The VLT-FLAMES Tarantula survey: III. A very massive star in apparent isolation from the massive cluster R136


DOI
10.1051/0004-6361/201117043

Publication date
2011

Document Version
Final published version

Published in
Astronomy & Astrophysics

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
LETTER TO THE EDITOR

The VLT-FLAMES Tarantula Survey

III. A very massive star in apparent isolation from the massive cluster R136*


1 Armagh Observatory, College Hill, Armagh BT61 9DG, UK
2 Centro de Astrobiología (CSIC-INTA), Ctra. de Torrejón a Ajalvir km-4, 28850 Torrejón de Ardoz, Madrid, Spain
3 UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill, Edinburgh, EH9 3HJ, UK
4 Excellence Cluster Universe, Boltzmannstr. 2, 85748 Garching, Germany
5 School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK
6 Institute of Astronomy & Astrophysics, National Observatory of Athens, I. Metaxa & Vas. Pavlou Street, P. Penteli 15236, Greece
7 European Southern Observatory, Karl-Schwarzschild-Strasse 2, 87548 Garching bei München, Germany
8 Harvard-Smithsonian CfA, 60 Garden Street, Cambridge, MA 02138, USA
9 Dept. of Physics & Astronomy, Hounsfield Road, University of Sheffield, S3 7RH, UK
10 Argelander-Institut für Astronomie der Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
11 SUPA, IfA, University of Edinburgh, Royal Observatory Edinburgh, Blackford Hill, Edinburgh, EH9 3HJ, UK
12 Departamento de Astrofísica, Universidad de La Laguna, 38205 La Laguna, Tenerife, Spain
13 European Southern Observatory, Alonso de Cordova 1307, Casilla 19001, Santiago 19, Chile
14 Astronomical Institute Anton Pannekoek, University of Amsterdam, Kruislaan 403, 1098 SJ, Amsterdam, The Netherlands
15 Astronomical Institute, Utrecht University, Princetonplein 5, 3584CC, Utrecht, The Netherlands
16 ESA, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
17 Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008 Granada, Spain
18 Warsaw University Observatory, Aleje Ujazdowskie 4, 00-478 Warsaw, Poland

Received 6 April 2011 / Accepted 2 May 2011

ABSTRACT

VFTS 682 is located in an active star-forming region, at a projected distance of 29 pc from the young massive cluster R136 in the Tarantula Nebula of the Large Magellanic Cloud. It was previously reported as a candidate young stellar object, and more recently spectroscopically revealed as a hydrogen-rich Wolf-Rayet (WN5h) star. Our aim is to obtain the stellar properties, such as its intrinsic luminosity, and to investigate the origin of VFTS 682. To this purpose, we model optical spectra from the VLT-FLAMES Tarantula Survey with the non-LTE stellar atmosphere code cmfgen, as well as the spectral energy distribution from complementary optical and infrared photometry. We find the extinction properties to be highly peculiar (RV ~ 4.7), and obtain a surprisingly high luminosity log(L/Lo) ∼ 6.5 ± 0.2, corresponding to a present-day mass of ~150 M⊙. The high effective temperature of 52.2 ± 2.5 kK might be explained by chemically homogeneous evolution – suggested to be the key process in the path towards long gamma-ray bursts. Lightcurves of the object show variability at the 10% level on a timescale of years. Such changes are unprecedented for classical Wolf-Rayet stars, and are more reminiscent of Luminous Blue Variables. Finally, we discuss two possibilities for the origin of VFTS 682: (i) the star either formed in situ, which would have profound implications for the formation mechanism of massive stars, or (ii) VFTS 682 is a slow runaway star that originated from the dense cluster R136, which would make it the most massive runaway known to date.

Key words. stars: Wolf-Rayet – stars: early-type – stars: atmospheres – stars: mass-loss – stars: fundamental parameters

1. Introduction

Recent claims for the existence of very massive stars (VMS) of up to 300 M⊙ at the centre of young clusters like R136 (Crowther et al. 2010) seem to link the formation of such objects to environments in the centres of massive clusters with ~10^4–10^5 M⊙. This finding thus appears to support massive star-forming models that invoke competitive accretion and possibly even merging in dense clusters (e.g. Bonnell et al. 2004). Such scenarios emerged after it became clear that the disk-accretion scenario – commonly applied to low- and intermediate star formation – had problems explaining the formation of stars with masses above 10 M⊙, as radiation pressure on dust grains would halt and reverse the accretion flow onto the central object (e.g. Yorke & Kruegel 1977). However, recent multi-dimensional hydrodynamical monolithic collapse simulations indicate that massive stars may form via disk accretion after all (e.g. Kuiper et al. 2010). This illustrates that the discussion on clustered vs. isolated massive star formation is still completely open (see de Wit et al. 2005; Parker & Goodwin 2007; Lamb et al. 2010; Bressert et al., in prep.).
In this Letter, we present evidence that VFTS 682 (RA 05h38m55.51s Dec −69°04′26.72″) in the Large Magellanic Cloud (LMC), found in isolation from any nearby massive, visible cluster, is one of the most massive stars known. The object suffers from high dust obscuration and is located in, or in the line-of-sight towards, an active star-forming region. On the basis of a mid-infrared (mid-IR) excess, Gruendl & Chu (2009) classified the star as a probable young stellar object (YSO). The VLT-FLAMES Tarantula Survey (VFTS) (Evans et al. 2011) identified it as a new Wolf-Rayet (WR) star, at a projected distance of 29 pc (for an assumed LMC distance of 50 kpc).

2. Spectroscopic analysis of VFTS 682

The analysis is based on spectroscopic observations (\( \lambda 4000−7000 \)) from MEDUSA mode of VLT-FLAMES (Evans et al. 2011). We first compared observations taken at different epochs (Evans et al. 2011) as to identify potential shifts in the radial velocity (RV) as a result of binarity. To this purpose, we used the N\textsc{iv} \( \lambda 4060 \) emission line. With detection probabilities of 96% for a period \( P < 10 \) d, 76% for 10 d \(< P < 1 \) yr, and 28% for 1 yr \(< P < 5 \) yr, we can basically exclude that VFTS 682 is a short period binary. We found the N\textsc{v} \( \lambda 4944 \) line to be particularly useful for RV determinations, as this line remained stable for different wind velocity laws. With particular emphasis on the centroid of the line we obtained 300 ± 10 km s\(^{-1}\). If we give more weight to the red wing, we obtain 315 ± 15 km s\(^{-1}\), with a similar number for the He\textsc{ii} \( \lambda 4686 \) line.

For the spectral analysis we use the non-LTE model atmosphere code cmfgen (Hillier & Miller 1998) which has been developed to provide accurate abundances, stellar parameters, and ionising fluxes for stars dominated by wind emission lines. We use atomic models containing H\textsc{i}, He\textsc{i}, C\textsc{iii}-\textsc{iv}, N\textsc{iii}-\textsc{v}, O\textsc{iii}-\textsc{vi}, Si\textsc{iv}, P\textsc{iv}, S\textsc{v}, Fe\textsc{iv}-\textsc{vii}, and Ni\textsc{iv}-\textsc{vi}. We made the following assumptions. We adopt a metallicity of half solar with respect to Asplund et al. (2005), and assume N and He to have been enriched by the CNO process. We adopt a 12-fold enhancement of the N mass fraction. We employ a \( \beta \) parameter of 1.6 for the wind velocity law and a wind volume filling factor of \( f = 0.25 \), assuming that the clumping starts at 10 km s\(^{-1}\). In order to estimate the error bars in the stellar temperature (\( T_\ast \)) and mass-loss rate (\( M \)), we computed a grid of models around the preferred values.

The core temperature (\( T_\ast \)) at high optical depth of 54 500 ± 3000 K is based on the N\textsc{iv} \( \lambda 4406 \) and N\textsc{v} doublet, \( \lambda 4604 \) and \( \lambda 4620 \) in emission (Fig. 2). N\textsc{iv} is also sensitive to the mass-loss rate, which is obtained from other lines. The hydrogen and the helium lines are used to determine both the helium abundance (45% by mass) and the mass-loss rate, with \( \log(M/M_\odot \text{yr}^{-1}) = −4.4 ± 0.2 \), where the volume filling factor corrected mass-loss rate is given in Table 1. This value is larger than the \( \log(M/M_\odot \text{yr}^{-1}) = −6.97 \) obtained from the mass-loss recipe of Vink et al. (2001) for non-clumped winds. The values can be brought into agreement for a volume filling factor of \( f = 0.1 \). In the absence of UV spectroscopy of the \( \lambda 1548, \lambda 1551 \) C\textsc{iv} doublet, we estimate the terminal velocity \( v_{\text{t}} = 2600 \text{ km s}^{-1} \) from the broadening of the He\textsc{ii} and H\textsc{i} lines. An overview of the stellar parameters and abundances is provided in Table 1.

The stellar parameters of VFTS 682 are similar to those of R136a3 (with a \( \log(L/L_\odot) = 6.58 \)) (Crowther et al. 2010). We note that there are other luminous WN\textsc{h} objects in 30 Dor, for instance, VFTS 617 (= Br 88) which has the same spectral type as VFTS 682 but with weaker emission lines. The spectral analysis of the additional VFTS WN\textsc{h} stars is currently in progress (Bestenlehner et al., in prep.).
Table 2. Apparent magnitude of VFTS 682.

<table>
<thead>
<tr>
<th></th>
<th>U</th>
<th>B</th>
<th>V</th>
<th>J</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evans et al. (2011)</td>
<td>–</td>
<td>16.66</td>
<td>16.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parker (1993)</td>
<td>16.40</td>
<td>16.75</td>
<td>16.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DENIS (2005)</td>
<td></td>
<td></td>
<td></td>
<td>14.89</td>
<td></td>
</tr>
</tbody>
</table>

Notes. (1) Transformed to the 2MASS system.

3. Luminosity and reddening

In its spectral appearance, VFTS 682 is almost identical to that of R136ab in the core of the dense cluster R136. The luminous objects in this cluster are thought to be the most massive stars known, with initial masses up to 300 $M_\odot$ (Crowther et al. 2010). As VFTS 682 is apparently isolated, and shows no signs of binarity, it offers the opportunity to study such a luminous WN5h object in isolation. The precise luminosity of VFTS 682 is thus of key relevance for this work. Its derivation is however complicated by the large extinction.

Matching the optical photometry with a standard extinction law, i.e., a ”Galactic average” extinction parameter $R_V = 3.1$, we obtain a luminosity of $\log(L/\odot) = 5.7 \pm 0.2$. With this relatively low luminosity we can explain the optical flux distribution, but we fail to match the observed spectral energy distribution (SED) at longer wavelengths. In the near–mid infrared (IR) the observed flux is ~3 times higher than the corresponding model flux. Below, we show that we can successfully explain this ”excess” IR emission, including its exact shape, with a reddening parameter $R_V = 4.7$, which leads to a much higher stellar luminosity. This effect is visualised in the colour–magnitude diagram (CMD) of Fig. 4. We note that high $R_V$ parameters, that deviate from the Galactic average, are not extra-ordinary for massive stars in the LMC (e.g. Bonanos et al. 2011).

3.1. Modelling the near IR flux

Because the extinction in the IR is very low, we can avoid the problems resulting from the uncertain $R_V$ parameter, by choosing the near-IR photometry as our flux standard. In more detail, we derive the luminosity of VFTS 682 by matching $B$, and $V$ from Parker (1993), and $K_s$ from the ”InfraRed Survey Facility (IRSF) Magellanic Clouds Point Source Catalog” (Kato et al. 2007, see Table 2). For this purpose we extract the intrinsic $B$, $V$, and $K_s$ magnitudes from our model, using appropriate filter functions. Based on the resulting values of $E(B-V) = 0.94 \pm 0.02$, and $E(V-K_s) = 3.9$, we derive $R_V = A_V/E(B-V)$ for two oft-used extinction laws.

To determine $R_V$, we use the relations $R_V = 1.1994 \times E(V-K_s)/E(B-V)$, as inferred from the extinction law by Cardelli et al. (1989), and $R_V = 1.12 \times E(V-K_s)/E(B-V) + 0.016$, from Fitzpatrick (1999). This way, we obtain $R_V = 4.7 \pm 0.1$, $A_V = 4.45 \pm 0.12$, and $A_{K_s} = 0.55 \pm 0.15$, where the uncertainties refer to the differences in the adopted extinction laws. As $A_V$ is much larger than $A_{K_s}$, the derived luminosity mostly relies on $K_s$, while the observed values of $B$, and $V$ mostly determine $R_V$. Small uncertainties in $B-V$ will thus mainly affect $R_V$, in a way that the absolute values of $B$, and $V$ stay the same. As $R_V = A_V/E(B-V)$, this introduces an anti-correlation between the derived $R_V$, and $E(B-V)$, where $A_V$ is preserved. The resulting luminosity is $\log(L/\odot) = 6.5 \pm 0.2$, where the error includes uncertainties in the stellar temperature, mass-loss rate, and extinction. The resulting SED fit is presented in Fig. 3.

In an independent analysis of the available $UBVIHK$ photometry, using the CHORIZOS code (Maíz-Apellániz 2007) for CHi-square cOde for parameteRized modelling and characterizAtion of phOtometry and Spectrophotometry, we obtain $E(B-V) = 0.98 \pm 0.03$, and $R_V = 4.55 \pm 0.17$, which, due to the aforementioned anti-correlation between $E(B-V)$ and $R_V$, results in an almost unchanged value of $A_V = 4.46 \pm 0.06$. The resulting luminosity, and high $R_V$ are thus confirmed.

Table 2 gives a summary of the available photometry for VFTS 682. In analogy to our previous findings, the differences between the optical photometry of Evans et al. (2011), and Parker (1993) mainly affect $R_V$, but not the derived luminosity. Based on the WFI photometry by Evans et al. (2011), we obtain $R_V = 5.2 \pm 0.1$ with $E(B-V) = 0.84 \pm 0.02$. The near-IR photometry however has a direct influence on our results. Based on the fainter Two Micron All Sky Survey (2MASS) photometry the derived luminosity decreases by about 0.1 dex to $\log(L/\odot) = 6.4$. In this work, we use the IRSF values, as they connect better to the observed Spitzer MIR photometry.

If we alternatively adopt the standard reddening parameter $R_V = 3.1$, and attribute the NIR excess to a second component,
such as a cool star and/or a warm (1000–2000 K) dust component (see Fig. 3), we obtain a luminosity of only log($L$) = 5.7 ± 0.2. We note that just one extra component (cool star and/or dust black body) cannot fit the entire SED slope, which implies that we would need a multitude of additional components. These would need to conspire in such a way as to precisely follow our SED. Although we cannot dispute such a configuration, it would be highly contrived.

To summarise, the most likely luminosity of VFTS 682 is log($L$) ≈ 6.5 ± 0.2, which would support the high luminosities that have been derived by Crowther et al. (2010) for the VMS in the core of R 136.

3.2. The MIR excess

We also investigate the issue of whether VFTS 682 has a mid-IR excess in Spitzer data. In contrast to the SAGE IRAC Catalog, Gruendl & Chu (2009) included spatially more extended sources. The MIR photometry data from both sources are listed in Table 2. Gruendl & Chu (2009) detected a mid-IR excess at 5.8 and 8.0 μm and categorised VFTS 682 as a YSO candidate. We are not able to confirm the MIR excess on the basis of the SAGE IRAC Catalog photometry, but the difference in the two data sources may be explained in the following way.

The MIR point-source data of Meixner et al. (2006) basically follow the slope of our optical-to-NIR fit continued into the MIR, whilst the larger scale MIR data of Gruendl & Chu (2009) show a clear MIR excess. Whereas the MIR excess could be consistent with an extended circumstellar shell, such as recently detected in Spitzer 24 micron images of the Galactic Centre WNH star WR102ka (Barniske et al. 2008), there is no evidence for such a shell (or bowshock) in Spitzer 8 micron images of VFTS 682 at similar angular scales as for WR102ka. However, given the resolution limit of ~2 arcsec the IR excess might be due to an unresolved circumstellar shell with a diameter of <0.5 pc.

4. Variability on timescales of years

To study the stability of VFTS 682 we show Optical Gravitational Lensing Experiment (OGLE-III) lightcurves (Udalski et al. 2008) in $V$ and $I$ in Fig. 5. On top of the short-term jitter, the object clearly dimmed by ~0.1 mag in both the $V$ and $I$ band during the years 2006–2009. Furthermore, the object shows an increase in the K-band by ~0.15 mag during 2010 (Evans et al., in prep.). This kind of long-term variability is unprecedented for Wolf-Rayet stars, and is more characteristic for Luminous Blue Variables (LBVs). However, we note that the nature of these changes is not the same as those of bona-fide LBVs with S Doradus cycles of 1–2 mag variations (Humphreys & Davidson 1994).

5. Discussion on the origin of VFTS 682

VFTS 682 is located in an active star-formation region of 30 Dor (Johansson et al. 1998). It is not anywhere close to the core of R136, or – as far as we can tell – to any other nearby cluster. This might be considered a surprise as VMS are normally found in the cores of large clusters, such as the Arches cluster or R136. By contrast, VFTS 682 is rather isolated at a projected distance of 29 pc from R136. This raises the question of whether the object formed in situ or is a slow runaway object from R136 instead.

In order to address these issues, we provide some velocity estimates. The measured RV shift of VFTS 682 is $v_t \approx 300$ km s$^{-1}$, which is somewhath higher than the average velocity in 30 Dor ($\sim$270 ± 10 km s$^{-1}$, Sana et al., in prep.; Bosch et al. 2009). If VFTS 682 is a runaway from R136, it would require a tangential velocity of 30 km s$^{-1}$ to appear at a projected distance of 30 pc within approximately 1 Myr. Together with an RV offset of ~30 km s$^{-1}$, VFTS 682 would then require a true velocity of ~40 km s$^{-1}$, i.e. at the lower range of velocities for classical OB runaway stars (e.g. Phlip et al. 1996). This, would make it the most massive runaway star known to date.

In case the object is a runaway star, a bow shock might potentially be visible as VFTS 682 is surrounded by dust clouds. Whilst there is currently no evidence for a bow shock, one of the possible explanations for the MIR excess is the presence of a bow-shock (e.g. Gvaramadze et al. 2010). Alternative explanations for the MIR excess may involve its (line-of-sight) association with an active star forming region, or a nebula formed by vigorous mass loss since the object started to burn hydrogen in its core. In this context, it may or may not be relevant that VFTS 682 shows slow photometric variations suggestive of LBV’s that may suffer from mass ejections.

The most probable luminosity of VFTS 682 is log($L$) = 6.5 ± 0.2. The question is what stellar mass the object corresponds to, and what is its most likely evolutionary age. The high temperature places the object right on the zero-age main sequence (ZAMS), which can be best understood as a result of chemically homogeneous evolution (CHE). Such an evolution has also been proposed for two WR stars in the SMC (Martins et al. 2009). Note that this type of evolution has been suggested for the production of long gamma-ray bursts (Yoon & Langer 2005). In order to obtain a meaningful mass limit, we employ the recent mass-luminosity relationships by Gräfener et al. (2011) for homogeneous hydrogen burners. Utilising the derived He abundance ($Y \approx 0.45$), the most likely present-day mass is ~150 $M_\odot$. In detailed stellar evolution models of Brott et al. (2011) and Friedrich et al. (in prep), CHE is achieved through rapid rotation, with $v_{\text{rot}} > 200$ km s$^{-1}$. A value of $Y = 0.45$ is obtained at an age of 1–1.4 Myr and the initial mass would be of ~120–210 $M_\odot$, where the mass range is defined through the uncertainty in the luminosity.

Finally, from our analysis it is clear that VFTS 682 is a very massive object. It is often assumed that such massive objects can only be formed in dense cluster environments, where they are normally found. The apparent isolation of VFTS 682 may thus represent an interesting challenge for dynamical ejection scenarios and/or massive star formation theory.
References

Bosch, G., Terlevich, E., & Terlevich, R. 2009, AJ, 137, 3437
DENIS. 2005, VizieR Online Data Catalog, 1, 2002

Maíz-Apellániz, J. 2007, ASPCS, 364, 227