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# A quantitative study of the O stars in NGC 2244

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**Abstract.** NGC 2244 located in the Rosette Nebula is a young open cluster composed of seven O-type stars. A first paper focused on the multiplicity of these stars, revealed only one binary system out of the seven studied stars. The minimum binary fraction of this cluster ( $\sim 14\%$ ) differs to the average fraction measured on the nearby clusters ( $\sim 44\%$ ). In order to better constrain this discrepancy, an analysis based on the determination of the stellar and wind parameters of these stars with the CMFGEN atmosphere code was performed. The main results confirm that all the stars have an age between 0 and 5 Myr, and that the N surface abundance appears to be consistent with the evolutionary models for a population of stars of the same age. Moreover, this investigation exhibits the existence of dynamical interactions inside this young open cluster sufficiently strong to eject the hottest component from its centre.

## 1. Introduction

Massive stars play a key role in the ecology of the galaxies mainly because of their strong ionizing fluxes, their powerful winds and the heavy chemical elements synthesized during their spectacular death as supernovae. However, these stars still hide a part of mystery. The earliest stages of their formation but also some of their physical properties are indeed poorly known. As their evolution is governed by several main parameters such as the binarity, their mass, their mass-loss rate or their rotation, a better knowledge of their multiplicity and their fundamental parameters can provide us additional constraints to improve our understanding of these stars.

In this context, several investigations were made on the northern Monoceros star-forming region and in particular the young open cluster NGC 2244 located at the core of the Rosette nebula. This region gathers seven O-type stars. The known age of about 1–6 Myrs (Bonatto & Bica [1]) and distance of about 1.4–1.7 kpc (Hensberge et al. [2]) also make the early-type stars of this cluster suitable candidates for asteroseismology. Four of these stars and two other massive stars in Mon OB2 association were thus recently observed by the CoRoT satellite (Baglin et al. [3]) and the data were analysed in a series of papers (Blomme et al. [4], Briquet et al. [5], Degroote et al. [6], Mahy et al. [7]). However, the comparison between the theoretical models and the observations is still challenging and needs a good knowledge of the fundamental parameters of these stars.

Therefore, the requirement of reliable stellar and wind parameters for such stars is strong. For that purpose, we thus performed an analysis of these objects by means of atmosphere models.

We describe in the present paper the main results of this investigation but a more detailed study of these results and of, notably, the wind properties, the N enrichment and the stellar masses is reported in Martins et al. [8]. We organized this paper as following. Section 2 summarizes the observations and the results of the spectroscopic investigation of the multiplicity of O-type stars in NGC 2244. Section 3 describes the analysis of the atmosphere models whilst Sect. 4 presents the results. Finally, our conclusions are provided in Sect. 5.

## 2. Observations and spectroscopic binary fraction

The data were collected in order to determine the binary fraction of the O-type stars in NGC 2244. A total of 207 spectra were gathered with several telescopes. The majority of our data were obtained with the 1.52m telescope equipped with the Aurélie spectrograph at the Observatoire de Haute Provence (OHP, France). We also retrieved several spectra taken with the Elodie spectrograph at the 1.93m OHP telescope.

In April 2007 and March 2008, another set of data was obtained at Observatorio Astronómico Nacional of San Pedro Mártir (SPM) in Mexico with the Espresso spectrograph mounted on the 2.10m telescope. This échelle spectrograph covers the wavelength domain [3780–6950] Å. Also in the ‘échelle spectra category’, we retrieved spectra taken with FEROS spectrograph mounted on the 2.20m telescope at La Silla (Chile).

Among this dataset, we selected, for the atmosphere models analysis, the spectra with the widest wavelength coverage, highest spectral resolution and highest signal-to-noise ratio.

These data, spread over nine years, already allowed us to determine the binary fraction of the O-type stars in NGC 2244. The details of this investigation were reported in Mahy et al. [9] but we summarize in the present paper the main results. Among the seven O stars in the young cluster, one, HD 258691, was however not studied because of its faintness. We detected for the first time the SB2 signature in the spectrum of HD 46149 and classified its components as an O8.5V and an B0–1V for the primary and the secondary, respectively. Located at the center of the cluster, HD 46150 (O5.5V((f))) was reported as a binary candidate. Indeed, small variations were detected in its line profiles but we were not able to attribute them to binarity or to atmosphere motion. HD 46223, the hottest member in NGC 2244, was classified as an O4V((f<sup>+</sup>)), this star does not present any variations in its radial velocity nor in its line profiles. The same conclusion was obtained for HD 46202, the latest O-type star in the cluster. Finally, the two remaining O stars, HD 46056 and HD 46485, are rapid rotators with projected rotational velocities estimated to about 330 and 300 km s<sup>−1</sup>, respectively. Both stars were classified as presumably single stars even though line profiles variations were observed. The latter are probably due to non-radial pulsations rather than a secondary component. Therefore, the spectroscopic binary fraction in NGC 2244 was established between 14% and 43%.

## 3. Modeling

In order to better know the stellar and wind parameters of these O stars, we performed a quantitative study of the optical and UV spectra on the basis of the CMFGEN atmosphere code (Hillier & Miller [10]). CMFGEN provides non-LTE atmosphere models including winds and line-blanketing. This code needs as input an estimate of the hydrodynamical structure that we constructed from TLUSTY models (taken from the OSTAR2002 grid of Lanz & Hubeny [11]) connected to a  $\beta$  velocity law of the form  $v = v_{\infty}(1 - R/r)^{\beta}$  where  $v_{\infty}$  is the wind terminal velocity. We adopted  $\beta = 0.8$  since this is the typical value for O dwarfs (e.g., Repolust et al. [12]). Our models include H, He, C, N, O, Ne, Mg, Si, S, Fe with the solar composition of Grevesse et al. [13] unless otherwise stated. The super-level approach is used to reduce the amount of memory requirements. We have included X-ray emission in the wind since this can affect the ionization balance and the strength of key UV diagnostic lines. For the formal solution of the radiative transfer equation leading to the emergent spectrum, a microturbulent velocity

varying linearly (with velocity) from  $10 \text{ km s}^{-1}$  to  $0.1 \times v_{\infty}$  was used. In practice we use the same diagnostic lines as in Martins et al. [8] to derive the stellar and wind parameters.

The obtained synthetic spectra were convolved a first time with a rotational profile. The  $v \sin i$  were determined from the Fourier transform method of Simón-Díaz & Herrero [14]. For slowly and moderately rotating objects, we convolved the resulting spectra with a Gaussian profile to introduce the macroturbulence in our profiles. We used He I 4713 as the main indicator of macroturbulence since it is present with sufficient SNR in all sample stars. Secondary indicators were the C IV 5801–5812 doublet and He I 5876.

We also determined the N content of stars from the N III absorption lines between 4500 and 4520 Å. They are not affected by winds and are strong enough for abundance determination. The uncertainties are of the order of 50%. The errors do not take into account any systematics related to atomic data.

Clumping is implemented in CMFGEN by means of a volume filling factor  $f$  following the law  $f = f_{\infty} + (1 - f_{\infty})e^{-v/v_{cl}}$  where  $f_{\infty}$  is the maximum clumping factor at the top of the atmosphere and  $v_{cl}$  a parameter indicating the position where the wind starts to be significantly clumped. As shown by Bouret et al. [15], O V 1371 and N IV 1720 are two UV features especially sensitive to wind inhomogeneities in early O stars. For mid to late O stars, these UV clumping diagnostic are not identified, as we confirmed by our study. Therefore, we decided to adopt  $f_{\infty} = 1$  (i.e., homogeneous model) for these stars.

#### 4. Results

The main stellar and wind parameters are listed in Table 1 whilst Figure 1 compares each synthetic spectrum to the observed spectrum in the UV and the optical domains. For all the presumably single stars, the best-fit CMFGEN models are rather of good quality. For the binary system HD 46149, we applied a disentangling program based on the method of González & Levato [16] to separate the contributions of the primary component from the secondary star. This method provides mean spectra of both components. The resulting spectra are then corrected from the light factor which is deduced from the brightness ratio (here  $l_1/l_2 = 2.3$ ). To derive this brightness ratio, we compute the equivalent widths of several lines on the observed spectra and compare these values to those given by Conti et al. [17] and Conti [18] as well as those obtained from synthetic spectra which have same spectral classifications as our two components. However, to obtain reliable spectra, three conditions have to be met:

- the sampling of the data has to be as uniform as possible (in Doppler shift or in orbital phase) over the orbital cycle,
- the spectral separation between both components has to be large enough to sample the full width of the lines, especially for the Balmer lines,
- the normalization has to be as perfect as possible to avoid oscillations in the continuum of the resulting spectra.

However, in the case of HD 46149, these conditions are not completely respected. Indeed, the orbital period of the system is estimated to be about 800 days but the collected data are not sufficiently well sampled to allow us to be more accurate on this value and compute its orbital solution. Indeed, the spectra were mainly taken at three different phases: when the difference between the radial velocities of the secondary and the primary ( $RV_S - RV_P$ ) are equal to  $-30$ ,  $\sim 0$  and  $+140 \text{ km s}^{-1}$ . Moreover, the large eccentricity and the orientation of the orbit imply an asymmetric excursion in radial velocity preventing the sampling of the full width of the Balmer lines. Therefore, the derived parameters and notably the  $\log g$  are rather uncertain, especially for the secondary component.

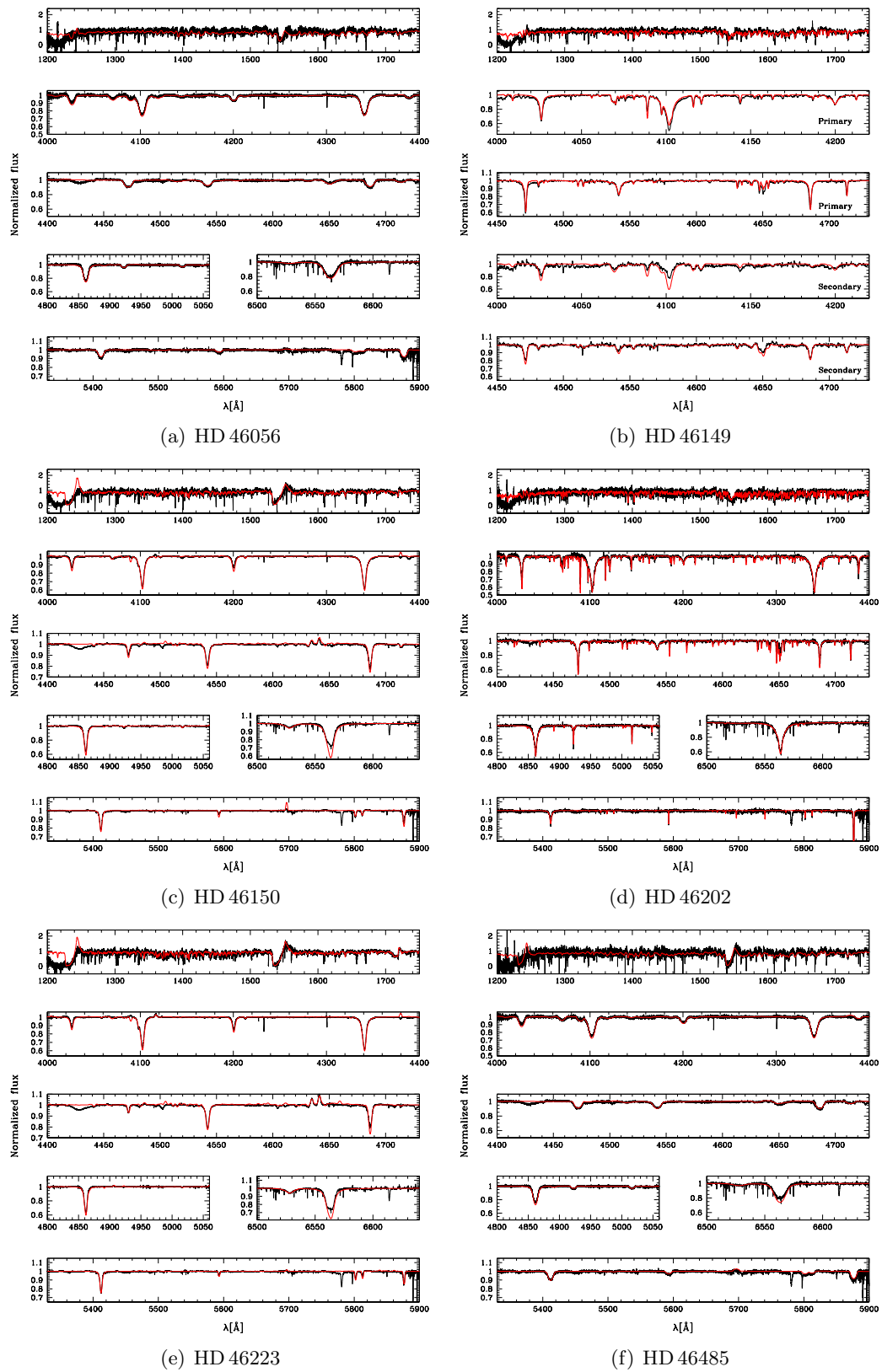
The O-type stars of NGC 2244 form a homogeneous sample of stars with the same age, distance, and chemical composition. The effective temperatures and the luminosities are

sufficiently accurate to report the positions of the O-type stars on the Hertzsprung-Russell diagram (Fig. 4). These results reveal that all the O stars in NGC 2244 have an inferred age between 0 and 5 Myrs. However, we clearly detect a trend between the two most massive stars (HD 46150 and HD 46223) and the other ones. Indeed, these two stars appear to be younger than the lower-mass O stars. The origin of this trend is unclear and could come either from real phenomena or from artefacts related to the comparison method. The former would assume that either the early-type stars emerge from their parental cloud faster than the later-type stars or that they form after these later-type stars. The latter would imply that the utilization of a same initial rotational velocity for the evolutionary tracks of all stars is unadapted. Unfortunately, in this case, we do not know whether the initial rotational velocity of more massive stars is larger than that of lower-mass O stars. If this trend was real, that would therefore confirm that dynamical interactions exist inside NGC 2244. The study made by Wang et al. [19] in the X-ray domain indeed revealed the presence of X-ray sources, associated to pre main-sequence (PMS) stars, around HD 46150 and not around HD 46223 which is however the most massive star of the cluster. The authors explained these observations by the fact that HD 46223 is either younger than HD 46150 or that it was ejected from the center of the cluster due to dynamical interactions. We can now assume that the second possibility seems to be the most probable one.

The determination of the  $\dot{M}$  systematically reveals that the mass-loss rates derived on UV P-Cygni profiles are smaller than those estimated from H $\alpha$  (see Table 1). Our estimates could however be biased because of the few available features to constrain the models, because of the CMFGEN code itself which requires an accurate wind ionization structure or because of the porosity (or vorosity) which could alter the shape of diagnostic lines, for example. This vorosity (i.e., the porosity in velocity space) could partly explain this discrepancy. Sundqvist et al. [20] have indeed shown that accounting for vorosity, the UV line profiles can be strongly reduced for a given mass-loss rate whilst H $\alpha$  mass-loss rate is less affected. Their simulations have notably emphasized the importance of vorosity on the formation of strong UV lines. However, as this property is observed in all the stars, the assumption of vorosity would mean that the winds of all the stars in our sample are clumped, even for the weak wind stars. Therefore, the H $\alpha$  mass-loss rates derived by using homogeneous models should be considered as upper limits.

In addition to the stellar and wind parameters, we have also derived the N abundances for all the stars in NGC 2244. These values are particularly interesting to compare the theoretical predictions with the observations. Indeed, rotation is supposed to affect the angular momentum and the chemical elements transport through mixing processes (Meynet & Maeder [21]). Therefore, we have put in perspective the N content with the projected rotational velocities (Fig. 3, left-hand panel). In this context, we observed a clear trend of larger N/H with larger  $v \sin i$ , except for the two rapid rotators (HD 46056 and HD 46485). When we compare the N content with the stars' luminosity (Fig. 3, right-hand panel), a clear trend of larger enrichment in higher mass stars is observed. We do not see any outliers, thereby meaning that these fast rotators are too young to have experienced a strong enrichment in spite of their large  $v \sin i$ . The binary system HD 46149 does not show any evidence of interaction between its components. That suggests that the components of this system have not been affected by a mass transfer or too severe tidal effects. They are still supposed to evolve as if they were single stars.

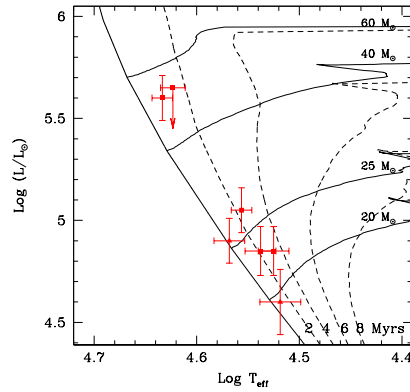
Finally, our investigation shows a discrepancy between the evolutionary masses and the spectroscopic masses (i.e., the masses derived from the radii and the gravities of the stars). The determination of both masses are given in Table 1.



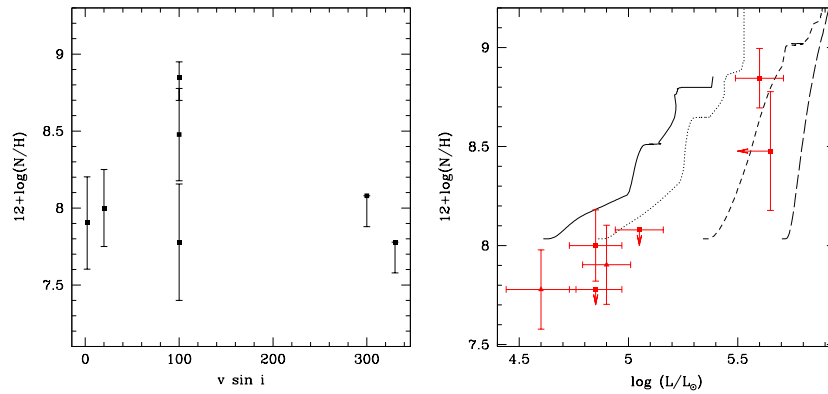
**Figure 1.** Best-fit CMFGEN models for the O-type stars in NGC 2244.

**Table 1.** Derived stellar properties of the sample stars: name, spectral type, effective temperature (uncertainty 1000 K, except for HD 46149, 2000 K), luminosity, effective gravity (uncertainty 0.1 dex, except for HD 46149, 0.2 dex), UV mass-loss rate, terminal velocity, projected rotational velocity, macroturbulent velocity, evolutionary mass, spectroscopic mass, nitrogen content, ionizing flux. Spectroscopic masses are computed from the true gravity (i.e.,  $\log g$  corrected from the effect of centrifugal force).

Source	$T_{\text{eff}}$ [K]	$\log \frac{L}{L_{\odot}}$	$\log g$	$\log(\dot{M}_{UV})$	$\log(\dot{M}_{H\alpha})$	$f_{\infty}$	$v_{\infty}$ [km s <sup>-1</sup> ]	$v \sin i$ [km s <sup>-1</sup> ]	$v_{\text{mac}}$ [km s <sup>-1</sup> ]	$M_{\text{evol}}$ [M <sub>⊙</sub> ]	$M_{\text{spec}}$ [M <sub>⊙</sub> ]	N/H [×10 <sup>4</sup> ]
NGC 2244												
HD 46223	43.0	5.60±0.11	4.01	-7.17	-6.20	0.1	2800	100	32	52.1 <sup>+6.2</sup> <sub>-5.9</sub>	48.3 ± 19.3	7.0±2.0
HD 46150	42.0	<5.65	4.01	-7.30	-6.40	0.1	2800	100	37	< 53.6	59.5 ± 23.7	3.0±2.0
HD 46485	36.0	5.05±0.11	3.85	-7.80	-6.45	1.0	1850	300	-	28.6 <sup>+3.3</sup> <sub>-4.3</sub>	19.5 ± 7.9	≤1.2
HD 46056	34.5	4.85±0.12	3.89	-8.50	-	1.0	1500	330	-	23.1 <sup>+2.4</sup> <sub>-1.9</sub>	15.8 ± 6.7	≤0.6
HD 46149-1	37.0	4.90±0.12	4.25	<-9.0	-	-	1300	~0	24	25.9 <sup>+3.1</sup> <sub>-3.5</sub>	30.9 ± 21.6	0.8±0.5
HD 46149-2	33.0	4.60±0.16	3.53	-	-	-	-	100	27	19.2 <sup>+2.9</sup> <sub>-2.5</sub>	4.7 ± 3.6	0.6±0.5
HD 46202	33.5	4.85±0.12	4.10	-9.0	-7.10	1.0	1200	20	17	22.7 <sup>+2.0</sup> <sub>-2.4</sub>	29.0 ± 12.4	1.0±0.5



**Figure 2.** HR diagram of NGC 2244. Curves, computed from an initial rotational velocity of  $300 \text{ km s}^{-1}$ , are from Meynet & Maeder [22].



**Figure 3.** *Left-hand panel:* Nitrogen surface abundance (in units of  $12 + \log(N/H)$ ) as a function of projected rotational velocity. *Right-hand panel:* Nitrogen surface abundance (in units of  $12 + \log(N/H)$ ) as a function of luminosity. Evolutionary tracks (shown by the solid, dot-long dashed, dot-dashed, dashed lines for  $M=20, 25, 40$  and  $60 M_{\odot}$ ) are from Meynet & Maeder [22].

## 5. Conclusions

We have analyzed six O-type stars belonging to NGC 2244 and among them HD 46149 which is a binary system. Optical and UV spectroscopy have been obtained. Atmosphere models computed with the code CMFGEN have been used to derive the main stellar and wind parameters of the target stars.

All the stars have an age between 0 and 5 Myr, with a trend of lower age for the most massive stars. Moreover, we confirm the existence of weak winds in the latest type stars of our sample and, for all the stars, we see a clear discrepancy between the mass-loss rates computed from the UV domain and those derived from  $H\alpha$  in the optical wavelengths. Finally, a discrepancy between the evolutionary masses and the spectroscopic masses (estimated from the radii and the gravities of the stars) is observed for the latest type O stars. However, we need to analyze more stars of the same age to confirm the trends observed from a point of view of their ages, their masses and their mass-loss rates.

Finally, this investigation improves our knowledge of these stars and paves the way for the



computations of excited modes and pulsations which could be compared to the results obtained from the CoRoT photometry.

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