The very massive binary NGC 3603-A1

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ABSTRACT
Using Very Large Telescope/Spectrograph for INtegral Field Observation in the Near-Infrared (VLT/SINFONI), we have obtained repeated adaptive-optics assisted, near-infrared spectroscopy of the three central WN6ha stars in the core of the very young (~1 Myr), massive and dense Galactic cluster NGC 3603. One of these stars, NGC 3603-A1, is a known 3.77 d, double-eclipsing binary, while another one, NGC 3603-C, is one of the brightest X-ray sources among all known Galactic WR stars, which usually is a strong indication for binarity. Our study reveals that star C is indeed an 8.9-d binary, although only the WN6ha component is visible in our spectra; therefore, we temporarily classify star C as an SB1 system. A1, on the other hand, is found to consist of two emission-line stars of similar, but not necessarily of identical spectral type, which can be followed over most the orbit. Using radial velocities for both components and the previously known inclination angle of the system, we are able to derive absolute masses for both stars in A1. We find $M_1 = (116 \pm 31) M_\odot$ for the primary and $M_2 = (89 \pm 16) M_\odot$ for the secondary component of A1. While uncertainties are large, A1 is intrinsically half a magnitude brighter than WR20a, the current record holder with 83 and 82 $M_\odot$, respectively; therefore, it is likely that the primary in A1 is indeed the most massive star weighed so far.

Key words: binaries: general – stars: evolution – stars: fundamental parameters.

1 INTRODUCTION

While models maintain that in the early Universe, the first generation of stars were very massive and reached masses between 100 and 1000 $M_\odot$ (e.g. Nakamura & Umemura 2001; Schaerer 2002), it is generally accepted that under present-day conditions, relatively fewer massive stars are formed, i.e. the initial-mass function (IMF) is much steeper and, more importantly, has a cut-off occurring around 150 $M_\odot$ (Weidner & Kroupa 2004; Figer 2005).

So far, however, whenever Keplerian orbits of binary systems are used to weigh stars, – the only way to obtain reliable, least model-dependent masses – measured masses fall short by almost a factor of 2 with respect to the putative cut-off. Currently, stars with the highest known masses are both WN6ha components of the Galactic WR binary WR20a, with 83 and 82 $M_\odot$, respectively (Bonanos et al. 2004; Rauw et al. 2004), and the O3f/WN6 star in the Galactic binary WR21a with a minimum mass of 87 $M_\odot$ (Niemela et al. 2008). Significantly more massive stars, however, have so far remained elusive.

A most remarkable result that has emerged from the search for very massive stars is, however, that the highest Keplerian masses are not found among absorption-line O-type stars – rather, masses of these stars remain below ~60 $M_\odot$, (e.g. Lamontagne et al. 1996; Massey, Penny & Vukovich 2002) – but among Wolf–Rayet (WR) stars, more precisely among the so-called WN5-7ha (or WN5-7h) stars, an extremely luminous and hydrogen-rich subtype of the nitrogen-sequence WR stars. Contrary to classical WR stars, which are identified with bare, helium-burning cores of evolved massive stars, theoretical work confirms that these luminous WN5-7ha stars are hydrogen burning, unevolved objects (de Koter, Heap & Hubeny 1997; Crowther & Dessart 1998) which mimic the spectral appearance of WR stars because their high-luminosities drive dense and fast winds (Graefener & Hamann 2008).

If it is true that the most massive stars can be found in the most massive clusters (Bate 2002; Weidner & Kroupa 2006), then it can be expected that the most massive WN5-7ha stars are hosted by the most massive among the youngest, least evolved clusters known. NGC 3603 is a Galactic example of such a cluster, and virtually a clone of its more famous LMC counterpart, the supermassive cluster R136, at the core of the giant H II region 30 Dor (Moffat, Drissen & Shara 1994). NGC 3603's very core, itself denoted HD 97950, contains three extremely luminous WN6ha stars (Drissen et al. 1995), with stellar luminosities well in excess of 10$^6$ $L_\odot$ (de Koter et al. 1997; Crowther & Dessart 1998). Moffat & Niemela...
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科学 spectra were rectified by fitting a low-order spline function

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of the target WN6ha stars, a Lorentzian was fitted to the absorption

highest possible spatial and spectral resolution. The field of view

Bonnet et al. 2004) with adaptive-optics (AO) correction to obtain

level. However, star C shows an extremely large X-ray luminosity

σ

of the region 21 340 to 22 140 Å, comprising the two emission

star B, radial velocities (RVs) were measured by cross-correlation

Averaged spectra of the three WN6ha stars are shown in Fig. 1. For

Total exposure times were 84 s per star and per visit, each organ-

in four detector integration times (DITs) of 21 s. Given the

brightness of our targets (K ∼ 7–8 mag) and the AO deployment,

for the very massive binary NGC 3603-A1

Figure 1. Montage of average spectra of our three target stars, limited
to the useful spectral region. The two strongest emission lines, Brγ/HeI
λ2.166 μm and He II λ2.188 μm are indicated. For clarity, the upper two
spectra have been shifted by 0.25 and 0.5 flux units, respectively.

Given is the error of the mean, i.e. σ/√(N), where N = 18 is the

number of data points.

A1 was found to consist of two emission-line stars, very similar to

WR20a (Rauw et al. 2004). An average spectrum around quadrature

(φ ∼ 0.74) is shown in Fig. 2. While both binary components

show Brγ/HeI λ2.166 μm and He II λ2.188 μm in emission, the two
components do not show the same line strengths. In the following,
we will hence refer to the stronger-lined star as ‘primary’, and to
the weaker-lined star as ‘secondary’.

RVs for star C and for both components of A1 were obtained by

independently fitting Gaussians to the respective He II λ2.188 μm
emission peaks of the two components, because this line is most
likely less affected by wind–wind collision in the binary than
Brγ/HeI. To take into account that in the case of A1, the He II
emission peak of the secondary moves up and down the flank of

2 OBSERVATIONS AND DATA REDUCTION

Observations were carried out in service mode at the VLT-UT4
under Program-ID P75-0576.D. We obtained repeated K-band (1.95
to 2.45 μm) spectroscopy using SINFONI (Eisenhauer et al. 2003;
Bonnet et al. 2004) with adaptive-optics (AO) correction to obtain
the highest possible spatial and spectral resolution. The field of view
was 0.8 × 0.8 arcsec⁻¹ with a ‘spaxel’ scale of 12.5 × 25 mas. Each
of our three target WN6ha stars was observed individually.

Total exposure times were 84 s per star and per visit, each organ-

ized in four detector integration times (DITs) of 21 s. Given the

brightness of our targets (K ∼ 7–8 mag) and the AO deployment,

no dedicated sky frames were taken. Other calibrations (dark and

flat-field frames, and the telluric standard star) were provided by

the European Southern Observatory (ESO) baseline calibration.

For most of the data reduction steps, ESO’s pipeline was used (cf.
Abuter et al. 2006). Standard reduction steps were taken. The two-
dimensional spectra produced by each illuminated slitlet were indi-
nually extracted using IRAF, and combined into one wavelength-
calibrated spectrum per star and visit. A main-sequence B-type star
was used for telluric corrections. To remove the B star’s Brγ
absorption which coincides with the Brγ/HeI λ2.166 μm emission blend
of the target WN6ha stars, a Lorentzian was fitted to the absorption
line and subtracted from the B star’s spectrum. Residuals were very
small, and proved to be harmless in the subsequent analysis. Finally,
science spectra were rectified by fitting a low-order spline function

to the stellar continuum. The final uniform stepwidth of the spectra
was 2.45Å/pixel, resulting in a conservative three-pixel resolving
power of ∼3000, and a velocity dispersion of ∼33 km s⁻¹ pixel⁻¹.

3 DATA ANALYSIS AND RESULTS

Averaged spectra of the three WN6ha stars are shown in Fig. 1. For
star B, radial velocities (RVs) were measured by cross-correlation
of the region 21 340 to 22 140 Å, comprising the two emission
lines Brγ/HeI λ2.166 μm and He II λ2.188 μm. Star B proved to
show constant RVs over the observed time-scales, with a scatter of
σ_RV ∼ 20 km s⁻¹, which was adopted as a posteriori error (see
Fig. 4). Fitting a single Gaussian to the He II λ2.188 μm emission line
yielded a slightly larger scatter, σ = 26 km s⁻¹, but was used to
obtain the systemic velocity of the star, γ = (167 ± 6) km s⁻¹.

Figure 2. Average of two spectra of A1, taken almost at quadrature
(φ ∼ 0.74). Both Brγ/HeI λ2.166 μm and He II λ2.188 μm are clearly
separated; the (stronger-lined) primary is indicated by ‘upward arrows, while
the (slightly weaker-lined) secondary is indicated by downward arrows.

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the stronger emission of the primary, a sloping, linear continuum was simultaneously fitted. Unfortunately, fitting the secondary’s emission peaks in A1 is only possible at phases where the respective He II lines are well separated, and particularly difficult when the weak He II line of the secondary blends with the strong Brγ/He I line of the primary, i.e. during most of the ‘blue’ half-wave of the companion’s motion. Moreover, due to blending with the steep slope of the primary, i.e. during most of the ‘blue’ half-wave of the composite He II lines are well separated, and particularly difficult when the stronger emission of the primary, a sloping, linear continuum gets significantly distorted, thereby further increasing the error of the fit. Both phenomena strongly affect the determination of the secondary’s orbit and hence the mass determination of the secondary were fitted simultaneously, forcing a circular orbit and the systemic velocity to be the same for both components. While emission lines in WR stars are well known to display some degree of redshift with respect to the true systemic velocity of the star (see e.g. Schnurr et al. 2008), both WR components in A1 will display emission peaks in A1 is only possible at phases where the respective He II lines are well separated, and particularly difficult when the weak He II line of the secondary blends with the strong Brγ/He I line of the primary, i.e. during most of the ‘blue’ half-wave of the companion’s motion. Moreover, due to blending with the steep slope of the primary, i.e. during most of the ‘blue’ half-wave of its orbital motion, the fit of the secondary’s orbit is dominated by the ‘red’ half-wave. This leads to a large RV amplitude for the secondary and, by consequence, a large mass ratio. A significantly smaller RV amplitude would have been obtained if the systemic velocity of the secondary was left as a free fitting parameter. However, given the problems with the ‘blue’ half-wave described above, we believe that it is more sensible to

Table 1. Journal of RVs for both components in A1 as obtained by Gaussian fits to the He II λ2.188 μm emission lines. The second column of each table provides the orbital phase corresponding to a period of P = 3.7724 d (from Moffat et al. 2004) and, as zero point in phase, the time of inferior conjunction E₀ = 2453 765.75 (this work). Note that it was not always possible to measure the RVs for the secondary; see the text for more details.

| HJD   | φ    | RV₁ | σ₁  | RV₂ | σ₂ |
|-------|------|-----|-----|-----|----|
| 2450 000.5+ |  |     |     |     |    |
| 3468.003 | 0.206 | 475 | 7   | −121 | 21 |
| 3470.030 | 0.743 | −138 | 16 | 601 | 7 |
| 3471.060 | 0.016 | 262 | 7   | 262 | 9 |
| 3472.019 | 0.270 | 478 | 4   | −267 | 55 |
| 3473.009 | 0.533 | 6 | 4   | 0   |   |
| 3474.146 | 0.834 | −160 | 7 | 427 | 7 |
| 3489.970 | 0.029 | 305 | 7   | 305 | 8 |
| 3528.976 | 0.369 | 410 | 8   | 0   |   |
| 3529.978 | 0.635 | −45 | 10  | 531 | 55 |
| 3531.040 | 0.916 | 48 | 10  | 0   |   |
| 3532.961 | 0.425 | 236 | 14  | 236 | 14 |
| 3552.963 | 0.727 | −184 | 7 | 630 | 7 |
| 3721.321 | 0.356 | 426 | 7   | 21  | 27 |
| 3723.325 | 0.888 | −121 | 27 | 210 | 21 |
| 3754.240 | 0.083 | 281 | 7   | 0   |   |
| 3758.243 | 0.144 | 285 | 21  | 0   |   |
| 3765.292 | 0.482 | 55 | 14  | 277 | 7 |
| 3765.213 | 0.991 | 177 | 7   | 177 | 8 |
| 3766.362 | 0.296 | 485 | 21  | −40 | 41 |
| 3790.163 | 0.605 | 19 | 14  | 0   |   |
| 3794.101 | 0.649 | −125 | 7 | 499 | 21 |
| 3794.212 | 0.679 | −100 | 21 | 507 | 21 |

Table 2. As for Table 1, but for star C, using the period of P = 8.89 d and, as zero point in phase, the time of periastron passage T₀ = 2453 547.11 (this work).

| HJD   | φ    | RV | σRV |
|-------|------|----|-----|
| 2450 000.5+ |  |     |     |
| 3467.994 | 0.157 | 394 | 4   |
| 3468.003 | 0.158 | 425 | 8   |
| 3470.021 | 0.385 | 255 | 5   |
| 3471.060 | 0.502 | 93  | 7   |
| 3472.019 | 0.609 | 114 | 7   |
| 3473.009 | 0.721 | −5  | 11  |
| 3474.146 | 0.849 | 0   | 10  |
| 3489.970 | 0.629 | 108 | 8   |
| 3528.976 | 0.016 | 263 | 10  |
| 3529.978 | 0.129 | 401 | 4   |
| 3531.040 | 0.249 | 381 | 10  |
| 3532.961 | 0.465 | 233 | 4   |
| 3552.963 | 0.715 | 19  | 7   |
| 3721.321 | 0.652 | 52  | 4   |
| 3723.325 | 0.878 | −5  | 11  |
| 3754.240 | 0.355 | 216 | 4   |
| 3758.243 | 0.806 | −21 | 8   |
| 3759.369 | 0.932 | 179 | 14  |
| 3763.292 | 0.374 | 244 | 14  |
| 3765.213 | 0.590 | 89  | 27  |
| 3766.353 | 0.718 | 45  | 11  |
| 3766.362 | 0.719 | 34  | 11  |
| 3769.387 | 0.059 | 293 | 12  |
| 3790.164 | 0.396 | 255 | 11  |
| 3791.102 | 0.502 | 110 | 18  |
| 3794.101 | 0.839 | −27 | 14  |
| 3794.212 | 0.852 | 21  | 11  |
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Figure 4. Orbital solutions obtained from weighted fits for A1 (upper panel) and C (middle panel), folded in the respective phases. In A1, the primary is indicated by filled symbols and the solid curve, while the secondary is shown with open symbols and the dotted curve. In star C, only the primary is visible. RVs of star B are constant during the observations (lower panel, same scale as for star C) with a scatter of $\sigma = 20 \text{ km s}^{-1}$. The dashed line indicates the systemic velocity of the star B, $\gamma = (167 \pm 6) \text{ km s}^{-1}$.

Table 3. Orbital parameters for both the primary and secondary components of A1 from the combined, weighted fit, forcing a circular solution. The inclination angle and the period have been adopted from Moffat et al. (2004).

| Parameter          | Primary   | Secondary  |
|--------------------|-----------|------------|
| $P$ (d)            | 3.7724    |            |
| $i$ (°)            | 71        |            |
| $e$                | 0         |            |
| $E_0$ (2450.000.5+) | 3765.25 ± 0.03 | 153 ± 12  |
| $\gamma$ (km, s$^{-1}$) | 330 ± 20  | 433 ± 53   |
| $\sigma_{o-c}$ (km, s$^{-1}$) | 42        | 82         |
| $M(M_\odot)$      | 116 ± 31  | 89 ± 16    |

Table 4. Orbital parameters for the WN6ha (primary) component in star C.

| Parameter          | Primary |
|--------------------|---------|
| $P$ (d)            | 8.89 ± 0.01 |
| $e$                | 0.30 ± 0.04 |
| $\omega$ (°)      | 281 ± 7   |
| $T_0$ (2450.000.5+) | 3546.61 ± 0.18 |
| $\gamma$ (km, s$^{-1}$) | 186 ± 6   |
| $K$(km, s$^{-1}$)  | 200 ± 23  |
| $\sigma_{o-c}$ (km, s$^{-1}$) | 27 |

The primary and $M_2 = (89 \pm 16) M_\odot$ for the secondary component of A1, respectively. Due to the problems with the secondary’s RVs described above, the uncertainties on the orbits, expressed by the large $\sigma_{o-c}$, and hence on the masses are uncomfortably large. However, Drissen et al. (1995) have reported an absolute magnitude of $M_V = -7.5$ for A1, i.e. brighter by ~0.5 mag than WR20a, for which Rauw et al. (2007) find $M_V = -7.04 \pm 0.25$. Since A1 and WR20a have very similar spectral types and, thus, bolometric corrections, A1’s brighter magnitude directly translates into a larger bolometric luminosity, qualitatively consistent with our result that A1 is more massive than WR20a. However, better data are currently being taken to verify the results.

In star C, the secondary is not visible in the spectrum; hence, we temporarily classify the system as SB1. While the intrinsic brightness difference between A1 and C is ~0.5 mag (Crowther & Dessart 1998), it is well possible that the WN6ha component in C is as massive as the primary in A1, where the luminosities of the primary and secondary are more similar; for the same reason, a large mass ratio can be expected between the primary and secondary component in C.

Star B, on the other hand, displays neither significant RV nor photometric variations (cf. Moffat et al. 2004), nor a strong X-ray flux. The latter is a strong indication against B’s possible long-period binarity. Therefore, B most likely is a truly single star. Remarkably, Crowther & Dessart (1998) report a luminosity for B which is only very slightly lower than that of the unresolved system A1. This renders B significantly more massive than the primaries in both A1 and C, and puts it close to (or even in excess of) the putative IMF cut-off mass, unless B turns out to be an unresolved, long-period binary as well. Clearly, line-blanketed atmosphere models will provide valuable insights into this problem once the known, very massive binary systems such as A1 and WR20a have been used as yardsticks.
SUMMARY AND CONCLUSION

We have obtained repeated, spatially resolved, AO assisted, near-infrared spectroscopy of the three central WN6ha stars in HD 97950, the core of the young, unevolved and very massive Galactic cluster NGC 3603. One of the stars, A1, is a previously known, double-eclipsing binary with an orbital period of 3.77 d (Moffat & Niemela 1984; Moffat et al. 1985, 2004), while a second star, C, was newly identified as a binary in this study. The third star, B, showed constant RVs over the observed time interval, and therefore is most likely not a binary, which is in line with its normal X-ray luminosity (Moffat et al. 2002).

While in star C only the primary (WN6ha) component is visible, – the system is therefore classified as an SB1 binary – A1 consists of two emission-line stars, most likely of similar, but hot identical spectral types. From the radial-velocity curves of the two components and the known inclination angle of the system (Moffat et al. 2004), we derived component masses of $M_1 = (116 \pm 31) M_\odot$ for the primary and $M_2 = (89 \pm 16) M_\odot$ for the secondary, respectively. Despite the large uncertainties, we consider the primary WN6ha component of A1 to be the most massive star ever directly weighed.

While the primary component of C might have a mass similar to or even greater than that of A1’s primary, it is possible that star B, single yet only slightly fainter than the combined binary system A1, is indeed the most massive member in NGC 3603 and, therefore, the most massive main-sequence star known in the Galaxy.

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