VLT/SINFONI time-resolved spectroscopy of the central, luminous, H-rich WN stars of R136

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ABSTRACT
Using the Very Large Telescope’s Spectrograph for INtegral Field Observation in the Near-Infrared, we have obtained repeated adaptive-optics-assisted, near-infrared spectroscopy of the six central luminous, Wolf–Rayet (WR) stars in the core of the very young (∼1 Myr), massive and dense cluster R136, in the Large Magellanic Cloud (LMC). We also de-archived available images that were obtained with the Hubble Space Telescope’s Space Telescope Imaging Spectrograph, and extracted high-quality, differential photometry of our target stars to check for any variability related to binary motion.

Previous studies, relying on spatially unresolved, integrated, optical spectroscopy, had reported that one of these stars was likely to be a 4.377-d binary. Our study set out to identify the culprit and any other short-period system among our targets. However, none displays significant photometric variability, and only one star, BAT99-112 (R136c), located on the outer fringe of R136, displays a marginal variability in its radial velocities; we tentatively report an 8.2-d period. The binary status of BAT99-112 is supported by the fact that it is one of the brightest X-ray sources among all known WR stars in the LMC, consistent with it being a colliding wind system. Follow-up observations have been proposed to confirm the orbital period of this potentially very massive system.

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

1 INTRODUCTION
30 Doradus (NGC 2070) is an active star-forming, giant HII region in the Large Magellanic Cloud (LMC). At the centre of 30 Dor is located the very massive star cluster R136 (HD 38268), which is regarded as the closest visible example of a ‘superstar cluster’, excluding its Galactic clone NGC 3603, which is not surrounded by a very massive cluster halo.

The inner arcsecond of R136, denoted R136a, is unsolvable by conventional ground-based telescopes, and it was suspected that R136a is in fact a single stellar object of more than 3000 M⊙ (Feitzinger et al. 1980; Cassinelli, Mathis & Savage 1981). However, careful ground-based work (both direct imaging: Moffat & Seggewiss 1983; Moffat, Seggewiss & Shara 1985 and speckle interferometry: Weigelt & Baier 1985) showed that R136a was not a single star. High-resolution imaging by the HST confirmed that R136a indeed consists of individual, hot and luminous stars (Campbell et al. 1992), while the region immediately surrounding R136 contains many dozens of massive O stars, many of them of spectral type O3, the hottest of all known O-type stars at the time (Massey & Hunter 1998).

It has been theorized that high stellar densities in the cores of very massive protoclusters are a prerequisite for the formation of very massive stars (Bate 2002). Moreover, there is empirical evidence that the mass of the most massive cluster member correlates with the total mass of the cluster (Weidner & Kroupa 2006). Therefore, it can be expected that the most massive stars known are found in the core regions of the most massive, and densest, unevolved clusters known. Given its core density of ∼105 M⊙ pc−3 (e.g. Moffat et al. 1985), R136a is hence a prime candidate for harbouring extremely massive stars.

It is a very remarkable fact that even the hottest and most massive O-type stars seem not to exceed ∼60 M⊙ (Lamontagne et al. 1996; Massey, Penny & Vukovich 2002). More massive stars are
invariably members of a very luminous and hydrogen-rich subtype of Wolf–Rayet (WR) stars of the nitrogen-rich sequence, the so-called WN5-7h stars. Studies using model atmospheres indicate that these WN5-7h stars are not classical, core-helium-burning objects, usually identified with the WR phase, but rather core-hydrogen-burning objects on the main sequence; their WR-like appearance is due to their very high luminosities, $\log(L/L_\odot) \gtrsim 6.0$; de Koter, Heap & Hubeny 1997; Crowther & Dessart 1998) which drive fast stellar winds, whose high densities give rise to the emission-line spectrum. As has been confirmed by weighing WN5-7h stars with Keplerian orbits in eclipsing binaries, the very high luminosities of WN5-7h stars indeed correspond to very high masses: the present record holder, NGC 3603-A1, tips the balance at 116 M$_\odot$ (Schnurr et al. 2008a).

Following the spectral classification of Crowther & Dessart (1998), R136a contains three hydrogen-rich WN5h stars and one O3f/WN6 star which is a transition type between the hottest OF stars and the least extreme WN5-7h stars (Walborn 1986) and thus weaker lined than the WN5h stars. Slightly off-centred are a cooler, evolved WN9h star (R136b), and another WN5h star (R136c). From ground-based, spatially unresolved (i.e. integrated), optical spectroscopy of R136a, Moffat & Seggewiss (1983) reported a 4.377-d WNh binary in R136a, with a dilated radial velocity (RV) amplitude $K \sim 38$ km s$^{-1}$; the subsequent study by Moffat et al. (1985) confirmed this finding. The situation in R136a seems thus very similar to that in NGC 3603, where from unresolved spectroscopy of the central arcsecond too, Moffat & Niemela (1984) had identified a 3.77-d binary among the three WN6h stars (this finding was confirmed by Moffat et al. 1985 as well). Followup observations of NGC 3603 confirmed these results (Moffat et al. 2004; Schnurr et al. 2008a), revealing a second close binary, C, in NGC 3603, with an orbital period $P = 8.9$ d. Hence, a more detailed investigation of the six WNh stars in R136a was warranted, since it offered the potential to increase considerably the number of known, very massive binary systems.

We have therefore obtained, for the first time, repeated, spatially resolved spectroscopy of the six WNh stars in R136, in order to single out the 4.377-d binary and to identify any further short-period system among our targets. To search for eclipsing systems (photospheric or atmospheric) among the stars, additional optical HST photometry of our target stars was extracted from publicly available, archival imaging data.

Our study also complements that of Schnurr et al. (2008b), who had surveyed the 41 of the 47 known, late-type WN stars in the LMC according to BAT99 located outside R136a, and thereby concludes the efforts of the Montréal hot-star group to monitor every WR star in the Magellanic Clouds to establish their binary status.

In this paper, we describe the data acquisition and reduction (Section 2) and the data analysis (Section 3). We discuss our findings in Section 4, and close with the summary and conclusion in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Near-infrared spectroscopy

Targets and their relevant properties are listed in Table 1, giving both the numbers from the BAT99 catalogue (Breysacher, Azzopardi & Testor 1999) and the older Radcliffe numbers (e.g. Feast, Thackeray & Wesselink 1960).

Observations were carried out in service mode at the Very Large Telescope (VLT) with Unit Telescope 4 under programme ID P076.D-0563, between 2005 November 13 and December 5. The observations thus cover a time-span of $\sim 22$ d. We obtained repeated $K$-band (1.95–2.45 $\mu$m) spectroscopy using the Spectrograph for INtegral Field Observation in the Near-Infrared (SINFONI) (Eisenhauer et al. 2003; Bonnet et al. 2004) with adaptive-optics (AO) correction to obtain the highest possible spatial and spectral resolution. BAT99-111 (R136b) served as AO reference star. The field of view was 0.8 × 0.8 arcsec$^2$ with a ‘spaxel’ scale of 12.5 × 25 mas$^2$. Our six target WNh stars were observed with four pointings (with R136a1, a2 and a5 all in one field), defined as telescope offsets from the AO guide star BAT99-111. Fig. 1 shows a montage of the four fields as seen on the sky, reconstructed from the SINFONI data cube. Stars here are separated at least as well as on HST images.

Total exposure times were 150 s per star and per visit, each organized in two detector integration times. Given the brightness of our targets ($K \sim 11–12$ 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 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 individually 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 $\mu$m emission blend of the target WNh stars, a Lorentzian was fitted to the absorption line and subtracted from the B star’s spectrum. Residuals were very

| BAT99 | Other name | Spectral type | $v$ (mag) | $(b - v)$ (mag) | $E(b - v)$ (mag) | $M_v$ (mag) |
|-------|------------|--------------|-----------|----------------|-----------------|------------|
| 106   | R136a3     | WN5h         | 13.1      | +0.20          | 0.28            | −6.6       |
| 108   | R136a1     | WN5h         | 12.9      | +0.18          | 0.28            | −6.8       |
| 109   | R136a2     | WN5h         | 13.1      | +0.21          | 0.28            | −6.7       |
| 110   | R136a5     | O3If*/WN6-A  | 14.0      | +0.21          | 0.28            | −5.7       |
| 111   | R136b      | WN9h         | 13.4      | ...            | ...             | −6.5       |
| 112   | R136c      | WN5h         | 13.6      | ...            | ...             | −6.3       |

Note. For easier identification, both BAT99 and Radcliffe numbers are given together with the spectral types (based on optical spectra), $(b - v)$ colours and $E(b - v)$ were directly adopted from Crowther & Dessart (1998), while their Johnson-V magnitudes were used to estimate narrow-band $v$-band magnitudes, applying $(v - V) \sim 0.1$ mag to take into account the contribution of emission lines.
The central WNh stars of R136

The central WNh stars of R136

3 DATA ANALYSIS AND RESULTS

3.1 Spectroscopy

The mean spectra of the six WNh stars are shown in Fig. 2. The systemic velocity $RV_{sys}$ of each star was measured by fitting Gaussians to the reasonably symmetric, top third of the $\text{He} \, \lambda 2.188 \mu$m emission line (below that, the line quickly becomes too asymmetric for this). For the WN5h stars, which have the strongest emission lines, this was done for each individual spectrum of the time series. The standard deviation of the series was adopted as error, $\sigma_{RV}$, and the error of the mean (eom) of the systemic velocity was calculated as $\text{eom} = \sigma_{RV}/\sqrt{N}$, with $N = 9$ the number of spectra.

For the two weaker lined stars, BAT99-110 (O3f/WN6) and 111 (WN9ha), the fit could only be carried out for the averaged spectrum since the signal-to-noise ratio (S/N) was better. Also these two stars display obvious P Cygni profiles in $\text{He} \, \lambda 2.188 \mu$m, hence two Gaussians (one absorption, one emission) plus a linear continuum were fitted to the entire line. The resulting errors on the fits are comparatively large, in particular for the faint O3f/WN6 star, because its very weak lines remained buried in the noise even in the mean spectrum. Since only one spectrum was used, no error of the mean was calculated. Values are listed in Table 2.

All four WN5h stars display systemic velocities that are redder (larger) than the systemic velocity expected from the LMC, $280 \pm 20 \text{ km s}^{-1}$ (e.g. Kim et al. 1998). This redshift is most likely of the same nature as that reported for the optical $\text{He} \, \lambda 4686$ line in other WN and O3f/WN6 stars in the LMC (e.g. Schnurr et al. 2008b), i.e. due to radiative transfer effects (Hillier 1989).

The mean systemic velocity of the four WN5h stars is $(384 \pm 4) \text{ km s}^{-1}$ (standard deviation), whose dispersion is comparable to their individual errors of the mean; these stars thus have systemic velocities which are statistically consistent with each other.

For BAT99-110, the emission part of the Cyg profile for $\text{He} \, \lambda 2.188 \mu$m surprisingly displays a significantly smaller redshift than the $\text{He} \, \lambda 2.188 \mu$m emission of WN5h stars. In fact, despite the large error, BAT99-110’s systemic velocity is in excellent agreement
with that of the LMC. Either near-infrared He II emission lines of O3f/WN6 stars do not display the intrinsic redshift of their optical counterparts (possibly because of optical depth effects, since their wind is thinner than that of, say, WN5h stars) or BAT99-110 is indeed travelling at relatively high differential velocity along the line of sight towards the observer. In this case, it could be that 110 is not actually in the core, but rather ejected from it towards the observer, i.e. along the line of sight (also see below). Thus, from a point of view of cluster dynamics and cluster evolution, it would be very interesting to carry out a more detailed RV study of the massive stars in the periphery of R136a to check for ejected cases (see also Brandl et al. 2007 for a more detailed discussion of this topic).

To identify the variable stars in our sample, relative RVs were measured by cross-correlation, limited to the region from 2.134 to 2.214 \( \mu \)m which comprises the two strongest emission lines, Br\(\gamma\)/He I \( \lambda \)2.166 \( \mu \)m and He II \( \lambda \)2.188 \( \mu \)m. The iterative approach of Schnurr et al. (2008b) was followed: a high S/N mean spectrum of the time series acted as cross-correlation template for each star. Then, all spectra of the time series were shifted by their respective RVs, to generate a better mean template spectrum, and the cross-correlation was repeated with the new template. Fig. 3 shows time plots of these relative RVs for each star.

Even without this iteration scheme, the resulting RV scatter of each individual star, \( \sigma_{RV,xcorr} \), is surprisingly small; final values are listed in Table 2. Following the approach of Schnurr et al. (2008b)
to derive a posteriori error bars, we proceeded to construct a RV reference star by using the least variable stars in our sample, the three WN5h stars in R136a. For each of these stars, relative RVs obtained by cross-correlation were normalized to \(RV = 0\) to correct for different velocities of the cross-correlation template, and combined. For the resulting 33 data points in total, the overall standard deviation \(\sigma_{RV, all} = 14\) km s\(^{-1}\) was obtained. This value was adopted as measurement error for each individual data point.

To determine whether or not the RV variability of a given star is statistically significant, we adopt \(\sqrt{2}\sigma_{RV, all} = \sigma_{cut}\) as a rough estimate of the threshold above which a star can be considered to be variable at the 99.9 per cent level (see Schnurr et al. 2008b for a more detailed discussion). We obtain \(\sigma_{cut} = 20\) km s\(^{-1}\) from our three reference stars, and find that R136a5, R136b and R136c exceed this threshold. However, the large scatter for the first two stars can be explained by very weak lines and thus relatively lower S/N, which greatly affects the precision of the RV measurement. In contrast to this, R136c is a stronger lined WN5h star, and well isolated, hence its large RV scatter is likely intrinsic.

Including R136c in our RV reference would yield a somewhat larger error, \(\sigma_{RV, all} = 19\) km s\(^{-1}\), and accordingly \(\sigma_{cut} = 27\) km s\(^{-1}\). Hence, R136c would have exceeded the cut-off value in any case (if just), thus regarded as variable, and been removed from the reference group.

A period search was carried out on the RV data of R136c, constrained to the range from 2 to 44 days. The lower limit of this range is set by the mean sampling frequency, while the upper limit is twice the total time covered by the observations, 22 d. However, due to the low level of variability, no significant (at or above 3\(\sigma\)) period can be found. Furthermore, the scarcity of data points leads to many empty phase bins if a phase-dispersion method is applied. Thus, more and better data are required to confirm the variability of R136c and eventually its binary status.

However, if a sine wave is fitted to the RV data of R136c (i.e. assuming zero orbital eccentricity), the (marginally) best fit is obtained for a period \(P = 8.2\) d, with an amplitude \(K = 42\) km s\(^{-1}\) (see Fig. 4). For this solution, \(\sigma(O - C) = 8\) km s\(^{-1}\), which is unrealistically small, and essentially produced by only one data point (around \(\varphi = 0.3\)), which does not lie on the curve. If this point is excluded from the fit, then \(\sigma(O - C) \sim 2\) km s\(^{-1}\), which is an indication for an ill-constrained fit (effectively six independent data points for four parameters) rather than real. While it is not impossible that SINFONI delivers such good data, it sheds some doubt on to the reality of the orbital solution. We therefore consider R136c as a marginal case for supporting a binary, subject to future confirmation.

3.2 Photometry

Crowded field, quasi-white-light photometry was extracted from each of the STIS frames using the DAOPHOT II package with the additional ALLSTAR and ALLFRAME subroutines (Stetson 1992, 1994). The point spread function (PSF) was iteratively fitted using a Moffat function (\(\beta = 1.5\)) whose full width at half-maximum (FWHM) was typically \(\sim 1.7\) pixels. The fitting radius around stars was set to 4 pixels and the extraction radius of the aperture was 1.5 FWHM \(\sim 2.5\) pixels. Sky was determined from an annulus between 7 and 9 pixels from the centre of the star. In order to separate all the stars in the crowded centre of the cluster, profile fitting was done iteratively. That way, we were able to obtain reliable photometry of BAT99-108, 109 and 100, as well as three other fainter stars in the crowded field around BAT99-109.

To carry out differential photometry, a single adjustment to the photometric zero point was applied as in Massey et al. (2002). For each star, the dispersion around the time-averaged magnitude is plotted against its instrumental magnitudes (Fig. 5). Indicated are both our programme stars and the binaries and variable stars reported by Massey et al. (2002). Since the exposures were very short (\(\sim 1.3\) s), our target stars, which are the brightest objects in the field, remain well below the non-linearity limit.

These very short exposures times have repercussion on the photometric error statistics. If there were no exterior noise sources, photometric accuracy would be simply described by Poissonian statistics, and related to the stellar intensity \(I\) such that \(\sigma_I = \sqrt{I}\). In reality, however, read-out noise becomes quickly very important for the photometric accuracy of fainter stars. The photometric precision of very bright stars, on the other hand, is limited by the quality of the flat-field frame. To obtain a reliable error statistics, we therefore have applied a more detailed noise model, taking into account the following noise sources: (i) the Poisson noise of the stellar intensity \(I\), which is simply \(\sigma_I\); (ii) the read-out noise \(\sigma_R\), which for STIS is \(4e^-/\text{pixel} \times \text{gain} = 1\). Note that the mean read-out level \(\langle R \rangle = 0\), since there is no flux associated with a read-out operation, only an error on the count rate. The extraction radius of the PSFs are \(\sim 2.5\) pixels (see above), hence PSFs cover a total area of \(2.5^2 \pi \sim 20\) pixels; hence, the total read-out noise sums to \(4\sqrt{20} = 18e^-\) and (iii) the noise \(\sigma_F\) of the flat-field frame, which we assume to be normalized to unity prior to dividing the science exposures by it, so that the mean flat-field factor \(\langle F \rangle = 1\).

Since the HST is in space and exposures are too short for a significant stray-light contribution, there is no sky background and its associated noise that need to be considered. We further note that the flat-field noise is multiplicative (it is proportional to the intensity recorded by a pixel), whereas the read-out noise is purely additive. Hence, the photometric precision for bright stars is limited by the quality of the flat-field frame, whereas faint stars are more affected by read-out noise.

Thus, from the usual relation

\[
m = m_0 - 2.5 \log(FI + R),
\]

where \(m_0\) is a magnitude zero-point, error propagation for independent values of \(F, I\) and \(R\) then yields the total error on the measured magnitude,

\[
\sigma_m^2 = \left(\frac{2.5 \log e}{FI + R}\right)^2 + [I(\sigma_I)^2(F \sigma_I)^2 + \sigma_F^2]
\]
Figure 5. Photometric dispersion of the times-series of each source in the STIS field of view, plotted against its instrumental magnitude. The solid line is the 1σ curve, the dashed line the 2σ curve according to the model described in the text. Our target stars are identified by their respective BAT99 number. We have also identified eclipsing binaries (squares) and other variables (triangles) that were reported by Massey et al. (2002), using their nomenclature (R136-nnn).

\[
\sigma_m^2 = \left(\frac{2.5 \log e}{I}\right)^2 \left[(I\sigma_F)^2 + I + \sigma_F^2\right].
\]

Using \(\sigma_F = 0.01\) (which is consistent with the typical S/N of a flat-field frame), and \(m_0 = 24.9\), this noise model fits the data very well. Both the 1σ and 2σ curves, based on this model, are shown in Fig. 5. As can be seen, even the brightest stars in our sample do not yet reach the noise floor that is determined by the flat-field noise.

As can clearly be seen, our target stars do not display any significant photometric variability; in fact, the dispersion around their respective mean magnitudes is very small (see Table 3 for individual values). Since we were perfectly able to identify the eclipsing binaries and other variable stars reported by Massey et al. (2002), we have to conclude that our target stars appear to be photometrically constant. This is especially relevant for BAT99-112 (R136c), which despite its short spectroscopic period does not show any indications of phase-dependent variability.

### Table 3. Mean instrumental magnitudes (through the long-pass filter) and standard deviation around the mean for our target stars as obtained from HST–STIS images using DAOPHOT II.

| BAT99 | Other name | STISmag (mag) | \(\sigma_{\text{phot}}\) |
|-------|------------|---------------|-----------------|
| 106   | R136a3     | 12.850        | 0.013           |
| 108   | R136a1     | 12.233        | 0.011           |
| 109   | R136a2     | 12.863        | 0.016           |
| 110   | R136a5     | 13.778        | 0.017           |
| 111   | R136b      | 13.124        | 0.015           |
| 112   | R136c      | 13.072        | 0.013           |

4 DISCUSSION

With our data, we cannot confirm the existence of the 4.377-d binary that was reported in optical emission lines by Moffat & Seggewiss (1983) and Moffat et al. (1985). Moreover, we cannot clearly identify any short-period binary among our six target stars; there only is one binary candidate, BAT99-112 (R136c). This star was already known to be a very bright X-ray source. Several studies have reported a very high X-ray luminosity of \(L_X \gtrsim 8.5 \times 10^{34}\) erg s\(^{-1}\) for BAT99-112 (Portegies Zwart, Pooley & Lewin 2002; Townsley et al. 2006; Guerrero & Chu 2008), in fact the second-brightest object in the greater R136 area after BAT99-116 (Mk 42). It is very likely that both stars are colliding wind binaries (cf. Usov 1992). Interestingly, Schnurr et al. (2008b) reported significant RV variability for BAT99-116 as well, but were unable to establish a periodicity. While it is thus very likely that both are long-period systems, we note that short-period systems, i.e. with a small orbital separation, are not ruled out by the high X-ray luminosities. NGC 3603-C is an 8.9-d binary with one of the highest X-ray fluxes known among all WR stars (Moffat et al. 2002; Schnurr et al. 2008a), so it seems that self-absorption of X-ray photons in the dense WN wind is not too much of a problem even in relatively close systems.

Thus, the following question arises: if one or more of our target stars in R136 are indeed short-period binaries, could their non-detection be the result of low orbital inclination angles? After all, very low inclination angles could comfortably explain why neither clear RV nor photometric variability (i.e. eclipses or ellipsoidal variations) are found, despite any possible enhancement of short-period systems (see above). To investigate this in more detail, we have calculated the RV scatter \(\sigma_{\text{RV,WN}} = K/\sqrt{2}\) of the primary (WN-type) component that would be expected from the continuous sampling of a circular binary with orbital periods ranging from 1 to 100 days. In this case study, the masses of the two components have been fixed to 90 M\(_\odot\) for the WN5h primary and 30 M\(_\odot\) for the presumed O-type secondary, i.e. the system has a total mass of...
Among the nine WNh stars, two are binaries with orbital periods shorter than 1000 d thus can reasonably hope to detect in our 22-d long campaign, 44 d.

The expected \( \sigma_{RV, WN} \) value for different values of the inclination angle, \( i = 15^\circ - 90^\circ \), is shown in Fig. 6. Also indicated are, with two vertical, dotted lines, the position of the expected 4.4-d binary and the long period we can reasonably hope to find in our data set, twice the time coverage of our observations, i.e. \( \sim 44 \) d. The dash–dotted, horizontal line marks the observed RV scatter for BAT99-112, \( \sigma_{RV, 112} = 28 \) km s\(^{-1}\). The two dotted, vertical lines indicate the period of the putative binary, 4.4 d, and the upper limit of periods we can reasonably expect an RV amplitude at least three times higher, i.e. 2/15 \( \sigma \).

Figure 6. RV scatter \( \sigma_{RV} = K/\sqrt{2} \) of the WN component in a fictive, continuously sampled, circular binary, with masses fixed at 90 M\(_\odot\) for the WN5h primary and 30 M\(_\odot\) for the O-type secondary, as a function of the orbital period of the system. Curves show different values of the orbital inclination angle, \( i = 90^\circ, 75^\circ, 60^\circ, 45^\circ, 30^\circ, 15^\circ \), from top. The dot–dashed, horizontal line indicates the measured scatter for R136c (BAT99-112), \( \sigma_{RV} = 28 \) km s\(^{-1}\). The two dotted, vertical lines indicate the period of the putative binary, 4.4 d, and the upper limit of periods we can reasonably hope to detect in our 22-d long campaign, 44 d.

\( 120 \) M\(_\odot\) (the exact value is not critical), and a mass ratio \( q = M_1/M_2 = 3 \). The large \( q \) value is reasonably pessimistic, given that such large ratios are observed even in very massive systems. In many reported cases, the companion is too faint to be (easily) detected (e.g. Schweickhardt et al. 1999; Schnurr et al. 2008a,b, 2009).

The expected \( \sigma_{RV, WN} \) value for different values of the inclination angle, \( i = 15^\circ - 90^\circ \), is shown in Fig. 6. Also indicated are, with two vertical, dotted lines, the position of the expected 4.4-d binary and the long period we can reasonably hope to find in our data set, twice the time coverage of our observations, i.e. \( \sim 44 \) d. The dash–dotted, horizontal line marks the observed RV scatter for BAT99-112, \( \sigma_{RV, 112} = 28 \) km s\(^{-1}\).

From Fig. 6, it becomes clear that if BAT99-112 were indeed a short-period binary, it would have to be seen under a very low inclination angle, \( i \leq 15^\circ \). However, in a sample with randomly distributed inclination angles, there would be

\[
\frac{\int_{15^\circ}^{90^\circ} \sin i \, di}{\int_{15^\circ}^{90^\circ} \sin i \, di} = \frac{\cos 15^\circ}{1 - \cos 15^\circ} \sim 28
\]

times more binaries between \( 15^\circ \) and \( 90^\circ \) than between \( 0^\circ \) and \( 15^\circ \); thus, it is very unlikely that there is a significant number of such low-inclination systems in our sample.

We note here that Moffat & Seggewiss (1983) and Moffat et al. (1985) had reported a RV amplitude of \( K \sim 37 \) km s\(^{-1}\) for R136a, which seems surprisingly consistent with \( \sigma_{RV, 112} = 40 \) km s\(^{-1}\). However, Moffat & Seggewiss (1983) and Moffat et al. (1985) only had integrated, i.e. spatially unresolved spectroscopy, and they reported the binary to be member of R136a, i.e. one of the three WN5h stars. (The fourth star, BAT99-110, is O3f/WN6 and hence too faint both in magnitude and emission-line strength to significantly have contributed to the integrated signal.) Our SINFONI observations, however, have individually resolved the stars; hence, one would expect an RV amplitude at least three times higher, i.e. \( K \sim 120 \) km s\(^{-1}\). Even if one allows for the fact that due to non-continuous sampling the measured \( \sigma_{RV} \) could be somewhat smaller, such large RV scatter is simply not seen among the WN5h stars in R136a.

Hence, we have to conclude that the large scatter in Moffat & Seggewiss’s (1983) and Moffat et al.’s (1985) data was not due to the binary motion of one of the target stars, but of different origin. A possible explanation could be that during the observations the slit was not located at exactly the same position each time, e.g. due to difficulties introduced by variable seeing conditions, and thus the light took different optical paths through the instrument. This could lead to an increased RV scatter, while well-isolated single stars are much less affected by this problem (see e.g. Schnurr et al. 2008b). It thus seems that with the exception of the 8.2-d (but possibly longer period) binary candidate BAT99-112, there is no binary among our six programme stars.

For BAT99-111 (R136b), this result does not come unexpectedly: Crowther & Dessart (1998) re-classified this star as WN9ha, and there seems to be a dichotomy between WN6,7 and WN8,9 stars when it comes to their binary status: no WN8,9 star is known to reside in a short (\( P \lesssim 200 \) d) WR-I-O binary system (Milky Way: Moffat 1989; LMC: Schnurr et al. 2008b). Also, if BAT99-111 is indeed a WN9ha star, then it is a descendent of an O8Iaf star (Crowther & Bohannan 1997), i.e. less massive but slightly more evolved than the O3f/WN6 and WN5h stars in R136. This could be an indication that BAT99-111 is not a member of R136a’s relatively unevolved stellar generation, but rather from an older population of massive stars outside R136, and simply located in the line of sight.

If, on the other hand, BAT99-111 is indeed an O4f+Iaf star, as classified by Massey & Hunter (1998), then both the spectral type and the fainter visual magnitude are consistent with BAT99-111 being a less extreme version of the brighter O3f/WN6 stars in and around R136, and a member of R136a all the same. Unfortunately, our data do not allow us to settle this classification issue.

For the other five, less evolved objects in our sample, in particular for the three very crowded WN5h stars in the core of R136a, the null result is somewhat surprising. We had expected to find at least one short-period binary in R136a, similar to the situation in its almost perfect, Galactic twin NGC3603, where Schnurr et al. (2008a) reported that of the three central WNh stars, two are binaries with \( P < 10 \) d. Also, Schnurr et al. (2008b) report that among the nine O3f/WN6 and WN5-7h stars in 30 Dor, but outside R136, only two \( (~20 \) per cent) are confirmed spectroscopic binaries. This value (at least) should have been recovered in the core of R136 as well, since in this study we are using data of almost identical quality.

Considering the small number of studied stars, however, our non-detection of systems is fully consistent with a frequency of \( \sim 20 \) per cent of binaries with \( P < 10 \) d. In fact, combining our results with that of Schnurr et al. (2008b), we can confirm that the short-period binary frequency among very massive stars around R136 within 30 Dor is not very high: out of the total of 15 O3f/WN6 and WN5-7h stars in 30 Dor, but outside R136, only two \( (~20 \) per cent) are confirmed spectroscopic binaries. This value (at least) should have been recovered in the core of R136 as well, since in this study we are using data of almost identical quality.

Very recently, Bosch, Terlevich & Terlevich (2009) have reported on the results of a spectroscopic monitoring campaign of absorption-line OB stars in the 30 Dor region; for 52 stars, six to seven spectra per star were obtained over a time-span of \( \sim 500 \) d. While this...
small number of spectra does not allow one to establish an orbital solution, Bosch et al. (2009) were able to identify binaries from their significantly large RV scatter compared to single stars and binaries with much longer periods; among the 52 stars monitored, 25 stars showed RV variability. If we suppose that with their method Bosch et al. (2009) were able to detect binaries with periods up to \( \sim 1000 \text{ d} \) (i.e. twice the covered time-span), the binary frequency is thus \( \sim 48 \text{ per cent} \). Taking into account all statistical errors, our null result for \( P < 10 \text{ d} \) reported here is perfectly consistent with this value. Remarkably, Monte Carlo simulations by Bosch et al. (2009) report that their observational results are consistent with a binary frequency of 100 per cent. Although our observations were only designed to identify the reported 4.4-d culprit, and we have not yet enough data points to identify systems much beyond \( P \sim 40 \text{ d} \), we can rule out such a high binary frequency for our stars with strong winds, because only BAT99-112 shows an X-ray excess.

5 SUMMARY AND CONCLUSION

We have obtained for the first time, spatially resolved, repeated, low-spectral-resolution, near-infrared spectroscopy of the most luminous stars in the core of R136 in an attempt to identify the 4.377-d binary that was reported by Moffat & Seggewiss (1983) and Moffat et al. (1985). Additional archival HST–STIS imaging was used to extract photometry of our target stars.

For none of the studied stars could significant photometric variability be found. Furthermore, we cannot confirm the presence of a binary system with the reported 4.4-d period, nor do we identify any other short-period (\( P \lesssim 44 \text{ d} \)) system among the most luminous stars in R136. One star, however, BAT99-112 (R136c), shows small, marginally significant RV scatter. A forced sine fit to the data yields a best period \( P = 8.2 \text{ d} \). While it is not entirely impossible, it is not very likely to see a binary under very low inclination angle (\( \iota \lesssim 15^\circ \)), which would be required to reconcile BAT99-112’s 8.2-d binary nature with the observed, low RV scatter. Thus, it is more probable that BAT99-112 is a longer period system that the limited time coverage of our observations could not detect, as is suggested by the fact that the star is one of the brightest X-ray sources among all known WR stars in the LMC.

To settle this issue, long-term monitoring of BAT99-112 will be required, but the possibility that it is indeed binary clearly harbours the potential to weigh one of the most massive stars known, and to obtain a clearer picture of the very upper main sequence in high-density, high-mass environments like R136.

The question as to why R136 appears to have a dearth in its short-period binary content, compared to its Galactic counterpart NGC 3603, remains to be explained, if not simply due to small numbers. A key difference, though, is the fact that NGC 3603 is not surrounded by a massive stellar halo as is R136 (i.e. 30 Dor). Another difference is the factor of 2 lower metallicity in R136. How these or other as yet unknown factors play out remains a mystery. In fact, ultimately, long-term monitoring of all the luminous stars in R136 is necessary to check for long-period systems.

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