 spectral type was introduced by Walborn et al. (2002). It was defined by the very weak/absent He I and N III lines and presented higher excitation via prominent N IV and N V lines. Their appearance suggests O2 stars have the highest effective temperatures of main-sequence stars. Temperature calibration of later O-star subtypes has always relied on the analysis of the helium lines, typically the ratio between He IIλ4541/He Iλ4471 (Gray & Corbally 2009). This becomes increasingly difficult for early O-stars due to the weakness of the He I line. Massey et al. (2005) studied seven O2 stars via this technique but concluded there was little benefit from the O2 type extension as the $T_{\rm eff}$ for O2-3.5 spectral types showed no strong correlation. Furthermore, they measured the equivalent width ratios of the N III/N IV and He I/He II lines but found neither to show a strong correlation with $T_{\rm eff}$. Mokiem et al. (2007) also studied 28 O-type and early B-type stars in the LMC, including two O2 dwarfs and two giants. They also employed the He lines diagnostic and, in contrast, found the O2 stars to be the hottest of their sample. However, due to the very weak He I line, uncertainties in $T_{\rm eff}$ were much larger (∼ 10%) than the remainder of their sample (∼ 3%). The need to refine the $T_{\rm eff}$ scale of O2 stars is evident and in turn, we establish more reliable stellar properties for this early subtype.

Ideally, one would seek to use the more prominent N IV and N V lines as a temperature diagnostic. However, they can be particularly difficult to model in comparison to hydrogen and helium lines given the much more complex atomic physics required. Nevertheless, developments to the latest stellar atmosphere codes such as CMFGEN and FASTWIND, have now made this approach possible and we applied the former code to six O2 stars in the LMC. Two of these stars were in common with the Walborn et al. (2004) study where updated parameters are used. A selection of luminosity classes was chosen as indicated in Table 1. Subsequently, we used the derived stellar properties to obtain masses and ages, and identify any evolutionary sequences within the O2 subclass, as well as a possible link to the H-rich WN stars studied by Crowther et al. (2010).

2 Observations and Analysis

Spectral analysis was carried out on VLT/Ultraviolet and Visual Echelle Spectrograph (UVES) observations of six O2 stars. Data sets covered wavelengths 3300-10250 Å, at a resolving power of about 40,000 with the exception of Mk 42 and HDE 269810 which only spanned 3300-6650 Å. These were supplemented by UV spectra obtained from different instruments including HST/GHRS, FOS and STIS. Photometric data in the UBV bands were taken from Massey (2002) and Walborn et al. (2002), and the 2MASS All Sky Catalog for the JHK bands. Mk 42 was an exception to this, due to its location in the crowded 30 Dor region, for which higher spatial resolution VLT/MAD photometry from Campbell et al. (2010) was adopted.

The physical properties were derived using the CMFGEN atmospheric modelling code (Hillier & Miller 1998). This solves the radiative transfer equation in the co-moving frame, under the constraint of statistical equilibrium. The temperature structure follows from the assumption of radiative equilibrium. Our detailed approach closely mimics that set out by Evans et al. (2010a) except that a clumped wind model was applied for the two supergiants, using a volume filling factor, f, as described by Hillier et al. (2003), for which we select f=0.1. Effective temperatures were calculated in all cases from the N IV λ4058 and N V $\lambda\lambda$4604-4620 lines. Since the nitrogen abundance of each star was unknown, this was simultaneously derived.

Stellar luminosities were estimated by adopting an LMC distance of 49±4 kpc (distance modulus = 18.45±0.18 mag). The photometric data sets were then reproduced by varying amounts of extinction that accounted for foreground Galactic and LMC dust. Furthermore, Mk 42 featured an additional term allowing for the extinction within 30 Dor. These extinction values and absolute magnitudes, derived for the K-band, are given in Table 1. In this provisional study, the UV spectra did not serve as diagnostics but allowed a consistency check with optical results. The broad wings of the He II λ4686 line were overestimated in the supergiants but theoretical models showed good agreement with the supplementary UV spectra. However, for the giants and dwarfs, the C IV λ1550 line was predicted too strong and the O V λ1371 line was underestimated. Current surface abundances for H, He, C, N and O were also estimated through various optical diagnostics. Only the supergiants showed signs of depleted H abundance and in turn indicated N enrichment as high as $N/N_{\rm ISM} \sim 35$ in the case of Mk 42.

3 Results

Effective temperatures of $T_{\rm eff} \gtrsim 50$ kK were obtained in all cases, together with high luminosities, $10^{5.8-6.6}\,L_{\odot}$. The giants presented the highest $T_{\rm eff}$, with the dwarfs and then supergiants being progressively cooler. This can be seen in Figure 1, which plots the positions of the stars on a Hertzsprung-Russell diagram. The two supergiants, in particular, showed quite different physical properties. Stellar mass-loss rates were compared with those predicted by Vink, de Koter & Lamers (2001), using masses we derived from evolutionary models. Empirical mass-loss rates exceeded predictions in all cases (up to a factor of 3) although modest wind clumping for dwarfs and giants would reduce this discrepancy.

Table 1: Spectral types of our O2 stars taken from Walborn et al. (2004) and Massey et al. (2005). An updated classification scheme (Walborn & Crowther, in prep.) was favoured for Mk 42 and Sk -67 22. V and K-band photometry together with interstellar extinctions and absolute magnitudes in K-band, assuming distance modulus 18.45±0.18 mag (49±4 kpc)

Star	Spectral Type	m_V (mag)	m_K (mag)	A_K (mag)	M_K (mag)
BI 237	O2 V((f*))	13.89	14.04±0.07	0.08±0.04	-4.49±0.19
BI 253	O2 V((f*))	13.76	13.68±0.05	0.09±0.04	-4.86±0.20
HDE 269810	O2 III(f*)	12.28	12.88±0.04	0.04±0.04	-5.61±0.19
LH 10-3061	ON2 III(f*)	13.68	13.52±0.05	0.12±0.04	-5.05±0.20
Mk 42	O2 If*	12.71	12.19±0.08	0.12±0.04	-6.38±0.20
Sk -67 22	O2 If*/WN 5	13.44	13.78±0.06	0.05±0.04	-4.73±0.19

Our nitrogen-derived results are consistent with the work by Mokiem et al. (2007) who also studied BI 237 and BI 253, based on their H and He lines. Massey et al. (2005) also studied these two stars, along with Sk -67 22 but in some cases could only set a lower temperature limit owing to the weakness of the He I λ4471 line. By utilising the N IV and N V lines, our results did not suffer from such ambiguity. Table 2 compares the various temperature estimates from previous studies with the present sample of O2 stars.

Table 2: Comparison of past studies on O2 star sample with respect to this work. Differences in analysis techniques along with resulting effective temperatures are given.

		Puls et al. (96)	Massey et al. (05)	Mokiem et al. (07)	This Work
Spectral Observations Atmospheric Code Temperature Diagnostic		ESO/Caspec Various H/He	CTIO/RC Spec FASTWIND He I/He II	VLT/UVES FASTWIND He I/He II	VLT/UVES CMFGEN N IV/N V
Star	Spectral Type	T_{eff} (kK)			
BI 237	O2 V((f*))	–	48	53.2	52.1
BI 253	O2 V((f*))	–	>48	53.8	52.8
HDE 269810	O2 III(f*)	60	–	–	54.3
LH 10-3061	ON2 III(f*)	–	–	–	54.7
Mk 42	O2 If*	50.5	–	–	49.8
Sk -67 22	O2 If*/WN 5	–	>42	–	49.3

In an attempt to establish ages, masses and a possible evolutionary sequence for O2 stars, their properties were compared to the latest main-sequence rotating and non-rotating evolutionary tracks of the Geneva group (R. Hirschi, private communication). These were based on the models from Hirschi, Meynet & Maeder (2004) at LMC metallicity (0.4 $Z_\odot$) and ranged from 60-200$M_\odot$. They used theoretical mass-loss rates from Vink, de Koter & Lamers (2001) during the main sequence phase and an initial to critical (maximum) rotational velocity ratio of v_{init}/v_{crit}=0.4 for the rotating case. Comparisons to our derived parameters, including predicted H and CNO abundances, favoured the rotating models in all cases. Figure 1 overlays these main-sequence evolutionary tracks on the H-R diagram.

The two dwarfs showed very little enhancement in N and within the uncertainties of our parameters, closely matched the zero-age main-sequence (ZAMS) predictions. Masses of $75\,M_{\odot}$ and $85\,M_{\odot}$ for BI 237 and BI 253, respectively, were in agreement with the typical mass ($<100\,M_{\odot}$) of O2 dwarfs found by Walborn et al. (2002). The giants had more enhanced N, especially LH 10-3061 and although both lay close to the ZAMS, we favoured a more evolved status for LH 10-3061. We therefore estimated HDE 269810 as a young $M_{\rm init}\sim150\,M_{\odot}$ giant, no older than 1 Myr, while LH 10-3061 is a less massive and more evolved giant of $M_{\rm init}\sim75\text{-}80\,M_{\odot}$ at an age of 2.5 Myr. For the two supergiants Mk 42 is $\sim$5 times more luminous than Sk -67 22. This supported a very high mass of $M_{\rm init}\sim180\,M_{\odot}$ for Mk 42, allowing it to achieve its greatly enriched nitrogen surface abundance through mixing at a relatively young age of $\sim$1.5 Myr. Meanwhile Sk -67 22 represented a star of much lower mass, $M_{\rm init}\sim60\,M_{\odot}$, at a later age, of at least 2.5 Myr.

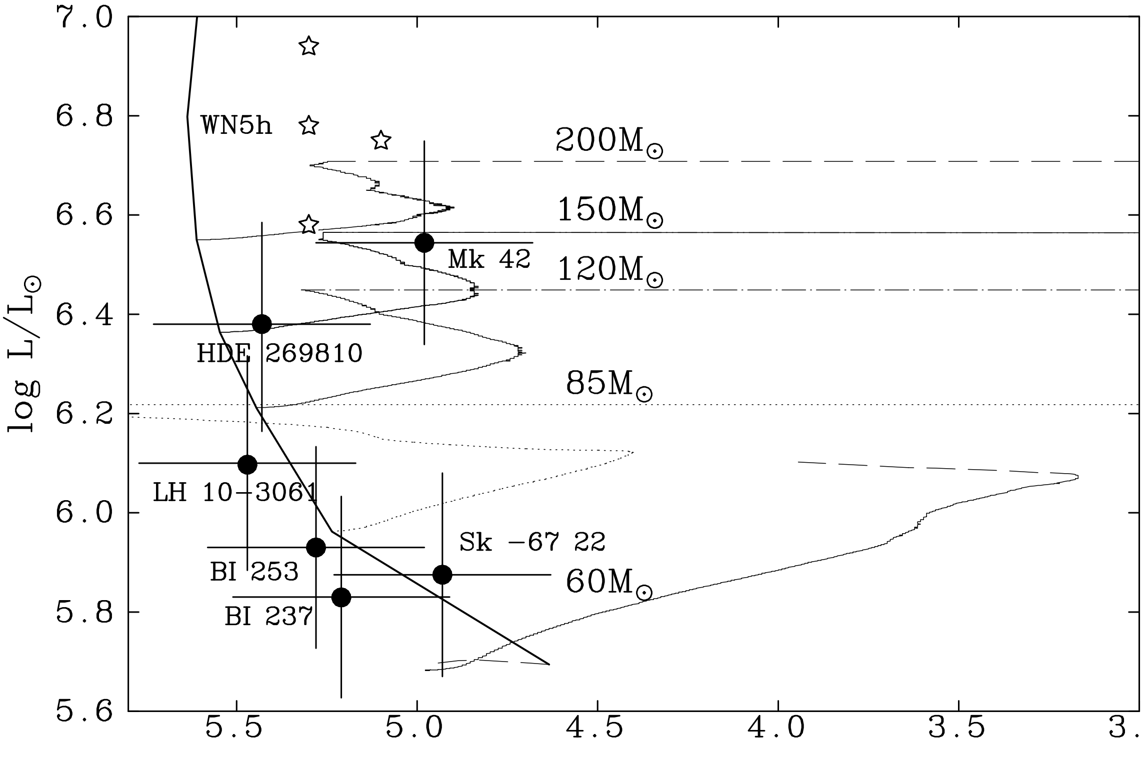

Figure 1: H-R diagram of O2 stars (filled circles) overlaid on Geneva evolutionary rotating models $60\,M_{\odot}$ (dashed-solid), $85\,M_{\odot}$ (dotted), $120\,M_{\odot}$ (dot-dashed), $150\,M_{\odot}$ (solid) and $200\,M_{\odot}$ (dashed). The thick solid line represents the ZAMS. R136 WN5h stars from Crowther et al. (2010) have also been included (hollow stars).

In summary, the O2 stars we have analysed all showed some of the highest known effective temperatures for main-sequence stars, ($T_{\rm eff} \gtrsim 50$ kK), determined using the N IV and N V lines. A typical evolutionary sequence could be followed for O2 stars with $M<100\,M_{\odot}$ starting from dwarfs such as BI 253, passing through a giant phase like LH 10-3061 and ending up as as supergiant in a similar mass regime to Sk -67 22. The high luminosities of stars with $M\gg100\,M_{\odot}$ naturally produce strong winds at the outset so we favour an O2 giant ZAMS stage for very high mass stars (eg. HDE 269810), rapidly followed by a supergiant stage (eg. Mk 42). These are likely precursors to massive H-rich WN stars studied by Crowther et al. (2010) at the core of the NGC 3603 and R136 clusters.

The parameters presented here are currently only initial values, having only been based on our analysis of the optical spectra. Our aim is to extend the modelling into the UV domain, thereby extending available diagnostics. Future targets, including W-R stars, from the FLAMES Tarantula Survey (Evans et al. 2010b) will help enhance our study of the earliest O-stars and allow better constraints to be placed on the evolutionary sequence of the most massive stars.

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References

Campbell, M.A., Evans, C.J., Mackey, A.D., Gieles, M., Alves, J., Ascenso, J., Bastian, N., Longmore, A.J., 2010, MNRAS, 405, 421
Crowther, P.A., Schnurr, O., Hirschi, R., Yusof, N., Parker, R.J., Goodwin, S.P., Kassim, H.A., 2010, MNRAS, 408, 731
Evans, C.J., Walborn, N.R., Crowther, P.A., et al., 2010a, ApJ, 715, L74
Evans, C.J., Bastian, N., Beletsky, Y., et al., 2010b, IAUS, 266, 35
Gray, R.O., & Corbally, C.J., 2009, Stellar Spectral Classification, Princeton University Press
Hillier, D.J., Lanz, T., Heap, S.R., Hubeny, I., Smith, L.J., Evans, C.J., Lennon, D.J., Bouret, J.C., 2003 ApJ, 588, 1039
Hillier, D.J., & Miller, D.L., 1998, ApJ, 496, 407
Hirschi, R., Meynet, G., Maeder, A., 2004, A&A, 425, 649
Massey, P., 2002, ApJS, 141, 81
Massey, P., Puls, J., Pauldrach, A.W.A., Bresolin, F., Kudritzki, R.P., Simon, T., 2005, ApJ, 627, 477
Mokiem, M.R., de Koter, A., Evans, C.J., et al., 2007, A&A, 465, 1003
Puls, J., Kudritzki, R.-P., Herrero, A., et al., 1996, A&A, 305, 171
Vink, J.S., de Koter, A., Lamers, H.J.G.L.M., 2001, A&A, 369, 574
Walborn, N.R., Howarth, I.D., Lennon, D.J., et al., 2002, AJ, 123, 2754
Walborn, N.R., Morrell, N.I., Howarth, I.D., Crowther, P.A., Lennon, D.J., Massey, P., Arias, J.I., 2004, ApJ, 608, 1028