A Galactic O2 If*/WN6 star possibly ejected from its birthplace in NGC 3603

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ABSTRACT
In this work we report the discovery of a new Galactic O2 If*/WN6 star, a rare member of the extremely massive hydrogen core-burning group of stars that, because of their high intrinsic luminosity (close to the Eddington limit), possess an emission-line spectrum at the beginning of their main-sequence evolution, mimicking the spectral appearance of classical Wolf–Rayet (WR) stars. The new star is named WR 42e and is found in isolation at 2.7 arcmin (~6 pc) from the core of the starburst cluster NGC 3603. From the computed $E(B-V)$ colour excess and observed visual magnitude it is possible to estimate its absolute visual magnitude as $M_V = -6.3$ mag, which is a value similar to those obtained by other researchers for stars of similar spectral type both in the Galaxy and in the Large Magellanic Cloud. Considering the derived absolute visual magnitude, we compute a bolometric stellar luminosity of about $3.2 \times 10^6 \, L_\odot$. Finally, we estimate the mass of the new O2 If*/WN6 star by comparing its observed magnitudes and colours with those of other probable NGC 3603 cluster members, finding that the initial mass of WR 42e possibly exceeds 100 $M_\odot$.

Key words: stars: individual: WR 42e – stars: Wolf–Rayet – open clusters and associations: individual: NGC 3603 – infrared: stars.

1 INTRODUCTION
NGC 3603 is one of the most massive and dense star-forming regions known in the Galaxy, being the closest exemplar of a starburst-like cluster very similar to the starburst cluster R136 in the Large Magellanic Cloud (LMC)], with dozens of massive stars in its core, some of them possibly presenting initial masses exceeding 100–150 $M_\odot$ (Crowther et al. 2010).

For a long time the O3 stars were considered to represent the most massive main-sequence stars. However, in the last decade it has become clear that some hydrogen-rich nitrogen sequence Wolf–Rayet (WR) stars may be in reality extremely massive and luminous main-sequence stars (de Koter, Heap & Hubeny 1997; Schnurr et al. 2008; Smith & Conti 2008; Crowther et al. 2010), which because of their proximity to the Eddington limit present an emission-line spectrum at the beginning of their main-sequence evolution, mimicking the spectral appearance of classical WR stars.

The empirical determination of stellar masses of high-mass binary systems, and the use of state-of-the-art stellar models, it is becoming clear that such kinds of massive stars probably belong to the O2 If*/WN6 and WNH spectral types (Smith & Conti 2008; Crowther & Walborn 2011), with this conclusion being supported by systematic studies of binaries made, for example, by Schnurr et al. (2008) for R145 (in 30 Dor), Smith & Conti (2008) for WR 25, Rauw, Vreux & Gosset (1996) for WR 22 (both in the Carina Nebula), Schnurr et al. (2009) for NGC 3603-A1, Rauw et al. (2004) and Bonanos et al. (2004) for WR 20a, Niemela et al. (2008) for WR 21a and more recently Crowther et al. (2010) for some very massive exemplars in the centre of the NGC 3603 and R136 clusters.

In this Letter we communicate the discovery of an O2 If*/WN6 star (WR 42e) at an angular distance of ~2.7 arcmin (about 6 pc) from the NGC 3603 cluster core, in apparent isolation in the field.

In Section 2 we describe some aspects of the selection criteria, the observations and data reduction procedures. In Section 3 we present our results and some discussion, and finally in Section 4 we give a summary of the work.

2 SELECTION CRITERIA, OBSERVATIONS AND DATA REDUCTION
In this section we comment on the selection criteria used to choose WR 42e as target for near-infrared (NIR) spectroscopic follow-up, as well as the observations and data reduction procedures.

2.1 Selection criteria
The newly identified O2 If*/WN6 star (WR 42e) was previously chosen for NIR spectroscopic follow-up observations based on its...
near- to mid-infrared colours, its Hα and X-ray emission characteristics, and its proximity to the NGC 3603 cluster. Details on the criteria and general selection methodology will be fully discussed in a forthcoming paper (Roman-Lopes, in preparation).

2.2 Observations and data reduction

In this work we use NIR spectroscopic data acquired with the Ohio State Infrared Imager and Spectrometer (OSIRIS) at the SOAR telescope. The observations were carried out on 2011 May 9 with the night presenting good seeing conditions. Besides WR 42e, we also acquired NIR spectra (to be used as comparison templates) for WR 20a (O3 If*/WN6 + O), WR 25 (O2.5 If*/WN6) and HD 93129A (O2 If*). In Table 1 we present a summary of the NIR observations. The raw frames were reduced following standard NIR reduction procedures, which are presented in detail in Roman-Lopes (2009), and briefly described here. The two-dimensional frames were sky-subtracted for each pair of images taken at two nod positions, followed by division of the resultant image by a master flat. The multiple exposures were combined, followed by one-dimensional extraction of the spectra. Thereafter, wavelength calibration was applied using the sky lines, and we estimate as ∼12 Å the 1σ error for such calibrations, which is evaluated as one-third of the mean full width at half-maximum (MFWHM) of the sky lines detected in all three NIR bands. Finally, the effects of the Earth’s atmosphere in the science spectra were corrected using J-, H- and K-band spectra of A-type stars.

3 RESULTS

3.1 Optical and Near-Infrared photometry of WR 42e

Coordinates, photometric data and some other physical parameters of the new O2 If*/WN6 star are shown in Table 2. The U-, B-, V- and J-band magnitudes were taken from the work of Sung & Bessell (2004), while the NIR photometry was obtained from the Two-Micron All Sky Survey (2MASS, Cutri et al. 2003), and searching in SIMBAD1 we found that WR 42e is not known to be a member of the NGC 3603 cluster.

Table 1. Summary of the SOAR/OSIRIS data set used in this work.

| Date       | 2011 May 9 |
|------------|------------|
| Telescope  | SOAR       |
| Instrument | OSIRIS     |
| Mode       | XD         |
| Camera     | f/3        |
| Slit       | 1 × 27 arcsec² |
| Resolution | 1000       |
| Coverage (µm) | 1.25–2.35 |
| Seeing (arcsec) | 1–1.5   |

Table 2. Coordinates, optical/NIR photometry, proper motion measurements (given in mas yr⁻¹), and X-ray and Hα parameters of the newly identified O2 If*/WN6 star. The UBVRI photometry and the R–Hα index were taken from Sung & Bessell (2004), while the NIR magnitudes are from Cutri et al. (2003). The proper motion parameters were obtained from the UCAC3 and PPMXL catalogues (Zacharias et al. 2009; Roeser et al. 2010) and the absorption-corrected 0.5–10 keV flux is from the work of Romano et al. (2008).

RA = 11ʰ14ᵐ45ˢ50''
Dec. = −61°15′00″1′′
U = 16.31
B = 16.05
V = 14.53
J = 12.05
H = 9.47 ± 0.02
Ks = 9.04 ± 0.02
X-ray (0.5–10 keV) = 3.3 × 10⁻¹⁷ W m⁻²
R–Hα = 4.49
pmRA (UCAC3) = −4.6 ± 4.0
pmDE (UCAC3) = 0.3 ± 4.0
pmRA (PPMXL) = −63.9 ± 5.0
pmDE (PPMXL) = 1.4 ± 5.0

3.2 NIR spectra of WR 42e compared with those for HD 93129A, WR 20a and WR 25

In Fig. 1 we present the telluric corrected (continuum normalized) J-, H- and K-band spectra of WR 42e and those for HD 93129A (O2 If*), WR 20a (O3 If*/WN6 + O) and WR 25 (O2.5 If*/WN6) (Crowther & Walborn 2011). The strongest features are the emission lines close to the 1.282-µm (Paβ) and 2.167-µm (Brγ) hydrogen lines, as well as the He I + N ii and He II emission lines at 2.115 and 2.189 µm, respectively. An exception occurs in the case of the prototype O2 If* star HD 93129A which (at least at the SOAR/OSIRIS spectral resolution and sensitivity) does not seem to present the He II 2.189-µm line in emission (or in absorption). Indeed this is the most evident difference (besides the relative intensities of the observed emission lines) between HD 93129A spectrograms and those for the O If*/WN6 stars. Interestingly, the O2 If* star R136a5 (30 Dor) does shows the 2.189-µm line in emission, but in this case its

Figure 1. The J-, H- and K-band continuum normalized SOAR/OSIRIS spectra of the star WR 42e, together with the NIR spectrograms of HD 93129A (O2 If*), WR 20a (O3 If*/WN6 + O3 If*/WN6) and WR 25 (O2.5 If*/WN6). The main H, He and N emission lines are identified by labels.

1 http://simbad.u-strasbg.fr/simbad/
3.3 Spatial location and interstellar reddening

In Fig. 2 we show a false colour RGB image made from the 3.6-µm (blue), 5.8-µm (green) and 8-µm (red) Spitzer IRAC images of the region towards NGC 3603. There we label both the core of NGC 3603 and the newly found emission-line star. As we can see, WR 42e is found in relative isolation in the NGC 3603 large field, being well displaced (2.7 arcmin) from the cluster core. O2 If*/WN6 stars are very rare and normally expected to be found in the centre of extremely massive clusters (like 30 Doradus and NGC 3603 itself). In the specific case of NGC 3603, all the presently known O2 If*/WN6 and WN6ha (for example NGC 3603-C and NGC 3603-B) stars are found in its core, so one relevant question is: was WR 42e formed at the place where it is now (in isolation), or was it formed inside the NGC 3603 centre and then expelled from its birthplace by its companions through some kind of dynamical interaction mechanism? WR 42e has a cluster core angular distance of 2.7 arcmin (about 6 pc), a value greater than the NGC 3603 maximum cluster radius of 2 arcmin (Sung & Bessell 2004). However, such an angular core distance is small when compared with those for other Galactic O2 If*/WN6 stars found in isolation [e.g. WR 20aa (16 arcmin) and WR 20c (25 arcmin) – Westerlund 2 (Roman-Lopes, Barbé & Morrell 2011)] in the Galactic field. Indeed, the relative proximity to the NGC 3603 core may be considered a strong indication that WR 42e possibly was formed at the same birth site as the NGC 3603 cluster. On the other hand, the visual extinction to WR 42e is another parameter that when compared with the value for the NGC 3603 cluster can give us additional clues about its possible membership. We notice that the interstellar reddening law for the NGC 3603 region is probably abnormal (Pandy, Ogura & Sekiguchi 2000; Sung & Bessell 2004), with a ratio of total to selective extinction $R_V = 3.55 \pm 0.12$ (Sung & Bessell 2004). The mean $E(B - V)$ colour excess for the NGC 3603 stellar population is in the range $1.25 \leq E(B - V) \leq 1.90$, with the $E(B - V)$ values increasing with the radial cluster centre distance (Sung & Bessell 2004). From fig. 5 of Sung & Bessell (2004) one can see that for the NGC 3603 cluster field, a cluster member candidate placed at a core distance of 2.7 arcmin should present a $(B - V)$ colour excess in the range $1.65 \leq E(B - V) \leq 1.90$. From Table 1 of the present work, we can see that WR 42e has a $(B - V)$ colour $\sim -1.5$ mag, which for an assumed mean $(B - V)_0$ value of $-0.3$ mag (typical for the hottest early-type stars) should correspond to a colour excess $E(B - V) \sim 1.8$ mag ($A_V \sim 6.4$ mag), a reddening value fully compatible with what would be expected for the early-type cluster members placed at a cluster core angular distance in the range $2.0-3.5$ arcmin (Sung & Bessell 2004).

3.4 Absolute magnitudes and mass of WR 42e

Once we have computed the colour excess for the new star, it is possible to estimate its absolute magnitude using the distance modules equation, assuming that the star is placed at a heliocentric distance (the same as for NGC 3603) of 7.6 ± 0.4 kpc (Crowther et al. 2010). We computed $M_V = -6.3$ mag [or $M_K = -6.1$ considering $A_K = 0.12 A_V$ (Crowther et al. 2010)], which is a value similar to those obtained by other researchers for stars of similar type. As examples we can mention the absolute magnitudes computed for WR 20a (corrected for binary – O3 If*/WN6 + O3 If*/WN6), WR 20aa and WR 20c ($M_V = -6.3$, $-6.5$ and $-6.1$ respectively) in Westerlund 2, MK 30 (O2 If*/WN5), MK 35 (O2 If*/WN5) and R136a5 (O2 If*) ($M_K = -5.9$, $-6.0$ and $-6.0$ respectively) in 30 Dor, and HD 93129A (O2 If*) plus HD 93131 (WN6ha) ($M_K = -6.2$ and $-6.1$ respectively) in the Carina region (Crowther et al. 2010; Roman-Lopes et al. 2011; Crowther & Walborn 2011). Considering the derived absolute visual magnitude and assuming a mean bolometric correction $BC \sim -4.2$ mag (Crowther et al. 2010; Crowther & Walborn 2011), we estimate the bolometric magnitude of the newly discovered star as $M_{bol} \sim -10.5$ mag, which corresponds

![Figure 2](Image)

Table 3. Wavelength and equivalent widths (Å) of the main emission lines detected in the SOAR/OSIRIS $I$-, $H$- and $K$-band spectra of WR42c.

| $\lambda$ (µm) | 1.282 | 1.681 | 1.693 | 1.736 | 2.078 | 2.100 | 2.115 | 2.166 | 2.189 |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| EW (Å)        | $-17.0 \pm 2.5$ | $-1.5 \pm 0.3$ | $>-0.2$ | $-2.3 \pm 0.3$ | $>-0.2$ | $-2.0 \pm 0.3$ | $-20.2 \pm 3.0$ | $-2.7 \pm 0.6$ |
to a total stellar luminosity of $3.2 \times 10^6 \, L_\odot$. Also it is possible to estimate the mass of WR 42e from its $V$- and $I$-band photometry. Indeed, we did that by comparing its observed magnitudes and colours with those of other probable NGC 3603 cluster members, presented in Fig. 7 of the work of Sung & Bessell (2004). In Fig. 3 we present an adapted version of their $V \times V - I$ diagram for NGC 3603, with WR 42e represented by a light blue circle. From this figure we can see that the initial mass of the new O2 If*/WN6 star possibly exceeds 100 $M_\odot$.

Finally, WR 42e was previously selected for spectroscopic follow-up due to its associated X-ray emission (Chandra source IBMC 111445.5-611500). From its absorption-corrected 0.5–10 keV flux (Table 2), and considering a heliocentric distance of 7.6 ± 0.4 kpc (Crowther et al. 2010), we estimate its X-ray luminosity as $L_X \sim 2.3 \times 10^{32} \, \text{erg s}^{-1}$, which compared to its bolometric luminosity results in $L_X/L_{bol} = 5 \times 10^{-8}$. This is a value compatible (considering the uncertainties in the measured X-ray flux, heliocentric distance, correction for absorption, etc.) with what is expected ($\sim 10^{-7}$) to be generated from single stars (Chlebowski, Harnden & Sciortino 1989).

### 3.4.1 Could WR 42e be a runaway star?

There is a reasonable consensus that very massive stars preferentially should be found in the cores of the most massive clusters, normally forming binary or multiple systems. However, it is an observational fact that a few very young and massive stars are found in isolation in the field, being placed relatively far from any cluster or association of stars. In this sense, there are two standard scenarios that try to account for such kinds of objects. One is known as the dynamical ejection scenario, and involves dynamical three- or multiple-body encounters in dense stellar systems; while the second is known as the binary-supernova scenario, and considers the disruption of a short-period binary system from the asymmetric supernova explosion of one of the binary components. While the time-scale for the binary-supernova scenario involves values larger than the expected age (1–2 Myr) for very massive hydrogen core-burning stars (Rochau et al. 2010), the multiple ejection of massive stars from dense massive clusters in principle could account for the very young objects like 30 Dor #16 in the LMC, and WR 20aa and WR 20c in the Milky Way. For more details on the two models, see for example the discussion in Gvaramadze & Gualandris (2010) and references therein.

In the specific case of WR 42e, we searched for proper motion data in order to support the hypothesis of a runaway nature for this star, following the idea where it was ejected from its birthplace in the NGC 3603 cluster centre. In this sense, we did find proper motion measurements for WR 42e in at least two catalogues. The most recent are those from UCAC3 (Zacharias et al. 2009) and PPMXL (Roeser, Demleitner & Schilbach 2010) (see Table 2). In the latter, WR 42 is identified as source 610173644692891020, which presents a very high RA proper motion component of $-63.9$ mas yr$^{-1}$. On the other hand, from the UCAC3 catalog WR 42e is identified as source 058-165111 which presents a quite moderate RA proper motion component value of $-4.6$ mas yr$^{-1}$ (see Table 2). The origin of such a discrepancy (within the quoted errors) between the RA proper motion measurements is unknown. As a comment, we should note that the corresponding values for the Dec. proper motion components of the two catalogues do not show such a discrepancy. In Fig. 1 we represent the corresponding proper motion vector (projected on to the sky plane) for WR 42e. It may suggest that the star could be travelling in a trajectory opposite to that to the NGC 3603 cluster centre. However, while the first RA proper motion value (from the PPMXL catalogue) can be considered significant (taking into account the associated uncertainty), the second from the UCAC3 catalogue is useless since the associated error is as large as the RA proper motion value itself.

Assuming that WR 42e was formed in the NGC 3603 core and using the proper motion values obtained from the PPMXL catalogue, we can estimate the epoch when the star was ejected from its birthplace in NGC 3603. In addition, considering 7.6 kpc as the heliocentric distance to the NGC 3603 cluster (Crowther et al. 2010), we can obtain estimates for the presumed projected travelling velocity of WR 42e. In the case of the proper motion values given by the PPMXL catalogue, one finds that the star should have been ejected from the NGC 3603 centre only 2500 yr ago, which for the quoted distance would imply an incredible travelling projected velocity of more than 2000 km s$^{-1}$, a value too high to be considered reliable. The reason for such a discrepancy probably resides in a wrong value for the RA proper motion presented in the PPMXL catalogue (perhaps due to a typographical error). On the other hand, considering that the age of the most massive stars in NGC 3603 has recently been derived to be 1.5 ± 0.1 Myr (Crowther et al. 2010), this leaves a time of 0.5 Myr for the possible dynamical interaction between the cluster members and the associated ejected O2 If*/WN6 star (Alisson et al. 2010). In this sense, we can estimate a lower value for the travelling velocity of WR 42e assuming that the star was ejected 1 Myr ago from the centre of NGC 3603. From the observed angular distance of $\sim 2.7$ arcmin ($\sim 6$ pc), a travelling time of 1 Myr would correspond to a proper motion of about 0.16 mas yr$^{-1}$, which in turn results in a somewhat lower travelling velocity of 6 km s$^{-1}$. However, Gvaramadze & Gualandris (2010) argue that the average velocity attained by the 70–80 $M_\odot$ stars can be quite moderate ($<30$ km s$^{-1}$), so that they cannot be formally classified as runaways.
4 SUMMARY

In this work we report the discovery of a new Galactic O2 If*/WN6 star, a rare member of the extremely massive hydrogen core-burning group of stars that, because of their high intrinsic luminosity (close to the Eddington limit), possess an emission-line spectrum at the beginning of their main-sequence evolution, mimicking the spectral appearance of classical WR stars. The new star is found in isolation at 2.7 arcmin (~6 pc) from the core of the starburst cluster NGC 3603. From the computed $E(B-V)$ colour excess and observed visual magnitude it has been possible to estimate its absolute visual magnitude as $M_V = -6.3$ mag [or $M_K = -6.1$ considering $A_K = 0.12A_V$ (Crowther et al. 2010)], which is a value similar to those obtained by other researchers for stars of similar spectral type both in the Galaxy and in the LMC. Considering the derived absolute visual magnitude and assuming a mean bolometric correction $BC \sim -4.2$ mag (Crowther et al. 2010; Crowther & Walborn 2011), we estimate the bolometric magnitude of the newly discovered star as $M_{\text{Bol}} \sim -10.5$ mag which corresponds to a total stellar luminosity of about $3.2 \times 10^6 L_\odot$. Finally, we estimate the mass of the new O2 If*/WN6 star, by comparing its V- and I-band photometry with those of other probable NGC 3603 cluster members, finding that the initial mass of WR 42e possibly exceeds 100 $M_\odot$.

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