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Properties of massive stars in four clusters of the VVV survey☆

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HIGHLIGHTS

- We present an analysis of massive stars in four of VVV clusters.
- Determination of stellar parameters and surface abundances of the stars.
- Confirmation that WC are more evolved than WN which are more evolved than O stars.

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ABSTRACT

The evolution of massive stars is only partly understood. Observational constraints can be obtained from the study of massive stars located in young massive clusters. The ESO Public Survey "VISTA Variables in the Vía Láctea (VVV)" discovered several new clusters hosting massive stars. We present an analysis of massive stars in four of these new clusters. Our aim is to provide constraints on stellar evolution and to better understand the relation between different types of massive stars. We use the radiative transfer code CMFGEN to analyse K-band spectra of twelve stars with spectral types ranging from O and B to WN and WC. We derive the stellar parameters of all targets as well as surface abundances for a subset of them. In the Hertzsprung–Russell diagram, the Wolf–Rayet stars are more luminous or hotter than the O stars. From the log(C/N)–log(C/He) diagram, we show quantitatively that WN stars are more chemically evolved than O stars, WC stars being more evolved than WN stars. Mass loss rates among Wolf–Rayet stars are a factor of 10 larger than for O stars, in agreement with previous findings.

1. Introduction

Through their powerful stellar winds, their strong UV radiation field and their violent end of life as supernova explosion, massive stars play a key role in the ecology and in the structure of the galaxies. They are major agents of galactic chemical enrichment and they give birth to new generations of stars by triggering star formation through their feedback effects (Deharveng et al., 2005).

Nevertheless, even-though their global evolution scheme as a function of initial mass is known (e.g. Crowther, 2007), the details are not well understood. At solar metallicity O-type stars with an initial mass above 40–60 $M_\odot$ evolve into H-rich WN stars, and Luminous Blue Variables (LBV), before turning into H-poor WN stars and finally WC stars (Crowther, 2007). For O-type stars with lower initial masses, the H-rich WN and LBV phases are replaced by a blue and a red supergiant phase, respectively. But the detailed evolutionary path of a star born with a given mass is not accurately determined. Indeed, numerous physical effects (rotation, mass loss rate, magnetic field, binarity) strongly impact the internal structure of massive stars and thus their evolution. Evolutionary calculations allow to study these effects and predict the life and death of massive stars. But such calculations rely on various assumptions (e.g. Martins and Palacios, 2013).

In this context, the study of young massive clusters containing WR stars is a key to understand the detailed evolution of massive stars. Indeed, if one assumes coeval star formation in massive clusters, the comparison of evolved and main sequence stars allow us to constrain the nature of the most massive and evolved objects (their mass being higher than main sequence objects still present in the cluster, since more massive stars live shorter). For instance Martins et al. (2007)

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Table 1
Position, photometry and spectral parameters of the spectroscopic targets.

ID	R.A. (J2000)	Dec (J2000)	J	H	K_s	Sp. typ.	MK
VVV CL009 (*d*= 5 ± 1 *kpc*)							
5	11:56:03.07	−63:18:54.63	11.87	11.31	11.04	O8-9V	−3.08
6	11:56:03.78	−63:18:54.44	10.55	9.93	9.65	OIf/WN7	−4.51
8	11:56:04.38	−63:18:54.44	12.14	11.59	11.34	O8-9V	−2.76
VVV CL073 (*d*= 4 ± 1 kpc)							
2	16:30:23.73	−48:13:04.90	15.40	12.51	11.08	O4-6If+/WN9	−4.65
4	16:30:23.98	−48:13:05.48	14.71	11.53	9.92	WN7	−6.09
VVV CL074 (*d*= 6 ± 1 kpc)							
1	16:32:05.24	−47:49:29.13	16.40	13.53	12.09	O8.5I	−4.51
3	16:32:05.46	−47:49:28.10	14.72	11.82	10.17	WN8	−6.58
5	16:32:05.49	−47:49:29.80	15.64	12.90	11.54	O8.5I	−4.94
7	16:32:05.67	−47:49:30.00	15.98	13.46	12.19	O8.5I	−4.10
9	16:32:05.93	−47:49:30.92	15.22	12.53	11.31	O4-6If+	−5.05
VVV CL099 (*d*= 4 ± 1 *kpc*)							
5	17:14:25.42	−38:09:50.40	13.43	11.70	10.64	WN6	−4.17
7	17:14:25.66	−38:09:53.72	11.67	10.06	9.26	WC8	−5.32

Columns include star's name, position (R.A. and Dec), J, H and K_s photometry, $E(J-K)$ and $E(H-K)$ colour excesses, extinction (A_K) from Chené et al. (2013). Spectral types have been refined compared to Chené et al. (2013).

showed that in the central cluster of the Galaxy, direct connections between O-type and WR stars could be established. More important, the identification of main sequence O-type stars is a crucial piece of information: it shows the position of the turn-off of the entire population, providing constraints on the age (e.g. Paumard et al., 2006) and consequently an upper limit on the main sequence life time of the WR's progenitors. The presence of red supergiants and WR star(s) in the same cluster constraint the link between hot and cool massive stars, and the evolutionary sequence between red supergiants and WR stars – Westerlund 1 (Clark et al., 2005) and central cluster (Paumard et al., 2014).

Because they are rare, far away and thus located behind lots of dust, young massive clusters cannot be observed at UV and optical bands where extinction is too strong. The infrared (IR) VISTA Variables in the Vía Láctea (VVV) survey (Minniti et al., 2010; Saito et al., 2012) provides hundreds of embedded clusters near-infrared photometry of tens of embedded clusters (Borissova et al., 2011; 2014a; Solin et al., 2014; Barbá et al., 2015). Borissova et al. (2011) discovered 96 new open clusters and stellar groups in the Galactic disk area. In this sample, six heavily-obscured clusters contain at least one WR star together with several main sequence OB stars (Chené et al., 2013). Although the census of the clusters' population is not complete, these clusters likely sample various stellar ages and thus different phases of massive star evolution. Studying their stellar content is thus a first step towards a global characterization of stellar evolution at high masses.

In this paper, we perform a quantitative spectroscopic analysis of massive stars in four of these six clusters. We determine their fundamental parameters and, when possible, their surface abundances. In Section 2, we summarize the observations and data reduction. We describe in Section 3 our modelling tools and analysis strategy. The results are described in Section 4 and discussed in Section 5. Conclusions are given in Section 6.

2. Sample, observations and data reduction

The observations and data reduction were already presented in Chené et al. (2013). They are briefly summarized below.

Spectra were collected on different instruments: ISAAC on the VLT at ESO/Paranal Observatory; SofI on the NTT at ESO/La Silla Observatory; OSIRIS on the SOAR telescope. Total exposure times were typically 200–400 s for the brightest stars and 1200 s for the faintest. Details are given in Chené et al. (2013).

All reduction steps were executed using both custom-written Interactive Data Language (IDL) scripts and standard *iraf4* procedures. Subsequent nodding observations were subtracted from one another to remove the bias level and sky emission lines. Flat fielding, spectrum extraction and wavelength calibration of all spectra were done in the usual way using *iraf*. Calibration lamp spectra (helium–argon and neon for OSIRIS, xenon–neon for SofI and ISAAC) taken at the beginning of each night were used for wavelength calibration. Correction for atmospheric absorption was done using the *iraf* task *telluric*. Finally, all spectra were rectified using a low-order polynomial fit to a wavelength interval that was assumed to be pure continuum, i.e. where no absorption or emission lines were observed nor expected. Due to some problems with the data, the ISAAC pipeline could not be used. A manual reduction was done. More details on the problems and solutions adopted are detailed in Chené et al. (2013).

In Table 1 we present the observational properties of the selected stars. The classification of the different stars, based on the catalogues of Hanson et al. (1996, 2005) and Figer et al. (1997), has been presented in Chené et al. (2013). They were refined for the O stars in cluster VVV CL074. We also provide the absolute K-band magnitudes. They have been computed using $(J-K)_0 = -0.21$ and $(H-K)_0 = -0.10$ (Martins and Plez, 2006) and $A_K = 0.6 \times E(j-K)$. We checked that the resulting absolute magnitudes corresponded to the calibrations of Martins and Plez (2006) for O stars, and Rosslowe and Crowther (2013) for Wolf–Rayet (WR) stars. In one case – star VVV CL074-2 – we found a large discrepancy between the calculated and tabulated values: this WC8 star has MK=−7.67 while the average value for such objects is about −5.0 (Rosslowe and Crowther, 2013). This may be explained by the presence of dust emission contributing to the K-band flux. We noted that the line intensities for that object are quite small, favouring this interpretation. We thus decided to exclude VVV CL074-2 from our study.

Compared to the sample of Chené et al. (2013) we have also excluded VVV CL099-04. The spectrum of this star clearly shows the presence of O-type absorption lines superimposed on top of broad WN-type emission lines, hinting at a binary nature. As we do not have multi-epoch spectra we are not able to disentangle the contribution on each star on the combined spectrum. Consequently we cannot perform an analysis of stellar wind parameters for this system. We did not consider VVV CL036-9, a WN6 star, since its line intensities are about 50% lower than that of normal WN6 stars (e.g. Figer et al., 1997). Test models revealed that it was not possible to reproduce both the line intensities and the absolute magnitude of the star.