

An O2If* star found in isolation in the backyard of NGC 3603*

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ABSTRACT

In this letter we communicate the identification of a new Galactic O2If* star (MTT 68) isolated at a projected linear distance of 3 pc from the centre of the star-burst cluster NGC 3603. From its optical photometry I computed a bolometric luminosity $M_{Bol} = -10.7$, which corresponds to a total stellar luminosity of $1.5 \times 10^6 L_{\odot}$. It was found an interesting similarity between MTT 68 and the well known multiple system HD 93129. From Hubble Space Telescope F656N images of the NGC 3603 field, it was found that MTT 68 is actually a visual binary system with an angular separation of $0.38''$, which corresponds to a projected (minimum) linear distance of $r_{A-B} = 1.4 \times 10^{-2}$ pc. This value is similar to that for the HD 93129A (O2If*) and HD 93129B (O3.5) pair, $r_{A-B} = 3.0 \times 10^{-2}$ pc. On the other hand, HD93129A has a third closer companion named HD 93129Ab (O3.5) at only $0.053''$, and taking into account that the X-ray to total stellar luminosity ratio for the MTT 68 system ($L_X/L_{Bol} \sim 1 \times 10^{-5}$) is about two orders of magnitude above the canonical value expected for single stars, I suspect that the MTT 68 system probably hosts another massive companion possibly to close to be properly resolved by the HST archive images.

Key words: Stars: Wolf-Rayet; Infrared: Stars: Individual: HD93129A, MTT 68; Galaxy: open clusters and associations: individual: NGC 3603

1 INTRODUCTION

NGC 3603 is the closest star-burst like cluster, being an invaluable template for the modern theory of formation and evolution of *very massive stars*. Indeed, with at least four exemplars in its core (three WN6ha + one O2If*/WN6 - Crowther & Walborn (2011)), plus two O2If*/WN6 stars (WR42e and MTT58) recently identified at only a few arcminutes from its centre (Roman-Lopes 2012, 2013), this cluster may be the host of the larger concentration of extremely massive *hydrogen core burning* stars in the Galaxy (Smith & Conti 2008; Crowther et al. 2010; Crowther & Walborn 2011).

Moffat et al. (2002) detected a large number of X-ray sources toward the cluster centre, concluding that the majority of them should be probably compound by pre-main sequence stars. However, the detection of two O2If*/WN6 stars in the NGC 3603's periphery may indicate that some other very massive stars could be present in the NGC 3603 cluster field. In this context and based on the presence of

very strong X-Ray counterparts in the BMW-Chandra catalogue (Romano et al. 2008), we performed NIR follow-up spectroscopic observations of a very interesting X-ray point source previously cataloged by Melnick, Tapia & Terlevich (1989) as MTT 68. It is now confirmed to be an O2If* star isolated in the periphery of NGC 3603, at about $1.4'$ from its core.

2 NEAR-INFRARED SPECTROSCOPIC OBSERVATIONS AND DATA REDUCTION

The NIR spectroscopic observations were performed with the Ohio State Infrared Imager and Spectrometer (OSIRIS) at the Southern Astrophysics Research (SOAR) telescope. The J-, H- and K-band data were acquired in 31th January 2012 with the night presenting good atmospheric conditions.

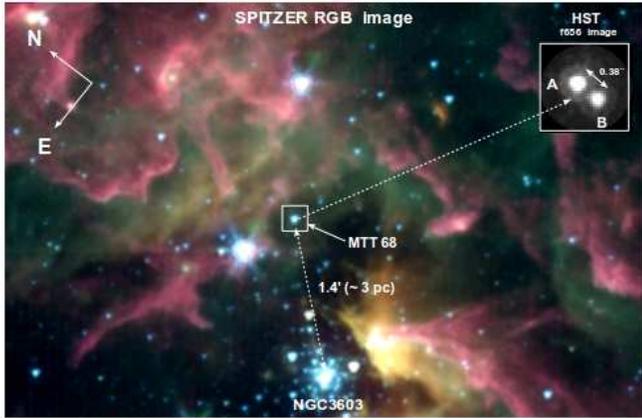
In Table 1 it is shown a summary of the NIR observations. The raw frames were reduced following well known NIR reduction procedures. The two-dimensional frames were subtracted for each pair of images taken at the two shifted positions, with the resultant images being divided by a master normalized flat. For each processed frame, the J-, H- and K-band spectra were extracted using the task APALL

* Based on observations obtained at the Southern Astrophysical Research (SOAR) telescope

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Table 1. Summary of the SOAR/OSIRIS spectroscopic observations.

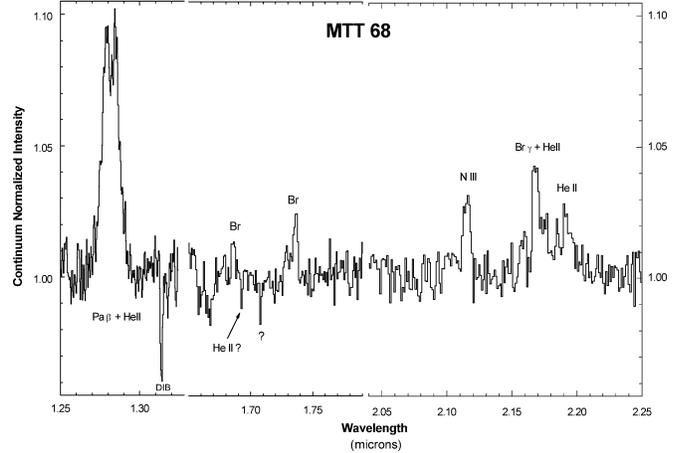
Date	31/01/2012
Telescope	SOAR
Instrument	OSIRIS
Mode	XD
Camera	f/3
Slit	1" x 27"
Resolution	1000
Coverage (μm)	1.25-2.35
Seeing (")	0.8-1.3

**Figure 1.** The three color image of the north and west regions towards the NGC 3603 cluster's centre, constructed from the $3.6\mu\text{m}$ (blue), $4.5\mu\text{m}$ (green) and $5.8\mu\text{m}$ (red) Spitzer IRAC data taken from the NASA/IPAC Infrared Science Archive. Notice that the new star is found in isolation at about 1.4 arcmin from the cluster's centre, which for an estimated heliocentric distance of 7.6 kpc corresponds to a projected distance of about 3 parsecs.

within IRAF, with the wavelength calibration made through the IRAF tasks IDENTIFY and DISPCOR applied to a set of OH sky line spectra in the range $12400\text{\AA} - 23000\text{\AA}$. The corrections of the telluric atmospheric features on the science data, were performed using J-, H- and K-band spectra of A type stars obtained before and after the science targets. The photospheric absorption lines present in the high signal-to-noise telluric spectra, were subtracted from a careful modeling (through the use of Voigt and Lorentz profiles) of the hydrogen absorption lines using the corresponding adjacent continuum. At the end, the J-, H- and K-band spectra were combined by using the IRAF task SCOMBINE with the mean signal-to noise ratio of the resulting spectra well above 100.

3 RESULTS

Coordinates and photometric parameters of MTT 68 are shown in Table 2. The V-, R- and I-band optical magnitudes were taken from the work of Sung & Bessell (2004), while the near-infrared values were obtained from the Two-Micron All Sky Survey (Cutri et al. 2003), with the absorption-corrected 0.5-10keV Chandra X-ray flux taken from the work of Romano et al. (2008).

**Figure 2.** The J- H- and K-band continuum normalized SOAR-OSIRIS spectra of MTT 68, with the main H, He and N emission lines identified by labels.

3.1 The OSIRIS NIR spectra of MTT 68: An O2If* star isolated in the backyard of NGC 3603

As mentioned before, the star subject of this letter was previously cataloged as MTT 68 by Melnick, Tapia & Terlevich (1989). In Figure 1 it is shown a three color image of part of the NGC 3603 field, made from the $3.6\mu\text{m}$ (blue), $4.5\mu\text{m}$ (green) and $5.8\mu\text{m}$ (red) Spitzer IRAC data taken from the NASA/IPAC Infrared Science Archive¹. From that figure, we can see that the new star appears isolated at about 1.4 arcmin from the cluster's centre, which for an estimated heliocentric distance of 7.6 kpc (Crowther et al. 2010) corresponds to a projected radial distance of about 3 parsecs. From a search in the CADC HST/HLA/WFPC2B Science Archive² for optical images of the NGC 3603 field, it was found a non-saturated F656N image (IB6WA1070 - P.I. O'Connell) in which we see that MTT 68 has a visual companion (MTT 68B - please see the inset in Figure 1) at an angular separation of $0.38''$. More on this subject will be discussed in Section 3.2.

Figure 2 shows the telluric corrected (continuum normalized) J-, H- and K-band SOAR-OSIRIS spectra of MTT 68, in which we can see the Paschen beta and Brackett hydrogen emission lines at $1.283\mu\text{m}$, $1.736\mu\text{m}$ and $2.166\mu\text{m}$, as well as the NIII and HeII lines (also in emission) at $2.116\mu\text{m}$ and $2.189\mu\text{m}$, respectively. In Figure 3 it is presented the MTT 68's J-, H- and K-band SOAR-OSIRIS spectra, together with those taken for HD93129A (O2If*), WR20a (O3If*/WN6 + O) and WR25 (O2.5If*/WN6). The spectral type O2If* was introduced in 2002 (Walborn et al. 2002), with HD93129A being probably the only known Galactic template of the class. It is considered the earliest, hottest, most massive and luminous O star in the Galaxy, showing an extremely powerful wind with a terminal velocity above 3000 km s^{-1} , and a mass-loss rate above $10^{-5}\text{ M}_{\odot}\text{ yr}^{-1}$ (Cohen et al. 2011). From the comparison of the MTT 68's NIR spectra with those for the templates, we can see that the

¹ <http://irsa.ipac.caltech.edu/data/SPITZER/docs/spitzerdataarchives/>

² <http://www3.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/hst/new/>

MTT 68's spectrograms resembles well those for HD93129A, indicating that it is probably a new Galactic exemplar of the rare O2If* type.

3.2 Mass, luminosity and binary status of MTT 68

We can estimate the mass of the MTT 68 components taking into account that the star is actually a visual binary system presenting an angular separation of $0.38''$, and by comparing their combined V-band magnitude and V-I color with those of other NGC 3603 cluster members, presented in Figure 7 of Sung & Bessell (2004). Also, from the comparison of the instrumental magnitudes of the two (non-saturated) point sources in the HST F656N image, we estimate as 1.2 mag the Δ_m difference for the MTT 68A and MTT 68B. Finally, and in order to simplify the process, we will assume that both stars have the same bolometric corrections, which is a reasonable assumption considering their probable very early spectral types. In Figure 4 we show an adapted version of the $V \times (V-I)$ diagram for NGC 3603 (Sung & Bessell 2004), with MTT 68A, MTT 68B and WR42e (estimated mass of $\sim 130 M_\odot$ - Roman-Lopes (2012); Gvaramadze et al. (2013) represented by black circles and gray triangle, respectively. WR42e is also shown there because it is a star of the O2If*/WN6 spectral type and as the MTT 68 system, possibly belongs to the same complex. From this diagram we can see that MTT 68A and MTT 68B probably presented initial masses well above $100 M_\odot$ and $40 M_\odot$, respectively.

To estimate the total luminosity of the MTT 68 binary system, it is necessary to compute the associated visual extinction considering that the interstellar reddening law for NGC 3603 is possibly abnormal, with a ratio of total to selective extinction value $R_V=3.55\pm 0.12$ (Sung & Bessell 2004). From Table 2, we can see that MTT 68 presents (B-V) color ~ 1.6 mag, which for an assumed mean intrinsic $(B-V)_0$ value of -0.3 mag (typical for the hottest early-type stars), corresponds to a color excess $E(B-V) \sim 1.9$ mag or $A_V \sim 6.7\pm 0.3$ mag. From the computed color excess and visual extinction, we can estimate the MTT 68's absolute magnitude using the distance modulus equation, assuming that the star is part of the NGC 3603 complex at a heliocentric distance of 7.6 ± 0.4 kpc (Crowther et al. 2010). We computed $M_V=-6.4$ mag for the binary system (or individually $M_V=-6.1$ and $M_V=-4.9$ for components A and B, respectively), which for an assumed mean bolometric correction $BC \sim -4.3$ mag (Crowther et al. 2010; Crowther & Walborn 2011), results in a bolometric magnitude $M_{Bol} \sim -10.7$ and in a total stellar luminosity of $1.5\times 10^6 L_\odot$. This total luminosity is similar to that derived by Moffat et al. (2002), which found $L\sim 1.3\times 10^6 L_\odot$ with an X-ray to total stellar luminosity ratio $L_X/L_{Bol} \sim 1\times 10^{-5}$, a value two orders of magnitude greater than the canonical value expected for single stars, e.g. $L_X/L_{Bol} \sim 10^{-7}$ (Cohen et al. 2011).

3.3 Similarities with the HD93129 system

From the measured angular separation ($0.38''$) and the assumed heliocentric distance of 7.6 kpc, it is possible to compute the linear projected (minimum) radial distance of the MTT 68 binary components as $r_{A-B} = 1.4\times 10^{-2}$ pc.

HD93129A is known to be an extremely powerful X-ray source, being part of the Trumpler 14 cluster in the Carina Nebula, at an heliocentric distance of 2.3 kpc (for more on it please see the work of Cohen et al. (2011) and references therein). As the new O2If* star, it has a visual companion named HD93129B (O3.5) at an angular separation of $2.7''$, which for the quoted distance corresponds to a linear projected radial distance of 3×10^{-2} pc, a value similar to that for the MTT 68 components. On the other hand, HD93129A has also another closer companion (HD 93129Ab) at only $0.053''$ that is supposed to be also of the same spectral type of HD 93129B (Cohen et al. 2011). Considering the observed X-ray to total stellar luminosity ratio of the MTT 68 system ($L_X/L_{Bol} \sim 1\times 10^{-5}$), it is reasonable to speculate that this might be also the case for MTT 68, e.g., the probable existence of a very close companion not resolved in the F656N HST images.

Certainly, new further spectro-photometric studies of the MTT 68 binary system are needed. In one hand, its present evolutionary stage can help us to better understand how such kind of system can be found (and build) in relative isolation (at about 3.1 pc from the NGC 3603 cluster centre). On the other hand (and may be even more important), its presence in the periphery of a star burst like cluster may represent a challenge to the present theory of formation and evolution of very massive stellar systems, in the sense that may be the unique conditions found in such kind of environment could produce very massive stars well beyond the core of stellar clusters like NGC 3603.

4 SUMMARY

In this work we communicate the identification of a new Galactic O2If* star (MTT 68) that is found in isolation at about $1.4'$ (about 3 pc considering a quoted heliocentric distance of 7.6 kpc) from the core of the star-burst cluster NGC 3603. Our main conclusions and results are:

1- By comparing its NIR spectra with those for HD 93129A (O2If*), WR20a (O3If*/WN6), and WR25 (O2.5If*/WN6), we conclude that the MTT 68's spectrograms resembles well those of the former, indicating that it is probably a new Galactic exemplar of the rare O2If* type.

2- From the inspection of F656N HST images of NGC 3603, it was determined that MTT 68 is actually a visual binary presenting an angular separation of $0.38''$. Also, from the instrumental photometry of the non-saturated MTT 68 point sources, it was possible to determine a magnitude difference $\Delta_m = 1.2$ magnitudes, which combined with the B-, V- and I-band photometry taken from the literature, resulted in a combined bolometric luminosity $M_{Bol} = -10.7$ ($M_{Bol} = -10.4$ and -9.2 for MTT 68A and MTT 68B, respectively) equivalent to a total stellar combined luminosity of $1.5\times 10^6 L_\odot$.

3- The total luminosity derived by us is similar to that obtained by Moffat et al. (2002), which found $L\sim 1.3\times 10^6 L_\odot$ with an X-ray to total stellar luminosity ratio $L_X/L_{Bol} \sim 1\times 10^{-5}$, a value two orders of magnitude above the canonical value for single stars, e.g. $L_X/L_{Bol} \sim 10^{-7}$ (Cohen et al. 2011).

4- From the associated V- and I-band photometry, the magnitude differences obtained from the HST F656N image

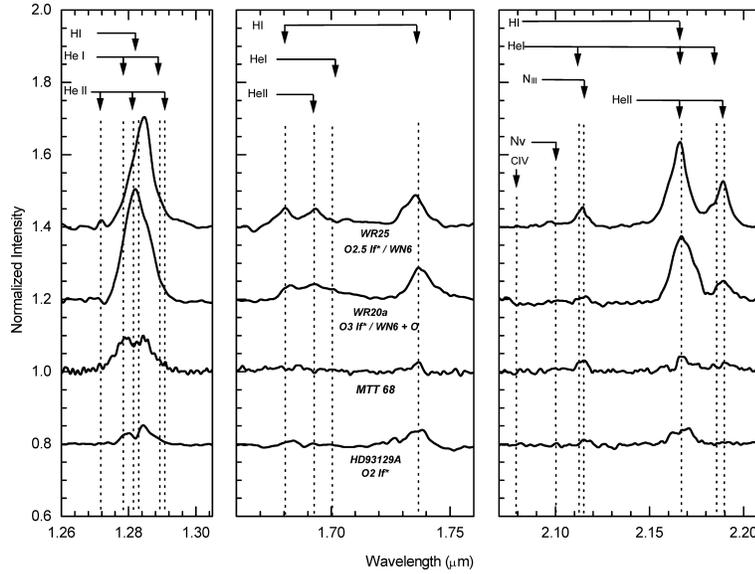


Figure 3. The J- H- and K-band continuum normalized SOAR-OSIRIS spectra of the MTT 68, together with the NIR spectrograms of HD93129A (O2If*), WR20a (O3If*/WN6 + O3If*/WN6) and WR25 (O2.5If*/WN6), with the main H, He and N emission lines identified by labels. By comparing the MTT 68's NIR spectra with those for the templates, we can see that the MTT 68's spectrograms resembles well those of HD93129A, indicating that it is probably a new Galactic exemplar of the O2If* type.

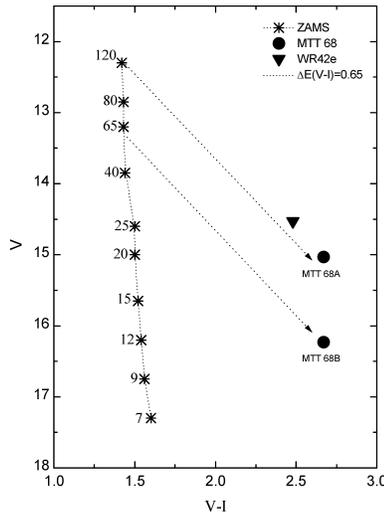


Figure 4. The $V \times (V-I)$ diagram (based on Figure 7 of the work of Sung & Bessell (2004), with MTT 68A and MTT 68B represented by the black circles, and WR42e $\sim 130M_{\odot}$ - (Gvaramadze et al. 2013) by the black triangle. The non-reddened main sequence at the quoted distance of 7.6 kpc (Crowther et al. 2010) for masses between $7M_{\odot}$ to $120M_{\odot}$ is represented by the black dotted vertical line, with the black stars indicating the position of each mass bin. Also, the reddening vector taken from the work of Sung & Bessell (2004) is represented by the line-dotted arrows. From this diagram we can see that the initial mass of MTT 68A (the new O2If* star), possibly exceed $100M_{\odot}$. On the other hand, despite the fact that MTT 68B is probably 1.2 magnitudes fainter than MTT 68A, it is still a very massive star with probable initial mass well above $40M_{\odot}$.

Table 2. Coordinates (J2000), Optical/NIR photometry, and X-ray parameters of MTT 68. The BVRI photometry was taken from Sung & Bessell (2004), while the near-infrared magnitudes are from Cutri et al. (2003), and the absorption-corrected 0.5-10keV flux was obtained from the work of Romano et al. (2008).

RA (J2000)	Dec (J2000)	B	V	R	I	J	H	Ks	X-Ray (Wm^{-2})
11:14:59.48	-61:14:33.9	16.31	14.72	13.64	12.05	9.98	9.17	8.74	12.9×10^{-16}

and stellar models previously published for the NGC 3603 massive stellar population, it was possible to conclude that MTT 68A and MTT 68B probably presented initial masses above $100 M_{\odot}$ and $40 M_{\odot}$, respectively.

5- We found some interesting similarities with the well known multiple system HD 93129. In one hand, the measured angular separation of the MTT 68 binary components ($0.38''$) corresponds to a projected (minimum) linear distance of $r_{A-B} = 1.4 \times 10^{-2}$ pc, a value similar to that for HD 93129A (O2If*) and HD 93129B (O3.5), e.g., $r_{A-B} = 3.0 \times 10^{-2}$ pc. On the other hand, HD93129A has another closer companion named HD 93129Ab (O3.5) at only $0.053''$ (Cohen et al. 2011). Considering the observed X-ray to total stellar luminosity ratio for the MTT 68 system ($L_X/L_{Bol} \sim 1 \times 10^{-5}$), it is possible that some another very close massive companion, not resolved in the F656N HST images, is still to be detected in the MTT 68's binary system.

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