The Lives and Death-Throes of Massive Stars
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Re-examing the Upper Mass Limit of Very Massive Stars: VFTS 682, an isolated $\sim$130 $M_\odot$ twin of R136's WN5h core stars.

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Abstract. Recent studies of WNh stars at the cores of young massive clusters have challenged the previously accepted upper stellar mass limit ($\sim$150 $M_\odot$), suggesting some of these objects may have initial masses as high as 300 $M_\odot$. We investigated the possible existence of observed stars above $\sim$150 $M_\odot$ by *i)* examining the nature and stellar properties of VFTS 682, a recently identified WNh5 very massive star, and *ii)* studying the uncertainties in the luminosity estimates of R136's core stars due to crowding. Our spectroscopic analysis reveals that the most massive members of R136 and VFTS 682 are very similar and our K-band photometric study of R136's core stars shows that the measurements seem to display higher uncertainties than previous studies suggested; moreover, for the most massive stars in the cluster, R136a1 and a2, we found previous magnitudes were underestimated by at least 0.4 mag. As such, luminosities and masses of these stars have to be significantly scaled down, which then also lowers the hitherto observed upper mass limit of stars.

1. Introduction

One of the key questions still to be addressed by the theory of very massive stars (VMS) formation is the existence and quantification of an upper stellar mass cutoff (Zinnecker *et al.* 2007). In 2005, Figer and Oey & Clark proposed an UPper Mass Limit (UPML) for massive stars around 150 $M_\odot$. However, this limit has been challenged by the massive stars located in the core of the young massive cluster R136 in the Large Magellanic Cloud. In particular, the initial masses estimated for the most deeply embedded stars in the core, a1, a2 and a3, by Crowther *et al.* (2010) (hereafter, CRW10) and Crowther *et al.* (2016) (hereafter, CRW16), range between 165-320 $M_\odot$.

Another question regards the nature of such massive objects, assuming they are single. Being located at the dense cores of young clusters, deep analysis of such VMS can be severely affected by crowding, which then can directly influence the photometric accuracy and, thus, the inferred luminosities and stellar masses.

Interestingly, in 2011 a new young WN5h VMS ($\sim$150 $M_\odot$), called VFTS 682 (#682), was discovered 30 pc from the young massive cluster, R136 (Evans *et al.* 2011, Bestenlehner *et al.* 2011; hereafter, BES11). Being in isolation, the aforementioned crowding problem disappears. Moreover, BES11 noted that this star shows a great resemblance in the optical with one of the members of R136's core stars, a3. In other words, #682 may be a key object for further examining the possible existence of VMS with initial masses above 150 $M_\odot$.

Thus, we obtained and analyzed VLT/XShooter full optical to NIR spectroscopic observations of #682, as well as available archival data at different wavelengths (FLAMES

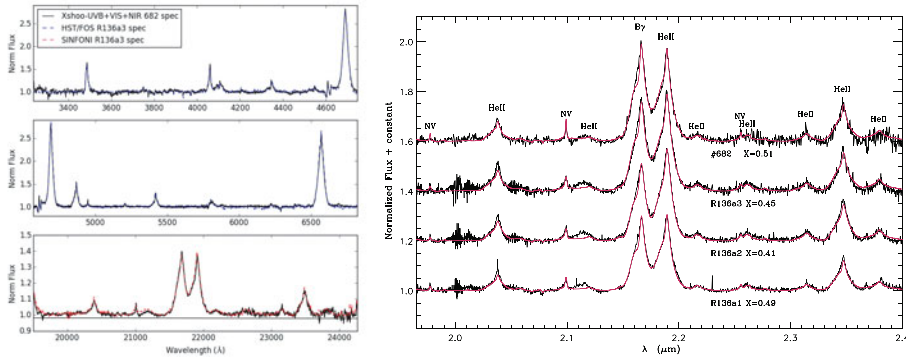

Figure 1. *Left:* a3 UV HST/FOS (blue) and VLT/SINFONI K-band (red) spectra compared to UVB and NIR XShooter #682 spectra (black). *Right:* From top to bottom, CMFGEN model fits (magenta) to XShooter and SINFONI K-band spectra of #682, a3, a2 and a1, respectively.

spectra). Simultaneously, we compared these data with available archive observations of a3 (FOS spectra; SINFONI/K-band spectral cubes).

2. Analyzing VFTS 682

Our detailed quantitative spectroscopy analysis by CMFGEN provided an excellent fit to the observed 3000 to 25000 Å of the spectrum of #682, together with an improved determination of the stellar properties and metal abundances ($T^{*}_{\tau 10}$ = 51.2 kK; log $L/L_{\odot}$=6.48; v_{∞} = 2350 Kms^{-1}; f = 0.1; log $\dot{M}$ = -4.53; X_H = 0.51) with respect to BES11. Using evolutionary tracks by Köhler *et al.* (2015), we estimated a $M_{current}$ ~130 $M_{\odot}$ and $M_{initial}$ ~ 145 $M_{\odot}$ for #682 (table 2).

In addition, the spectral resemblance between XShooter spectra of #682 and FOS optical and SINFONI K-band spectra of a3 is quite clear: they are almost spectroscopic twins (see fig.1-left). Furthermore, by comparing K-band spectra of #682, a1, a2 and a3†, we observed that the stars are very similar, being the hydrogen mass fraction in these four stars slightly different‡ (see fig.1-right). Moreover, according to CRW10 and CRW16, a1, a2 and a3 also have the same T_{eff} and extinction parameters. However, their luminosity estimates, and therefore their stellar masses, are quite different. Thus, the main difference between these stars comes from their estimated K magnitudes. In order to understand this apparent contradiction, we revisited the SINFONI K-band estimates of R136's core stars.

3. Revisiting SINFONI R136 data

We performed spectrophotometry of the SINFONI spectral data cubes of the most massive members of R136's core, i.e. c, b, a3, a2 and a1. We used a 2MASS filter curve and two different absolute flux calibrators, the standard star (STD) of the night and the star c (K = 11.34 ± 0.08, Campbell *et al.* 2010). We also included b and c in our study and used c as calibrator star for consistency with the procedure followed by CRW10.

The spectra of the stars were extracted for aperture radii from 1×FWHM (~4 pixels) to 2×FWHM (~11 pixels), except for a1 and a2. Because of their proximity, the higher the aperture radius, the higher the contamination by the closer companion. Therefore, for a1 and a2 only spectra with aperture radii as large as 7 px were extracted.

† SINFONI K-band observations cover R136's core stars b, c, a3, a2 and a1.
‡ The Br_{γ} to HeII lines ratio is very sensitive to changes in the Hydrogen mass-fraction

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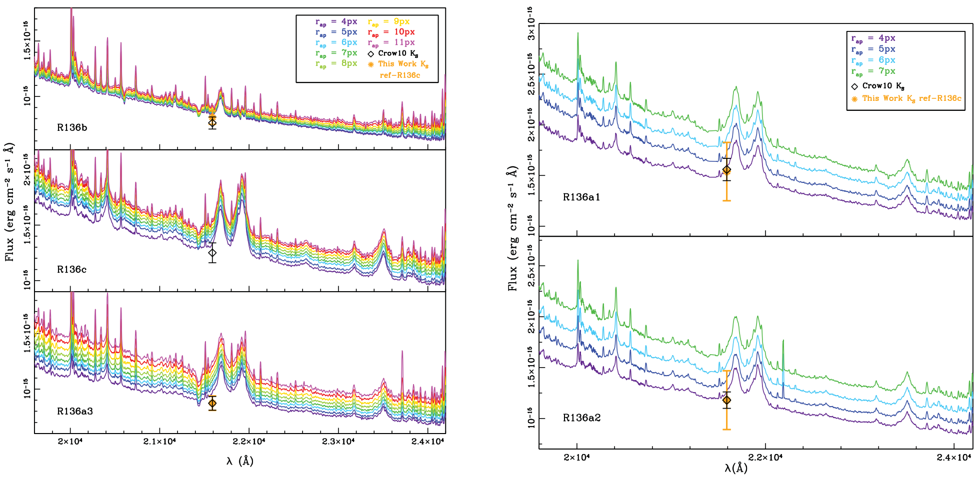

Figure 2. Flux calibrated SINFONI K-band spectra of c, b, a3, a2 and a1 for the noBS approach. Each color represents the flux-calibrated spectra extracted with different aperture radii. Black symbols represent photometric values by CRW10. Yellow symbols represent our computed K values an aperture radius of ∼4 pixels and c as flux calibrator.

In order to analyze how crowding affects flux estimates, we applied two different approaches, not subtracting (noBS) and subtracting (BS) the background estimated from an annulus aperture.

Thus, in the noBS approach (fig.2) we found not only that the flux of the stars increases with aperture radius but also that this increment is larger for those stars placed in areas with higher crowding. We recovered CRW10's K-band estimates of b, a1, a2 and a3, for the smallest aperture radii and using c as flux calibrator (fig.2). On the other hand, when appliying the BS approach the flux converges with increasing aperture radius, as expected in aperture photometry. However, this is true only for the "most" isolated stars in the sample, i.e. b, c and a3 (fig.3-left). For the most embedded stars, a1 and a2, the flux not only never converges with aperture radius but also shows an irregular behaviour, which is very likely due to crowding (fig.3-right). In sight of this, it is not possible to compute reliable K-band estimates for a1 and a2, but just to provide lower limits to their K magnitudes.

We concluded that the most reliable K-band estimates are those obtained with the BS approach and using the STD star as absolute flux calibrator. We discarded c as reliable flux calibrator since it is suspected to be a binary system (Townsley *et al.* 2006, Schnurr *et al.* 2009), and also has a high uncertainty in its estimated K magnitude (Campbell *et al.* 2010).

We present the estimated K magnitudes in this work for R136's core stars compared with previous published values (CRW10) in table 1. Note that as crowding increases (from c to a2), not only the uncertainty in the measurement increases but also the difference between the K values estimated in this work and by CRW10. For a1 and a2, the K magnitudes in table 1 are actually lower limits (upper limits to their luminosities), corresponding to the computed values for an aperture radius of 4 pixels, for which the estimated flux will be less contaminated by the closer companion.

4. Discussion and Conclusions

The major findings in this work are that, in general, the uncertainty in the flux measurements heavily depends on the followed methodology and the used flux calibrator, and

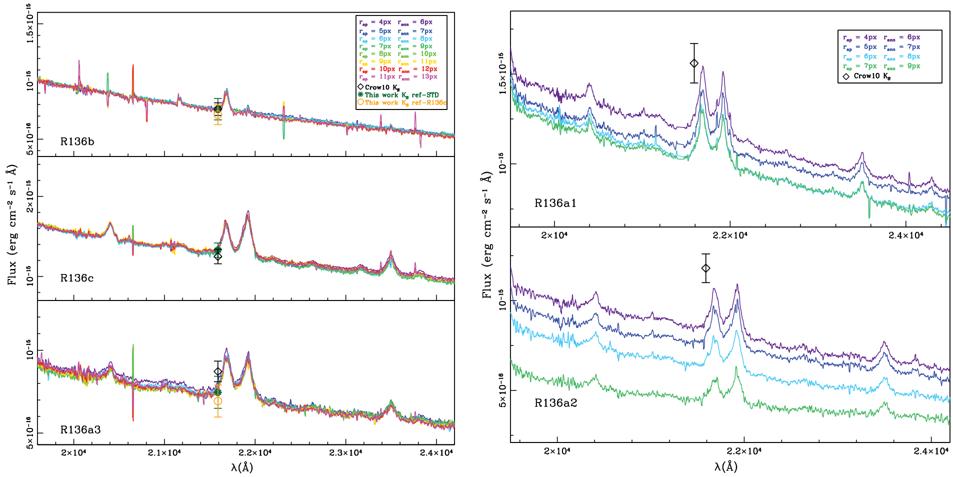

Figure 3. Flux calibrated SINFONI K-band spectra of c, b, a3, a2 and a1 for the BS approach. Each color represents the flux-calibrated spectra for different aperture and annulus radii. Black symbols represent previous estimates by CRW10. Yellow and green symbols represent our computed K values, using c and the STD star as flux calibrators, respectively.

Table 1. K_S magnitudes derived in this work for R136's core stars compared with previous values by CRW10.

Source	This work	CRW10
R136c	11.27 ± 0.09	11.34 ± 0.08
R136b	11.89 ± 0.11	11.88 ± 0.08
R136a3	11.91 ± 0.20	11.73 ± 0.08
R136a2*	$\gtrsim$ 11.89± 0.30	11.40 ± 0.08
R136a1*	$\gtrsim$ 11.51± 0.30	11.10 ± 0.08

* Corresponding to the smallest aperture radius.

that neglecting background contamination in crowded regions can lead to underestimating magnitudes. In particular, we found that the K magnitudes previously derived for the R136's core stars studied in this work were underestimated, by 0.2 magnitudes in the case of a3, and by 0.4 magnitudes, at least, for a2 and a1. To check how reliable our magnitude corrections are and if they are consistent with the measurements at other wavelengths, we compared the estimated K-band flux in this work with their UV fluxes in the literature (Hunter *et al.* 1995, Heap *et al.* 1994, de Marchi *et al.* 2011, CRW16). If a1, a2 and a3 have the same spectral type (WN5h), temperature and extinction (CRW10, CRW16), then the ratio between the fluxes of the stars in UV is the same as their flux ratio in K-band. Of the three stars, a3 is least affected by crowding† and its measured fluxes at UV and 5550Å are relatively stable ($\mathrm{F1500A}^{a3}_{Heap1994} \approx \mathrm{F1500A}^{a3}_{CRW16}$; $\mathrm{WFC2}^{a3}_{Hunter1995} \approx \mathrm{WFC3}^{a3}_{deMarchi2013}$). Therefore, we decided to use a3 as the reference star. Following this rationale, the UV a3/a1 and a3/a2 flux ratios are 0.71 and 1.24, respectively (CRW16). Thus, if K(a3) = 11.91, we would obtain a K-band value of 11.54 and 12.14 for a1 and a2, respectively. Note that whereas the K magnitude estimated this way for a1 is very close to our computed lower limit of 11.51, for a2 this value is even higher than our lower

† Multi-wavelength images show a3 as less contaminated by crowding than a1 and a2 (HST/WFC2-WFC3, MAD/H-K; SINFONI/K-band)

limit estimate of 11.89 (table 1). In other words, our K-band values are quite consistent, while, probably, the lower limit of the K magnitude for a2 is still underestimated.

Finally, our K-band corrections for a3, a2 and a1 lead to the determination of lower luminosities than previous estimates, by 0.1, 0.14 and 0.3 dex for a3, a2, a1, respectively. Using evolutionary tracks by Köhler *et al.* (2015), these corrections in luminosity translate into lower current masses and, therefore, into considerably lower initial masses than previous estimates for a1, a2 and a3 (table 2).

Source	**log L/L**$_\odot$	**M**$_{curr}$ $(M_\odot)$	**M**$_{ini}$ $(M_\odot)$	τ (Myr)	**Ref.**
#682	**6.48 ± 0.2**	**131 ± 25**	**147 ± 29**	**1.44 ± 0.25**	**This work**
R136a3	**6.48 ± 0.2**	**123 ± 24**	**141 ± 30**	**1.70 ± 0.16**	**This work**
	6.58 ± 0.09	175 ± 35	180 ± 35	1.5 ± 0.2	CRW16
R136a2	$\lesssim$ **6.49**	$\lesssim$ **120**	$\lesssim$ **140**	**1.74 ± 0.55**	**This work**
	6.63 ± 0.09	190 ± 35	195 ± 35	1.6 ± 0.2	CRW16
R136a1	$\lesssim$ **6.64**	$\lesssim$ **171**	$\lesssim$ **194**	**1.2 ± 0.42**	**This work**
	6.94 ± 0.09	315 ± 55	325 ± 50	0.8 ± 0.2	CRW16

Table 2. Luminosities, ages (τ) and current and initial masses estimated in this work and by CRW16.

In summary, our analyses reveal that the most massive members of R136 and #682 are very similar stars, a3 and #682 are basically twins, and confirm that crowding can severely affect flux estimates. In particular, we find that previous SINFONI K-band magnitudes of R136's core stars were underestimated. Our K magnitude corrections result in lower luminosities and therefore in lower stellar masses. As such, for #682, a3, and a2, we estimated initial masses similar or lower than 150 $M_\odot$, whereas for a1 we derived an initial mass lower than 195 $M_\odot$ (and, actually, the crowding issues discussed above suggest it is quite likely even smaller). In conclusion, the hitherto observed upper mass limit for massive stars, as large as ~325 $M_\odot$, has to be significantly scaled down, and the violation of the UPML by a1 needs more evidence to be settled.

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