The Tarantula Massive Binary Monitoring project: II. A first SB2 orbital and spectroscopic analysis for the Wolf-Rayet binary R145

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ABSTRACT

We present the first SB2 orbital solution and disentanglement of the massive Wolf-Rayet binary R145 ($P=159\,\mathrm{d}$) located in the Large Magellanic Cloud. The primary was claimed to have a stellar mass greater than $300\,M_\odot$, making it a candidate for the most massive star known. While the primary is a known late type, H-rich Wolf-Rayet star (WN6h), the secondary could not be so far unambiguously detected. Using moderate resolution spectra, we are able to derive accurate radial velocities for both components. By performing simultaneous orbital and polarimetric analyses, we derive the complete set of orbital parameters, including the inclination. The spectra are disentangled and spectroscopically analyzed, and an analysis of the wind-wind collision zone is conducted.

The disentangled spectra and our models are consistent with a WN6h type for the primary, and suggest that the secondary is an O3.5 If*/WN7 type star. We derive a high eccentricity of e=0.78 and minimum masses of $M_1 \sin^3 i \approx M_2 \sin^3 i = 13 \pm 2 \, M_{\odot}$, with $q=M_2/M_1=1.01\pm0.07$. An analysis of emission excess stemming from a wind-wind collision yields a similar inclination to that obtained from polarimetry ($i=39\pm6^{\circ}$). Our analysis thus implies $M_1=53^{+40}_{-20}$ and $M_2=54^{+40}_{-20}\,M_{\odot}$, excluding $M_1>300\,M_{\odot}$. A detailed comparison with evolution tracks calculated for single and binary stars, as well as the high eccentricity, suggest that the components of the system underwent quasi-homogeneous evolution and avoided mass-transfer. This scenario would suggest current masses of $\approx 80\,M_{\odot}$ and initial masses of $M_{i,1}\approx 105$ and $M_{i,2}\approx 90\,M_{\odot}$, consistent with the upper limits of our derived orbital masses, and would imply an age of $\approx 2.2\,\mathrm{Myr}$.

Key words. Stars: Massive stars – Binaries: spectroscopic – Stars: Wolf-Rayet – Magellanic Clouds – Stars: individual: R145 – Stars: atmospheres

1. Introduction

There are ever growing efforts to discover the most massive stars in the Universe (e.g., Massey & Hunter 1998; Schnurr et al. 2008a; Bonanos 2009; Bestenlehner et al. 2011; Tramper et al. 2016). Because of their extreme influence on their environment, understanding the formation, evolution, and death of massive stars is imperative for a multitude of astrophysical fields. Establishing the upper mass limit for stars is one of the holy grails of stellar physics, laying sharp constraints on the initial mass function

(Salpeter 1955; Kroupa 2001) and massive star formation (Bonnell et al. 1997; Oskinova et al. 2013). Current estimates for an upper mass limit range from $\approx 120\,M_\odot$ (e.g., Oey & Clarke 2005) to $\gtrsim 300\,M_\odot$ (e.g., Crowther et al. 2010; Schneider et al. 2014a; Vink 2015).

However, the only reliable method to weigh stars is by analyzing the orbits of stars in binaries (Andersen 1991; Torres et al. 2010). This is especially crucial for massive Wolf-Rayet (WR) stars, whose powerful winds make it virtually impossible to estimate their surface gravities. Fortunately, massive stars

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 $(M \gtrsim 8 \, M_\odot)$ tend to exist in binary or multiple systems (Mason et al. 2009; Maíz Apellániz 2010; Oudmaijer & Parr 2010; Sana et al. 2012, 2014; Sota et al. 2014; Aldoretta et al. 2015).

Primarily due to mass-transfer, the evolutionary path of a star in a binary can greatly deviate from that of an identical star in isolation (Paczynski 1973; Langer 2012; de Mink et al. 2014). The impact and high frequency of binarity make binaries both indispensable laboratories for the study of massive stars, as well as important components of stellar evolution. Hence, it is imperative to discover and study massive binary systems in the Galaxy and the Local Group.

R145 (BAT99 119, HDE 269928, Brey 90, VFTS 695) is a known massive binary situated in the famous Tarantula nebula in the Large Magellanic Cloud (LMC), about 19 pc away from the massive cluster R 136 in projection (see Fig. 1). The system's composite spectrum was classified WN6h in the original BAT99 catalog (Breysacher et al. 1999), which, according to this and past studies (e.g., Schnurr et al. 2009, \$2009 hereafter), corresponds to the primary. The primary thus belongs to the class of late WR stars which have not yet exhausted their hydrogen content, and is likely still core H-burning.

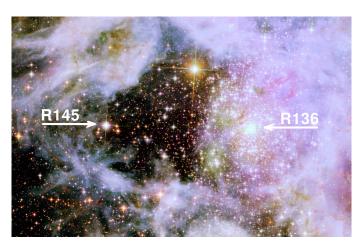


Fig. 1: The area of sky around R145 (Credit: NASA, ESA, E. Sabbi, STScI). The image was obtained using the Hubble Space Telescope's (HST) WFC3 and ACS cameras in filters which roughly overlap with the I, J, and H bands. The image size is $\approx 2.5' \times 1.7'$. North is up and east to the left. The arrows indicate the positions of R145 and the star cluster R136. The distance between R145 and R136 is $\approx 1.3'$ or in projection $\approx 19\,\mathrm{pc}$.

The system was speculated to host some of the most massive and luminous stars in the Local Group. Erroneously assuming a circular orbit, Moffat (1989) detected a periodic Doppler shift with a period of P = 25.17 d, concluding R145 to be an SB1 binary. A significantly different period of 158.8 ± 0.1 d was later reported by S009, who combined data from Moffat (1989) with their own and found a highly eccentric system. S009 could not derive a radial velocity (RV) curve for the secondary. However, they attempted to estimate the secondary's RV amplitude by looking for "resonance" velocity amplitudes which would strengthen the secondary's features in a spectrum formed by co-adding the spectra in the secondary's frame of reference, under the assumption that the secondary is mainly an absorption-line star moving in anti-phase to the primary star. Combined with an orbital inclination of $i = 38^{\circ} \pm 9$ they derived, their results tentatively implied that the system comprises two incredibly massive stars of ≈ 300 and $\approx 125 M_{\odot}$, making it potentially the most massive binary system known. For comparison, binary components of similar spectral type typically have masses ranging from ≈ 50 to $\approx 100 \, M_\odot$ (e.g., WR 22, Rauw et al. 1996; WR 20a, Bonanos et al. 2004, Rauw et al. 2004; WR 21a, Niemela et al. 2008, Tramper et al. 2016; HD 5980, Koenigsberger et al. 2014; NGC 3603-A1, Schnurr et al. 2008a); masses in excess of 300 M_\odot were so far only reported for putatively single stars (e.g., Crowther et al. 2010) based on comparison with evolutionary models.

With such high masses, signatures for wind-wind collisions (WWC) are to be expected (Moffat 1998). WWC excess emission can be seen photometrically as well as spectroscopically, and can thus also introduce a bias when deriving RVs. WWC signatures do not only reveal information on the dynamics and kinematics of the winds, but can also constrain the orbital inclination, which is crucial for an accurate determination of the stellar masses. Polarimetry offers a further independent tool to constrain orbital inclinations of binary systems (Brown et al. 1978). Both approaches are used in this study to constrain the orbital inclination *i*. For high inclination angles, photometric variability due to photospheric/wind eclipses can also be used to constrain *i* (e.g., Lamontagne et al. 1996). At the low inclination angle of R145 (see Sects. 4 and 7, as well as S2009), however, eclipses are not expected to yield significant constraints.

Using 110 high-quality Fibre Large Array Multi Element Spectrograph (FLAMES) spectra (Sect. 2), we are able to derive for the first time a double-lined spectroscopic orbit for R145. We identify lines which enable us to construct a reliable SB2 RV curve (Sect. 3). The majority of the spectra were taken as part of the VLT FLAMES-Tarantula survey (VFTS, Evans et al. 2011) and follow up observations (PI: H. Sana). The study is conducted in the framework of the Tarantula Massive Binary Monitoring (TMBM) project (Almeida et al. 2016, submitted to A&A, paper I hereafter).

The RVs of both components are fitted simultaneously with polarimetric data to obtain accurate orbital parameters (Sect. 4). In Sect. 5, we disentangle the spectrum to its constituent spectra. Using the disentangled spectra, an XSHOOTER spectrum, and additional observational material, we perform a multiwavelength spectroscopic analysis of the system using the Potsdam Wolf-Rayet (PoWR) model atmosphere code to derive the fundamental stellar parameters and abundances of both stars (Sect. 6). An analysis of WWC signatures is presented in Sect. 7. A discussion of the evolutionary status of the system in light of our results is presented in Sect. 8. We conclude with a summary in Sect. 9.

2. Observational data

The FLAMES spectra (072.C-0348, Rubio; 182.D-0222, Evans; 090.D-0323, Sana; 092.D-0136, Sana) were secured between 2004 and 2014 with the FLAMES instrument mounted on the Very Large Telescope (VLT), Chile, partly in the course of two programs: the VLT FLAMES Tarantula Survey (Evans et al. 2011) and the TMBM project. They cover the spectral range $3960-4560\,\text{Å}$, have a typical signal-to-noise (S/N) ratio of 100, and a resolving power of $R\approx 8000$ (see paper I for more information). The spectra are rectified using an automated routine which fits a piecewise first-order polynomial to the apparent continuum, and are cleaned from cosmic events using a self-written Python routine.

For the spectral analysis, we use an XSHOOTER (Vernet et al. 2011) spectrum (085.D-0704, PI: Sana) taken on 22 April 2010 ($\phi \approx 0.5$, i.e. apastron, with the phase calculated using the ephemeris given in Table 1 in Sect. 4). The spectrum covers the range $3000-25000\,\text{Å}$. It has S/N ≈ 100 and a resolving power

of $R \approx 7500$ in the spectral range 5500 - 10000 Å and $R \approx 5000$ in the ranges 3000 - 5500 Å and 10000 - 25000 Å. It is rectified by fitting a first-order polynomial to the apparent continuum. A segment of the spectrum is shown in Fig. 2.

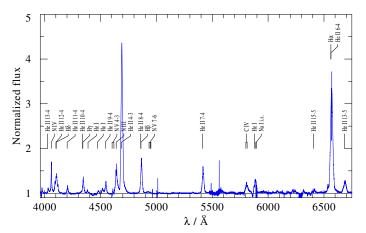


Fig. 2: Segment of the XSHOOTER spectrum of R145.

We make use of two high-resolution (HIRES), flux-calibrated International Ultraviolet Explorer (IUE) spectra available in the IUE archive. The two spectra (swp47847, PM048, PI: Bomans; swp47836, PM033, PI: de Boer) were obtained on 08 and 10 June 1993 at roughly $\phi = 0.7$ and are thus co-added to enhance the S/N. The co-added spectrum has a resolving power of $R \approx 10000$ and S/N ≈ 10 . The spectrum is rectified using the composite PoWR model continuum (see Sect. 6).

Linear polarimetry was obtained between 1988 and 1990 at the 2.15-m "Jorge Sahade" telescope of the Complejo Astronómico El Leoncito (CASLEO) near San Juan, Argentina, with the Vatican Observatory Polarimeter (VATPOL, Magalhaes et al. 1984) and at the European Southern Observatory (ESO)/Max-Planck-Gesellschaft (MPG)-2.2m telescope at La Silla, Chile, with Polarimeter with Instrumentation and Sky COmpensation (PISCO, Stahl et al. 1986). The data were obtained and originally used by \$2009, where more details can be found.

3. SB2 orbit construction

As discussed in the introduction, R145 is a known SB1 binary. However, no previous studies could unambiguously isolate the secondary in the spectrum. Thanks to the moderate resolution, high S/N of the FLAMES spectra, we are now able to detect spectral features which belong solely to the secondary and thus construct an SB2 orbit for the system.

Figure 3 shows two FLAMES spectra taken shortly before and after periastron ($\phi = 1$), where the RV differences are most extreme. It is readily seen that almost all spectral features shift in the same direction, i.e. they stem primarily from one component, the primary. However, a closer inspection reveals that the secondary contributes to the N IV $\lambda 4058$ emission and to some absorption features seen on top of He II and Balmer lines. Most importantly, the Si IV emission doublet at $\lambda\lambda 4089$, 4116 moves in pure antiphase to the majority of the available spectral features, implying that the Si IV lines stem from the secondary alone. A zoom-in of Fig. 3 which focuses on the N IV $\lambda 4058$ spectral region and a neighboring member of the Si IV doublet is shown in Fig. 4, where we also plot a spectrum taken close to apastron ($\phi \approx 0.5$).

To measure the RVs of the components in the individual FLAMES spectra, we perform a 1D cross-correlation algorithm

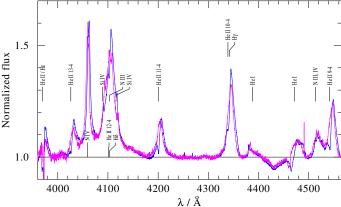


Fig. 3: Two FLAMES spectra taken slightly before ($\phi = -0.03$) and after ($\phi = 0.07$) periastron passage (extreme velocity amplitudes).

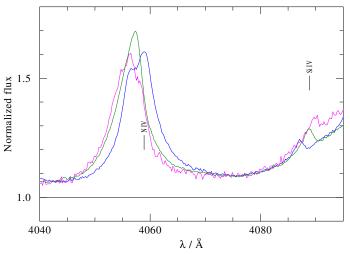


Fig. 4: Zoom-in of Fig. 3 showing the N IV and Si IV lines moving in anti-phase. A FLAMES spectrum at $\phi\approx 0.5$ is also shown (green). The primary dominates the N IV line, while the Si IV lines originate solely in the secondary. The spectra are shifted by the systemic LMC velocity of $270\,\mathrm{km\,s^{-1}}$.

to different spectral features in all available spectra. We tried two types of templates to cross-correlate with: a Gaussian, and the observations themselves. Both methods resulted in comparable values, although the Gaussians resulted in a worse fit quality, and are therefore omitted here.

We first used one of the FLAMES spectra as a template to cross-correlate with. A calibration of the template to the restframe using rest wavelengths λ_0 is known to lead to systematic errors since the barycenter of emission lines rarely coincides with λ_0 . Thus, to calibrate the template, we cross-correlated specific features with two preliminary PoWR models (see Sect. 6) calculated for the primary and secondary. We used the relatively symmetric and isolated N IV $\lambda 4058$ line and Si IV doublet to calibrate the templates of the primary and secondary, respectively. Note that, while the calibration to the restframe depends to a certain extent on our PoWR models, this only affects the systemic velocity V_0 , and *not* the remaining orbital parameters.

Once the two template spectra are calibrated, we cross-correlated them against the individual FLAMES spectra, identifying the RV with the maximum of the cross-correlation function.

For the primary, we measured RV shifts using the lines N IV $\lambda 4058$, He II $\lambda 4200$, He II $\lambda 4542$, and H γ . The secondary contributes to all these lines, but its contribution is significantly smaller due to its lower mass-loss rate, and, judging by the cross-correlation fits, we do not expect that it should influence the derived RVs. For the secondary, the Si IV doublet offers the most reliable way to track the secondary's motion, although the weak N III $\lambda 4379$ line also shows a clear antiphase behavior, and was therefore measured for RVs. The Si IV lines, which are blended with the H δ line, were rectified relatively to the contribution of the underlying H δ emission for a more accurate derivation of the RVs.

With the preliminary velocities at hand, we created "master templates" for the primary and secondary by shifting the individual FLAMES spectra to the rest frame and co-adding them. We then used these master templates to perform a new cross-correlation with the individual observations. The newly derived RVs differed only slightly from the previous ones and generally show less scatter. Errors on the RVs are estimated to be of the order of $10 \, \mathrm{km \, s^{-1}}$ for the primary and $5 \, \mathrm{km \, s^{-1}}$ for the secondary.

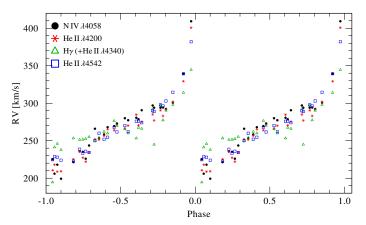


Fig. 5: RVs for the primary component plotted over phase as measured for selected lines (see text).

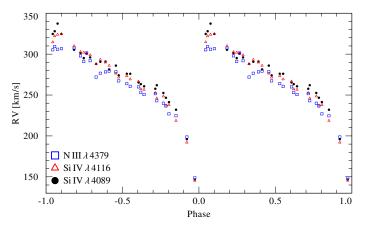


Fig. 6: As Fig. 5, but for the secondary.

The derived RVs for the primary and secondary as a function of phase are shown in Figs. 5 and 6. The phase is calculated relative to our final orbital solution (Table 1). The measured RVs for the N IV (primary) and Si IV lines (secondary) are listed in Table A.1. The points are binned at intervals of 0.01 on phase (note that often three FLAMES spectra were secured in a single observing night, cf. Table A.1).

From Fig. 5, it is evident that N IV $\lambda4058$ and the He II $\lambda4200$ and $\lambda4542$ lines predict similar RVs, with N IV showing a slightly larger velocity amplitude. In contrast, H γ (+ He II $\lambda4340$) shows significantly more scatter and a phase-dependent deviation from the other lines. As we will show in Sect. 7, the reason is likely a contamination of H γ by WWC, as well as its large formation radii. The preliminary PoWR model for the primary (see Sect. 6) suggests that the He II lines form a few stellar radii away from the stellar surface, as opposed to the N IV line, which forms about ≈ 0.1 stellar radii away. This implies that the N IV line is more likely to represent the motion of the WR primary, and is therefore used for the orbital fitting.

As for the secondary, we use the Si IV doublet. PoWR models calculated for the secondary (see Sect. 6) suggest that it forms very close to the stellar surface ($\approx 0.05\,R_*$ above the stellar surface), and should be very reliable for measuring the secondary's RVs. The two Si IV components agree well with each other and show a typical scatter of $\sigma \approx 7\,\mathrm{km\,s^{-1}}$ (Fig. 6). For the final RVs of the secondary, we average the results of these two lines.

In principle, we can derive orbital parameters using these velocities. However, the data only cover a few orbits and suffer from large gaps between them. We therefore combine old velocity measurements obtained by Moffat (1989) and S2009 for the primary with our datasets to assemble the longest possible time series, hence to obtain *P* with the highest possible accuracy. We note that the older velocities portray a significant systematic shift compared to the velocities derived here. This is mostly due to the different restframe calibration method used here. When performing the fitting, we therefore also fit for the systematic shifts for both sets of velocities. The SB1 fitting procedure is performed through a Levenberg–Marquardt technique using the results of a Fourier analysis as a guess value for the initial period (Gosset et al. 2001).

From the SB1 fit, we derive the period $P_{\text{orb}} = 158.760 \pm$ 0.017 d, the epoch of periastron passage $T_0[MJD] = 56022.4 \pm$ 0.8, the RV amplitude of the primary $K_1 = 78 \pm 3 \,\mathrm{km \, s^{-1}}$, the eccentricity $e = 0.75 \pm 0.01$, and the argument of periastron $\omega = 61 \pm 1^{\circ}$. Since the older velocities suffer from significantly larger errors, we do not adopt all orbital parameters derived, but only the period, which benefits significantly from the $\approx 30 \,\mathrm{yr}$ of coverage. We do not find evidence for apsidal motion in the system, which may, however, be a consequence of the fact that the new data are of much higher quality than previous ones. In the next section, we analyze the polarimetric data simultaneously with the FLAMES data to better determine the orbital parameters and the orbital inclination. Note that the assumption here is that the period change due to mass-loss from the system is negligible during these 30 years. Since roughly $10^{-4.3} M_{\odot}$ are lost from the system each year (see Sect. 6), approx. $\Delta M_{\rm tot} = 0.001 \, M_{\odot}$ were lost within 30 yr. The period change within 30 years can be estimated via $P_i/P_f = (M_{\text{tot, f}}/M_{\text{tot, i}})^2$ (Vanbeveren et al. 1998). Assuming $M_{\text{tot}} = 100 \, M_{\odot}$ for an order-of-magnitude estimate, we obtain a difference in the period which smaller than our error, and thus negligible.

4. Simultaneous polarimetry and RV fitting

Fitting the polarimetric data simultaneously with the RV data enables us to lay tighter constraints on the orbital parameters. Furthermore, as opposed to an RV analysis, polarimetry can yield constraints on the inclination i. As the orbital masses scale as $M_{\rm orb} \propto \sin^3 i$, knowing i is crucial.

The polarimetric analysis is based on ideas developed by Brown et al. (1978, 1982), later corrected by Simmons & Boyle

Table 1: Derived orbital parameters

Parameter	Value
P_{orb} [days]	158.760
T_0 [MJD]	56022.6 ± 0.2
$K_1 [{\rm km s^{-1}}]$	96 ± 3
$K_2 [{\rm km s^{-1}}]$	95 ± 4
e	0.788 ± 0.007
$\omega [^{\circ}]$	61 ± 7
$M_{ m orb, 1} \sin^3 i \left[M_{\odot} \right]$	13.2 ± 1.9
$M_{\rm orb, 2} \sin^3 i \left[M_{\odot} \right]$	13.4 ± 1.9
$a_1 \sin i [R_{\odot}]$	302 ± 10
$a_2 \sin i [R_{\odot}]$	299 ± 10
$V_0 [{\rm km s^{-1}}]$	270 ± 5
$\Omega\left[^{\circ} ight]$	62 ± 7
<i>i</i> [°]	39 ± 6
$ au_*$	0.10 ± 0.01
Q_0	-2.13 ± 0.02
U_0	0.58 ± 0.02
γ	0.87 ± 0.07
$M_{ m orb,\ 1}\ [M_{\odot}]$	53+40
$M_{\mathrm{orb, 2}} [M_{\odot}]$	54+40
$a_1 [R_{\odot}]$	480_{-65}^{+90}
$a_2 [R_{\odot}]$	475^{+100}_{-70}

Notes. Derived orbital parameters from a simultaneous fit of the FLAMES RVs and the polarimetry. The period is fixed to the value found from the SB1 fitting using all published RVs for the primary (see Sect. 3)

(1984). A similar analysis for the system was performed by S2009. As such, light emitted from a spherically-symmetric star is unpolarized. While Thomson scattering off free electrons in the stellar wind causes the photons to be partially linearly polarized, the total polarization measured in the starlight cancels out if its wind is spherically-symmetric. However, when the light of a star is scattered in the wind of its binary companion, the symmetry is broken, and some degree of polarization is expected. The degree of polarization depends on the amount and geometry of the scattering medium, which depends on the properties of the wind (e.g., mass-loss) and on the orbital phase.

In our case, the dominant source of free electrons would clearly be the wind of the primary WR star (see also Sect. 6), although some of the primary's light may also be scattered in the wind of the secondary star. We first assume that only the wind of the primary contributes to the polarization, given its dominance over that of the secondary. We will later relax this assumption. Following Robert et al. (1992), the Stokes parameters $U(\phi)$ and $Q(\phi)$ can be written as the sum of the (constant) interstellar polarizations U_0 , Q_0 and phase-dependent terms:

$$U(\phi) = U_0 + \Delta Q(\phi) \sin \Omega + \Delta U(\phi) \cos \Omega$$

$$Q(\phi) = Q_0 + \Delta Q(\phi) \cos \Omega - \Delta U(\phi) \sin \Omega,$$
(1)

where Ω is the position angle of the ascending node, and $\Delta Q(\phi)$, $\Delta U(\phi)$ (in the case of spherically-symmetric winds) are given by

$$\Delta U(\phi) = -2\tau_3(\phi)\cos i\sin(2\lambda(\phi))$$

$$\Delta Q(\phi) = -\tau_3(\phi)\left[\left(1 + \cos^2 i\right)\cos(2\lambda(\phi)) - \sin^2 i\right].$$
(2)

Here, $\lambda(\phi) = \nu(\phi) + \omega - \pi/2$ is the longitude of the scattering source (primary) with respect to the illuminating source (secondary). ν is the true anomaly, ω is the argument of periastron. τ_3 is the effective optical depth of the scatterers (see eqs. 4,5 in Robert et al. 1992) which scales with the (constant) total optical depth τ_* of the primary star (see Moffat et al. 1998). St.-Louis et al. (1988) assumed that $\tau_3(\phi) = \tau_* (a/D(\phi))^\gamma$, where $D(\phi)$ is the separation between the companions, and γ is a number of the order of unity. Brown et al. (1982) showed that $\gamma \approx 2$ in the case of a wind which is localized closely to the primary's stellar surface. However, this need not be the case for WR stars.

The free parameters involved in the polarimetry fitting are therefore Ω , i, τ_* , Q_0 , U_0 , and γ , as well as the orbital parameters P, ω , and e. One may generalize this model easily if both companions possess winds which can significantly contribute to the total polarization. In this case, τ_* is the sum of optical depths of both stars, weighted with the relative light ratios (see Eq. 2 in Brown et al. 1982). The formalism may be therefore implemented here, with the only consequence that τ_* relates to the mass-loss rates of both companions.

The simultaneous fitting of the FLAMES RVs and the polarimetric data is performed through a χ^2 minimization algorithm, with a relative weight given to the RV and polarimetric data chosen so that both types of data have a similar contribution to the total χ^2 . Best fit RV and Q/U curves are shown in Figs. 7 and 8. During the fitting procedure, the period is fixed to the value inferred from the combined RV sample (see Sect. 3). The corresponding best-fitting parameters are given in Table 1.

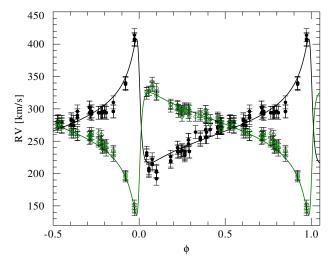


Fig. 7: Orbital solution plotted against the measured RVs for the N IV $\lambda 4058$ line (primary, black stars) and the averaged velocities of the Si IV $\lambda \lambda 4089$, 4116 doublet (secondary, green triangles).

The inclination found in this study is very similar to that reported by S2009, which is not surprising given that we make use of the same polarimetric data. We note that clumps in the wind can generally enhance the scattering and may therefore lead to an overestimation of the inclination. The eccentricity is found to be larger, $e = 0.788 \pm 0.007$ as opposed to $e = 0.70 \pm 0.01$ found by S2009. This also affects the remaining orbital parameters (cf. Table 5 in S2009). Most importantly, the orbital masses found

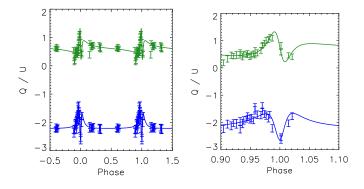


Fig. 8: Our polarimetric solution for Q (blue) and U (green) plotted against measured polarimetric data. The right panel is a zoom-in of the left panel around periastron passage

here are much lower, $\approx 55^{+40}_{-20}~M_{\odot}$ for each component compared to $M_1 \gtrsim 300$ and $M_2 \gtrsim 125$ which were inferred by S2009. The reason for this discrepancy is the improved derivation of K_2 in our study. While we cannot supply a definitive reason for the erroneous derivation of K_2 by S2009, we suggest that it may be related to the fact that the secondary exhibits emission features as well as a blue-shifted absorption. Furthermore, the spectra used in the latter study are of significantly lesser quality compared with the FLAMES spectra.

The masses derived here are in much better agreement with the brightness of the system, as discussed by S2009. While the masses obtained here are close to the lower limit of what would be expected for these spectral types, as measured from eclipsing systems (e.g., Rauw et al. 2004; Bonanos et al. 2004; Schnurr et al. 2008b; Koenigsberger et al. 2014), they are not inconsistent, especially considering the errors. Moreover, given the bias of the polarimetric fitting towards higher inclination angles (e.g., Aspin et al. 1981; Wolinski & Dolan 1994), the masses derived here are likely underestimated.

From Fig. 1, it is evident that the binary R145 is located outside the dense, massive cluster R 136. The projected separation between the system and the cluster is only $\approx 20\,\mathrm{pc}$, which, accounting for an age of $\approx 2\,\mathrm{Myr}$ (cf. Table 3), implies an average velocity of a mere $\approx 10\,\mathrm{km\,s^{-1}}$. The derived systemic velocity (cf. Table 1), which is comparable to the LMC mean velocity, would be consistent with a slow runaway ejected due to dynamical interactions within the cluster, as claimed for VFTS 682 (Banerjee et al. 2012). Alternatively, it may have formed in situ in the halo of the massive cluster R 136.

5. Spectral disentanglement

Using the orbital parameters given in Table 1 as an initial guess, we apply the disentanglement code Spectangular (Sablowski & Weber 2016) to the FLAMES spectra. The code performs the disentangling on a set of spectra in the wavelength domain rather than in the Fourier space (Hadrava 1995). Disentangling is coupled to an optimisation algorithm on the orbital parameters. Hence, it provides revised orbital parameters and the separated component spectra.

It has been shown by Hadrava et al. (2009) that the disentangling can be successful as long as the line-profile variability is small compared to a mean profile and the orbital motion. However, these conditions are hardly met by the system under study, both due to the intrinsic variability of WR stars (e.g., due to clumping) as well as due to WWC. Indeed, we find that the or-

bital solution severely depends on the spectral domains used and the initial solution assumed. We therefore adopt the orbital parameters obtained in Sect. 4. In contrast, the resulting disentangled spectra are hardly influenced by the different solutions. We are therefore confident that the disentangled spectra obtained here represent the true spectra well, except in cases where the lines are heavily contaminated by variability.

With no eclipses in the system, it is impossible for the disentanglement procedure to provide the light ratio of the primary and secondary components. The adopted light ratio influences the strength of the lines in the disentangled, rectified spectra. Based on a calibration with equivalent widths (EWs) of putative single stars (see below), we estimate the light ratio to be $F_{v,2}/F_{v,\text{tot}} = 0.55 \pm 0.10$, where F_v is the visual flux in the Smith v band. This ratio is assumed for the rectified disentangled spectra, shown in Fig. 9.

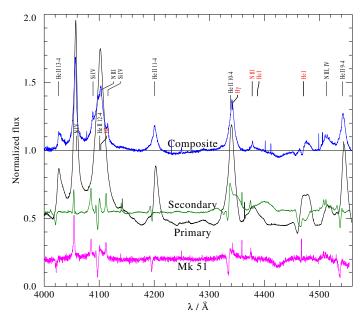


Fig. 9: The disentangled normalized spectra of the primary (black) and secondary (green), shifted to their relative light ratio. A composite FLAMES spectrum ($\phi \approx 0.5$) is shown for comparison (blue), as well as an observed normalized spectrum of Mk 51 for comparison with the secondary, shifted by -0.8 for clarity.

The disentangled spectrum of the primary is consistent with it being of WN6h type. We compared the spectrum with two WN6h spectra in the LMC: BAT99 30 and BAT99 31. The adopted light ratio results in EWs of the He II lines which agree well with the two latter objects, but also results in an EW of the He I λ 4471 line which is about three times larger, suggesting a strong He I excess in the system, likely originating in WWC (see Sect. 7).

The spectrum of the secondary is suggestive of a so-called slash star (Crowther & Walborn 2011). Unfortunately, the FLAMES spectra do not include diagnostic lines which are important for the classification (e.g., $H\beta$, $N v \lambda\lambda 4603$, 4619 and $N \coprod \lambda\lambda 4634$, 4640, 4642). Moreover, some lines, marked in red in Fig. 9, are strongly affected by WWC (see Sect. 7). This is especially significant for the secondary's spectrum, which generally shows weaker features compared to the primary. Especially the shape and strength of the lines in the range 4000 – 4200 Å is suggestive of an O3.5 If*/WN7 star, for which the star Melnick 51 (Mk 51) is a prototype. For comparison, we plot in Fig. 9 an observed normalized FLAMES spectrum of Mk 51 (P. Crowther,

priv. com.). The Si IV doublet is stronger in R145 than observed for MK51, and the N IV line weaker. However, the derived model and parameters for the secondary (see Sect. 6) are suggestive of the spectral class O3.5 If*/WN7. We therefore adopt this spectral class in this study. The light ratio adopted here is also chosen so that the EWs of the majority of the Balmer and He II lines agree with this spectral type (see Fig. 9).

6. Spectral analysis

The disentangled spectra, together with the high-quality XSHOOTER spectrum and the complementary UV and photometric data, enable us to perform a spectral analysis of both components. The spectral analysis is performed with the Potsdam Wolf-Rayet¹ (PoWR) model atmosphere code, applicable to any hot star (e.g., Shenar et al. 2015; Todt et al. 2015; Giménez-García et al. 2016). The code iteratively solves the co-moving frame, non-local thermodynamic equillibrium (non-LTE) radiative transfer and the statistical balance equations in spherical symmetry under the constraint of energy conservation, yielding the occupation numbers in the photosphere and wind. By comparing the output synthetic spectra to observed spectra, fundamental stellar parameters are derived. A detailed description of the assumptions and methods used in the code is given by Gräfener et al. (2002) and Hamann & Gräfener (2004). Only essentials are given here.

A PoWR model is defined by four fundamental stellar parameters: the effective temperature T_* , the surface gravity g_* , the stellar luminosity L, and the mass-loss rate \dot{M} . The effective temperature T_* is given relative to the stellar radius R_* , so that $L=4\pi\sigma R_*^2T_*^4$. R_* is defined at the model's inner boundary, fixed at mean Rosseland optical depth of $\tau_{\rm Ross}=20$ (Hamann et al. 2006). The outer boundary is set to $R_{\rm max}=1000\,R_*$. The gravity g_* relates to the radius R_* and mass M_* via the usual definition: $g_*=g(R_*)=G\,M_*R_*^{-2}$. We cannot derive g_* here because of the negligible effect it has on the wind-dominated spectra, and fix it to the value implied from the orbital mass.

The chemical abundances of the elements included in the calculation are prespecified. Here, we include H, He, C, N, O, Si, and the iron group elements dominated by Fe. The mass fractions $X_{\rm H}$, $X_{\rm C}$, and $X_{\rm N}$, and $X_{\rm Si}$ are derived in this work. Based on studies by Korn et al. (2000) and Trundle et al. (2007), we set $X_{\rm Fe} = 7 \cdot 10^{-4}$. Lacking any signatures associated with oxygen, we fix $X_{\rm O} = 5 \cdot 10^{-5}$ for both components. Values larger than 10^{-4} lead to spectral features which are not observed.

Hydrostatic equilibrium is assumed in the subsonic velocity regime (Sander et al. 2015), from which the density and velocity profiles follow, while a β -law (Castor et al. 1975) with $\beta=1$ (e.g., Schnurr et al. 2008b) is assumed for the supersonic regime, defined by the β exponent and the terminal velocity v_{∞} . Optically thin clumps are accounted for using the microclumping approach (Hillier 1984; Hamann & Koesterke 1998), where the population numbers are calculated in clumps which are a factor of D denser than the equivalent smooth wind (D=1/f, where f is the filling factor). Because optical WR spectra are dominated by recombination lines, whose strengths increase with \dot{M} \sqrt{D} , it is customary to parametrize their models using the so-called transformed radius (Schmutz et al. 1989),

$$R_{\rm t} = R_* \left[\frac{v_{\infty}}{2500 \,\mathrm{km} \,\mathrm{s}^{-1}} / \frac{\dot{M} \,\sqrt{D}}{10^{-4} \,M_{\odot} \,\mathrm{yr}^{-1}} \right]^{2/3}, \tag{3}$$

Table 2: Derived physical parameters for R145.

Parameter	Primary	Secondary
Spectral type	WN6h	O3.5 If*/WN7
T_* [K]	50000 ± 3000	43000 ± 3000
$\log L \left[L_{\odot} ight]$	6.35 ± 0.15	6.33 ± 0.15
$\log R_{\rm t} [R_{\odot}]$	1.05 ± 0.05	1.50 ± 0.15
v_{∞} [km s ⁻¹]	1200 ± 200	1000 ± 200
$R_* [R_{\odot}]$	20^{+6}_{-5}	26^{+9}_{-7}
$D\left[R_{\odot} ight]$	$10 \pm 0.3 \text{dex}$	$10 \pm 0.3 \mathrm{dex}$
$\log \dot{M} [M_{\odot} \mathrm{yr}^{-1}]$	-4.45 ± 0.15	-4.9 ± 0.3
$v \sin i [\text{km s}^{-1}]$	< 200	< 150
$v_{\rm rot} [{\rm km s^{-1}}]$	< 350	< 270
$X_{\rm H}$ (mass fraction)	0.4 ± 0.1	0.5 ± 0.2
$X_{\rm C}/10^{-4}$ (mass fraction)	0.8 ± 0.3	0.7 ± 0.4
$X_{\rm N}/10^{-3}$ (mass fraction)	8 ± 4	8 ± 4
$X_{\rm O}/10^{-4}$ (mass fraction)	≲ 1	≲ 1
$X_{\rm Si}/10^{-4}$ (mass fraction)	7 (fixed)	7 ± 3
$M_{\rm v}[{\rm mag}]$	-7.21 ± 0.25	-7.43 ± 0.25
$M_{\rm V}[{\rm mag}]$	-7.15 ± 0.25	-7.30 ± 0.25
$M_{ m MLR,hom}[M_{\odot}]$	101^{+40}_{-30}	109^{+60}_{-40}
$M_{ m MLR, He-b}[M_{\odot}]$	55 ⁺¹⁵ ₋₁₂	54^{+15}_{-12}
E_{B-V} [mag]	0.34 ± 0.01	
A_V [mag]	1.4 ± 0.2	

defined so that EWs of recombination lines of models with given abundances, T_* , and R_t are approximately preserved, independently of L, \dot{M} , D, and v_{∞} .

The effective temperature of the primary is derived mainly based on the ionisation balance of N III, N IV, and N V lines. For the secondary, the weakness of associated He I lines, as well as the presence of a strong N III component and a weak N IV component constrain T_* . Once the temperatures and light ratio (see Sect. 5) are constrained, mass-loss rates (or transformed radii) can be determined. For the primary, this is straightforward, while for the secondary, this can only be done approximately. The terminal velocity v_∞ is determined primarily from P-Cygni lines in the UV. Clumping factors are determined using electron scattering wings, primarily of He II λ 4686. Hydrogen content is derived based on the balance of the Balmer series (He II + H) to pure He II lines. The remaining abundances are derived from the overall strengths of their associated lines.

The luminosity and reddening follow from a simultaneous fit to available photometry, adopting a distance of 50 kpc (Pietrzyński et al. 2013). We use U photometry from Parker et al. (1992), BVRI photometry from Zacharias et al. (2012), JHK and IRAC photometry from the compilation of Bonanos et al. (2010), and WISE photometry from Cutri & et al. (2013). The reddening is modelled using the reddening law published by Howarth (1983). In the latter, we find $R_V = 4.0 \pm 0.5$ is most consistent in reproducing the complete photometry, comparable to other stars in 30 Dorados (Maíz Apellániz et al. 2014), and we therefore fix $R_V = 4$ and fit for E_{B-V} . Maíz Apellániz et al. (2014) derived new laws for the 30 Dor region, but since the difference between these laws and older ones are negligible in the reddening regime involved here (see figures 11 and 12 in the latter paper) especially for the purpose of this study - these new laws are not implemented here.

¹ PoWR models of Wolf-Rayet stars can be downloaded at http://www.astro.physik.uni-potsdam.de/PoWR.html

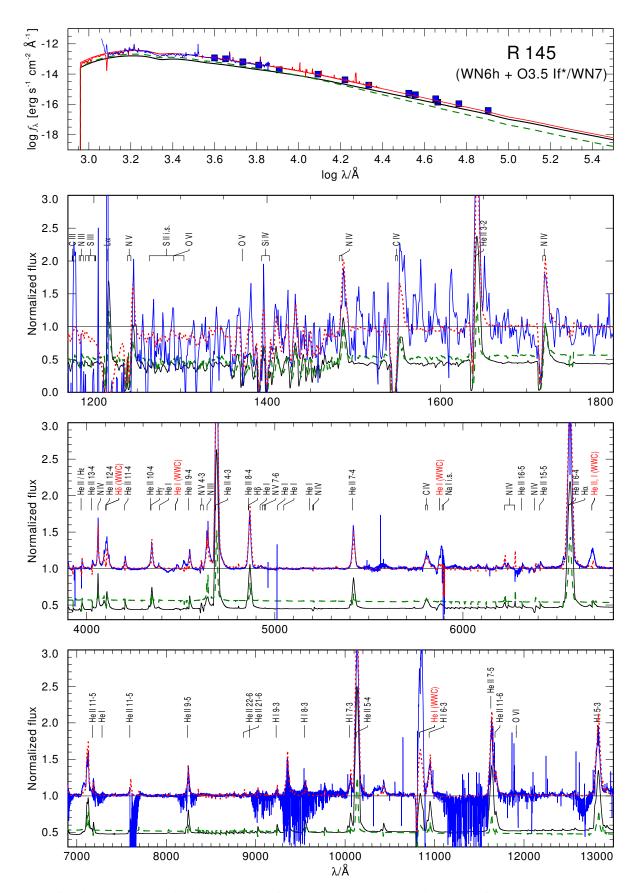


Fig. 10: Comparison between observed (blue squares and lines) SED (upper panel) and the normalized IUE and XSHOOTER spectra (lower panel) and the synthetic composite spectrum (red dotted line). The composite spectrum is the sum of the primary (black solid line) and secondary (green dashed line). The observed and modelled spectra in the UV are binned at 1\AA for clarity. Lines which are strongly affected by WWC are marked with red idents.

The nitrogen abundance is found to be about a factor of two larger in both components compared to the typical LMC values (cf. Hainich et al. 2014), mostly due to the strong N III doublet at ≈ 4640 Å. However, this enhancement may be insignificant given the errors. Furthermore, to reproduce the Si IV doublet originating in the secondary, it is necessary to set $X_{\rm Si}$ to an abundance comparable to the Galactic one (\approx two times larger than typical LMC abundance, cf. Trundle et al. 2007). Since $X_{\rm Si}$ is not expected to change throughout the stellar evolution, we assume that silicon was initially overabundant, and fix the same value for the primary. Unfortunately, the poor quality of the UV data does not enable us to determine the abundance of the iron group elements. Because of the relatively large associated errors, we refrain from interpreting this apparent overabundance.

A comparison of the best-fitting models to the observed spectral energy distribution (SED) and normalized spectra is shown in Fig. 10. Note that the composite spectrum strongly underpredicts low-energy transitions such as He I lines. We will show in Sect. 7 that these lines are expected to be strongly contaminated by WWC. The derived stellar parameters are listed in Table 2, where we also give the Smith and Johnson absolute magnitudes $M_{\rm v}$ and $M_{\rm V}$, as well as the total extinction $A_{\rm V}$. We also give upper limits derived for the projected and actual rotation velocity $v \sin i$ and v_{rot} for both components, as derived by comparing lines formed close to the stellar surface (N IV λ 4058, Si IV doublet) to synthetic spectra which account for rotation in an expanding atmosphere, assuming co-rotation up to $\tau_{Ross} = 2/3$ and angular momentum conservation beyond (cf. Shenar et al. 2014). Given the low inclination angle, these only lay weak constraints on the actual rotation velocities $v_{\rm rot}$ of the stars. Errors are estimated from the sensitivity of the fit quality to variations of stellar parameters, or via error propagation.

Table 2 further gives stellar masses which are based on mass-luminosity relations calculated by Gräfener et al. (2011) for homogeneous stars. The relations depend on L and $X_{\rm H}$ alone. $M_{\rm MLR,\ hom}$ assumes the derived value of $X_{\rm H}$ in the core, i.e. a homogeneous star. $M_{\rm MLR,\ He-b}$ assumes $X_{\rm H}=0$, i.e. the relation for pure He stars, which is a good approximation if the hydrogen rich envelope is of negligible to moderate mass (see discussion by Gräfener et al. 2011). If indeed $M_{\rm orb}\approx 55\,M_{\odot}\approx M_{\rm MLR,\ He-b}$, as is implied from Tables 1 and 2, the stars are likely already core He-burning. However, this is very unlikely to be true for the secondary given its spectral type and luminosity. Rather, the orbital masses are likely underestimated due to an overestimated inclination (e.g., Aspin et al. 1981), and may in fact be more similar to $M\approx 80-90\,M_{\odot}$, which is consistent with the upper boundary of our errors (see further discussion in Sect. 8).

Within errors, the derived physical parameters are in good agreement with the spectral types of the primary and secondary (cf. Crowther & Walborn 2011; Hainich et al. 2014). Bestenlehner et al. (2014) and Hainich et al. (2014) both analyzed R145 assuming a single component, which explains why they derive a luminosity in excess of $\log L = 6.5 [L_{\odot}]$, about 0.2 - 0.3 dexhigher than found here for the primary. Hainich et al. (2014) found a comparable effective temperature to that found for the primary in our study, while Bestenlehner et al. (2014) found a significantly lower temperature of 40 kK (comparable to the secondary), which is a consequence of attributing strong features stemming partially from the secondary (e.g., strong N III lines) to the primary. Similarly, the mass-loss rates derived here are different than in the previous studies because they did not account for line dilution and adopted wrong luminosities. Given the careful binary analysis performed here, we are inclined to believe

that our results represent the system much more accurately than previous studies.

7. Variability and wind-wind collision

Our results from the previous sections imply that both binary components in R145 have significant stellar winds. In this case, it is expected that a cone-shaped wind-wind collision (WWC) zone would form, its tip situated along the line connecting the centers of both stars at the point where the dynamical pressures of the two outflows equalize (Stevens et al. 1992; Moffat 1998). The temperatures at the immediate vicinity of the collision zone can reach a few 10⁷ K. The plasma rapidly cools and emits radiation as it streams outwards along the cone.

Observationally, the emission takes on two forms. On the one hand, WWC leads to excess emission which can be seen photometrically, either in X-rays (Cherepashchuk 1976; Corcoran et al. 1996) or in non-thermal radio, infra-red and optical (e.g., Williams et al. 1997). If the WWC occurs after the winds have reached their terminal velocities, the overall strength of the emission is expected to reach a maximum at periastron. In the adiabatic case, an inverse proportion with the separation D between the stars is predicted (Usov 1992). A sharper scaling $(\propto D^{-n}, n > 1)$ is expected in highly radiative cases. On the other hand, WWC emission can also be spotted spectroscopically on top of prominent emission lines in the optical, as the plasma cools off via recombination (e.g., Rauw et al. 1999; Hill et al. 2000; Sana et al. 2001). A spectroscopic analysis of the excess emission arising from the WWC zone can place strong constraints on the kinematics and inclination of the system (Luehrs 1997).

In Fig. 11, we show V- and I-band light-curve of R145 (K. Ulaczyk, private communication) obtained with the OGLE-III shallow survey (Ulaczyk et al. 2012), phased with the ephemeris in Table 1. One can see a clear emission excess of $\approx 5\%$ during periastron passage. Possible mechanisms which could cause a phase-dependent variability include wind eclipses, ellipsoidal deformations (e.g., Soszynski et al. 2004), and WWC. Wind eclipses are expected to cause a dip as the components align along the line of sight (phases 0.01 and 0.82), and while the outliers seen in Fig. 11 around these phases could indicate a wind eclipse, the data points are too sparse to tell. Ellipsoidal deformations could play a role, although it is unclear whether they are expected to be important for spectra which are wind-dominated. However, the emission excess seen during periastron is most easily explained by WWC. Given the sparseness of the data, however, we refrain from modelling the light-curve.

To study the spectroscopic variability, we calculated the EWs of several lines in all 110 FLAMES spectra to check for periods present in the dataset. Figure 12 shows the EWs plotted versus phase, binned on intervals of $\Delta\phi=0.01$. It is evident that lines associated with "cooler" ions such as He i, N iii, and Balmer lines show a clear increase of the emission near periastron ($\phi=0$). The largest increase in flux (factor of two) is seen at the He i $\lambda 4471$ transition, followed by an increase of $\approx 40\%$ for $H\gamma$. This is significantly more that observed for the continuum (see Fig. 11). This behavior is not seen at all in the He ii $\lambda 4200$ and N iv $\lambda 4058$ lines, but is seen in the He ii $\lambda 4541$ line, possibly because it is blended with an N iii component.

In Fig. 13, we plot the same data points as in Fig. 12 for H γ , but include three curves which correspond to functions of the form $A_1 + B_1 D^{-1}(\phi)$, $A_2 + B_2 D^{-2}(\phi)$, and $A_3 + B_3 D^{-\alpha}(\phi)$ with the constants A_i , B_i , and α chosen to minimize the sum of the squared differences χ^2 . When leaving the exponent α as a free parameter, we obtain $\alpha \approx 0.25$. A similar test for N III $\lambda 4378$

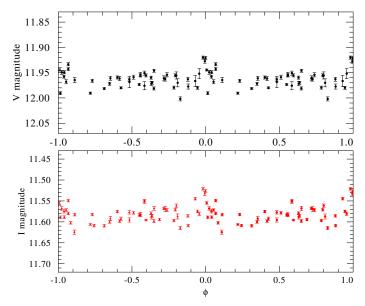


Fig. 11: Phased OGLE-III V- and I-band light-curve of R145.

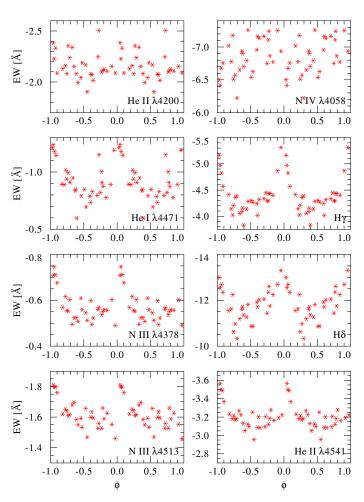


Fig. 12: EWs as a function of orbital phase ϕ measured for selected lines in the FLAMES spectra, binned at $\Delta \phi = 0.01$ intervals.

line results in $\alpha \approx 1$, while for the He II $\lambda 4541$ line, we obtain $\alpha \approx 1.2$. Given the intrinsic scatter in the EWs and the poor

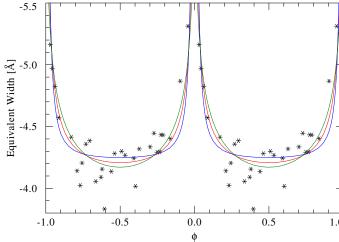


Fig. 13: Fits of the form $A_1 + B_1 D^{-2}$ (blue curve), $A_2 + B_2 D^{-1}$ (red curve), and $A_3 + B_3 D^{-\alpha}$ (green curve) to the data points describing the EW as a function of phase ϕ for the line H γ .

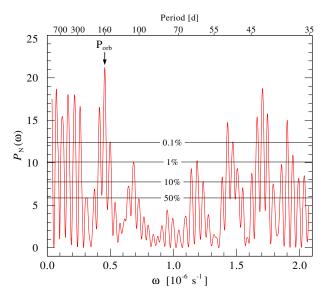


Fig. 14: Periodogram of the EWs of the H δ line. The periodogram was calculated from $\omega = 2\pi/T$ to $\omega = \pi N_0/T$ with a spacing 0.1/T, where N_0 is the number of data points and T the total time of the observation. Various false-alarm probability levels are marked.

coverage during periastron, we cannot exclude the 1/D adiabatic dependence predicted by Usov (1992).

We checked for the presence of periodic signals on the EWs of the lines shown in Fig. 12. In most cases, we find significant detections of periods which agree with the orbital period. The remaining periods are found to be insignificant. In Fig. 14, a periodogram (Scargle 1982; Horne & Baliunas 1986) is shown as an example. The most prominent peak appears for a period of 158.9 ± 0.8 days, in very good agreement with the orbital period found (cf. Table 1). The occurrence of further apparently significant peaks is caused primarily by spectral leakage due to the unevenly spaced data (Horne & Baliunas 1986), as we confirmed by subtracting the main signal and constructing a second periodogram. We find a marginal detection of a further period of $P_2 \approx 21$ d, which may be related to stochastic variability in the system, but could also be spurious.

Figure 15 shows dynamic spectra calculated for three prominent lines: He I $\lambda 4471$, H γ , and He II $\lambda 4200$. The He I image is especially striking. There is a clear pattern of emission excess traveling from $\approx -600\,\mathrm{km\,s^{-1}}$ at $\phi \approx 0$ to $\approx 300\,\mathrm{km\,s^{-1}}$ at $\phi \approx 0.7$, and back again. This velocity amplitude clearly does not stem from the motion of the stars, which trace a different RV pattern and move at amplitudes of $\approx 100\,\mathrm{km\,s^{-1}}$. In fact, the emission pattern is fully consistent with a rotating WWC cone, as suggested by Luehrs (1997). Also interesting are the two strong absorption dips seen close to periastron, which likely occur when the cone arms tangentially sweep along the line of sight, thereby instantaneously increasing the optical depth.

To proceed with a more quantitative analysis of the WWC zone, we follow the simple argumentation by Hill et al. (2000). Typically, very strong emission lines are needed for a quantitative analysis of WWC. However, our FLAMES spectra do not contain these lines. The most suitable line for the analysis is found to be He 1 λ 4471. Due to its weakness, only a rough analysis can be made here. The basic model predicts the dependence of the full width half maximum (FW) of the emission excess profile and its mean RV as a function of orbital phase ϕ . FW(ϕ) and $\overline{\text{RV}}(\phi)$ can be written as

$$FW(\phi) = C_1 + 2v_{\text{str}} \sin \theta \sqrt{1 - \sin^2 i \cos^2 (\phi - \delta \phi)}$$

$$\overline{RV}(\phi) = C_2 + v_{\text{str}} \cos \theta \sin i \cos (\phi - \delta \phi), \tag{4}$$

where C_1 and C_2 are constants, $v_{\rm str}$ is the streaming velocity of the shocked gas, θ is the opening angle of the cone, i is the orbital inclination, and $\delta \phi$ is a phase shift introduced due to Coriolis forces (see figure 6 in Hill et al. 2000).

An unbiased measurement of FW and RV could not be performed because of the low S/N of the line. Instead, the blue and red "edge" velocities of the emission excess, v_b and v_r , were estimated directly from the gray-scale plot shown in Fig. 15, from which FW and $\overline{\rm RV}$ were calculated via FW(ϕ) = $v_{\rm r}(\phi) - v_{\rm b}(\phi)$ and $\overline{\rm RV}(\phi) = 0.5 \, (v_{\rm b}(\phi) + v_{\rm r}(\phi))$. The stream velocity can be deduced from the position of the strong absorption dips around $\phi \approx 0$, seen at approximately 600 km s $^{-1}$. Accounting for the systemic velocity of the system ($\approx 300 \, {\rm km \, s^{-1}}$), we fix $v_{\rm str} = 900 \, {\rm km \, s^{-1}}$. The value found here is slightly lower than the terminal velocity of the primary ($v_{\infty} \approx 1200 \, {\rm km \, s^{-1}}$), as is expected.

Having fixed $v_{\rm str}$, we look for a set of parameters C_1, C_2, θ, i , and $\delta\phi$ which minimize χ^2 . For this purpose, a standard python routine (lmfit) is used. Our measurements of FW and $\overline{\rm RV}$, compared with the best-fitting solutions, are shown in Fig. 16. We find $C_1 = 150 \pm 30 \, {\rm km \, s^{-1}}$, $C_2 = 450 \pm 20 \, {\rm km \, s^{-1}}$, $\theta = 73 \pm 6^\circ$, $i = 40 \pm 5^\circ$, and $\delta\phi = 8 \pm 3^\circ$. The errors given here are strongly underestimated, as the true error lies in the measurement technique of the velocities and the simplified model.

It is immediately apparent that both our polarimetric analysis as well as the WWC analysis deliver almost identical inclinations. Admittedly, the value obtained here is biased by the method of measuring v_b and v_r , and should therefore only be considered a further confirmation, rather as an independent derivation of i. It is also interesting to consider the opening angle θ . Usov (1995) showed that the opening angle can be calculated from

$$\theta = 2.1 \left(1 - \frac{\eta^{2/5}}{4} \right) \eta^{1/3},\tag{5}$$

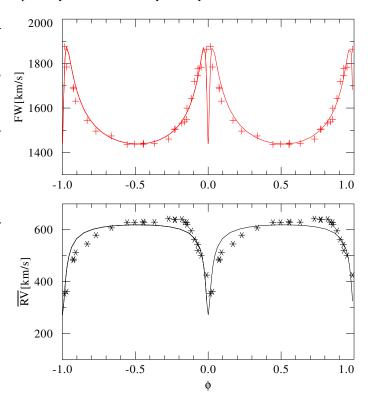


Fig. 16: Measured FW(ϕ) and $\overline{\text{RV}}(\phi)$ of the WWC emission excess profiles compared to their best-fitting models.

where $\eta = \dot{M}_2 v_{\infty,2} / \left(\dot{M}_1 v_{\infty,1}\right)$ is the wind momentum ratio of both companions. Adopting our derived values from Table 2, we find $\eta = 0.48$, which yields $\theta = 76^{\circ}$, in agreement with our results.

WWC may also manifest itself via powerful X-ray emission (Rauw & Naze 2015, and references therein). However, the presence of strong X-ray emission is not a necessary attribute of a colliding wind binary. Oskinova (2005) demonstrated that, on average, the ratio between stellar bolometric and X-ray luminosity $(\log L_{\rm X}/L_{\rm bol} \approx -7)$ is similar among Galactic massive binary and single stars, not without exceptions (e.g., Eta Car, Corcoran et al. 1995). R145 was detected by *Chandra* X-ray observatory (Xray source designation CXOU J053857.06-690605.6, Townsley et al. 2014). The observations were taken over a period of 9 days around T = 53760.7 [MJD], corresponding to $\phi \approx 0.75$. Using $E_{\rm B-V}$ from Table 2 to estimate the interstellar neutral hydrogen column density, the observed count rate, and the median energy of the X-ray photons (Townsley et al. 2014), the X-ray luminosity of R145 in the 0.2-12 keV band is $L_X \approx 2 \times 10^{33} \, \mathrm{erg \, s^{-1}}$. This corresponds to² log $L_X/L_{\mathrm{bol,tot}} \approx -6.9$. Thus, R145 is not an especially luminous X-ray source, albeit it may be somewhat harder than a typical single star, as observed in other massive binaries (e.g., Nazé et al. 2011). Overall, the X-ray luminosity of R145 is similar to that of other detected massive stars in the LMC (e.g., Naze et al. 2014)

The components of R145 follow a highly eccentric orbit. Therefore, modulations of the X-ray emission with orbital phases are expected. Previous snap-shot observations are not suitable for detecting such orbital modulations. Dedicated monitoring X-ray observations of R145 should provide the required information about energetic processes in its interacting stellar winds.

² Note that we compare with the total bolometric luminosity of the system because both stars are expected to intrinsically emit X-rays.

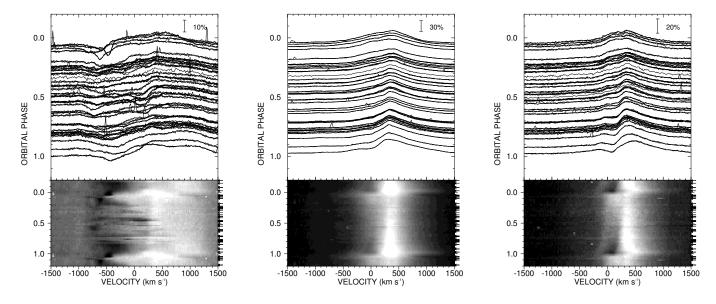


Fig. 15: Dynamic FLAMES spectra of He I λ4471 (left), Hγ (center), He II λ4200 (right)

8. The evolution of the system

We now exploit the rich information derived here to constrain the evolutionary path of R145. Unfortunately, despite using high-quality data in this study, the derived orbital masses suffer from large uncertainties (cf. Table 1). This is mainly due to the small inclination angle $i=39^\circ$, at which even a modest formal error of 6° translates to an error of $\approx 50\%$ in the mass. Moreover, due to non-linear biases, the value of i obtained here is likely overestimated. Another hindrance is that the FLAMES spectra poorly cover the periastron passage (see Fig. 7), and so further monitoring would be desirable. Nevertheless, the masses of both components could be derived to an unprecedented precision, and set important constraints on the system.

The first question that comes to mind is whether the stars in this system have interacted in the past via mass-transfer. Evaluating the Roche lobe radii via the Eggelton approximation (Eggleton 1983) using the semi major axis a, one finds $R_{\text{RLOF},1} \approx R_{\text{RLOF},2} \approx 360\,R_{\odot}$. At closest approach (periastron), the distance between the stars is (1-e) a, and the Roche lobe radii would be $R_{\text{RLOF},1} \approx R_{\text{RLOF},2} \approx 80\,R_{\odot}$. Thus, with radii of $20-30\,R_{\odot}$ (cf. Table 2), the stars are safely within their Roche lobes, even at closest approach.

This, however, does not imply that the system had not interacted in the past. Although the primary is likely still core H-burning, it cannot be excluded that the primary exhibited larger radii in the past. How compact the primary was throughout its evolution is strongly related to how homogeneous it was. Stars undergoing quasi-homogeneous evolution (QHE) tend to maintain much higher temperatures throughout their evolution and therefore remain relatively compact (e.g., Brott et al. 2011). Homogeneity is typically enhanced in stellar evolution codes by adopting large initial rotation velocities, which induce chemical mixing (Meynet & Maeder 2005; Heger & Langer 2000). Very massive stars may also be close to homogeneous simply due to their large convective cores and strong mass-loss rates (e.g., Gräfener et al. 2011; Vink et al. 2015). If the primary underwent QHE, mass-transfer was likely avoided in the system. Otherwise, mass-transfer would have occurred in the system. The fact that the system is highly eccentric is indicative that no mass-transfer has occurred, since RLOF tends to efficiently circularize an orbit (Hurley et al. 2002).

8.1. Comparison with single star tracks

To gain more insight on the evolutionary course of the system, we compare the observables derived here to a set of evolution tracks calculated for single stars. These tracks are valid as long as the stars do not interact during their lifetime. We use tracks calculated by Brott et al. (2011) and Köhler et al. (2015) for initial masses in the range $5 \le M_i \le 500 \, M_\odot$ and initial rotational velocities $0 \le v_{\rm rot,\,i} \lesssim 500 \, {\rm km \, s^{-1}}$ at a metallicity of Z = 0.0047, using the Bonn Evolutionary Code ("BEC" tracks hereafter), as well as tracks calculated with the BPASS³ (Binary Population and Spectral Synthesis) code by Eldridge et al. (2011) and Eldridge & Stanway (2012) for homogeneous and non-homogeneous single stars with $5 \le M_i \le 150 \, M_\odot$ and Z = 0.004 ("BPASS" tracks hereafter).

Finding the initial parameters and age which best reproduce the properties of both components according to the BEC tracks is done most easily with the BONNSAI⁴ Bayesian statistics tool (Schneider et al. 2014b). The disadvantage of the BEC tracks is that they, unlike the BPASS tracks, do not include post core H-burning phases. While the secondary is almost certainly core H-burning given its spectral type, this cannot be considered certain for the WR primary, although its properties and spectral type imply that it is likely core H-burning as well (e.g., Hainich et al. 2014).

Fig. 17 shows the Hertzsprung-Russell diagram (HRD) positions of the primary (A) and secondary (B) components of R145 compared to a selected number of BEC (left panel) and BPASS (right panel) evolution tracks. The colors code the amount of surface hydrogen content (see legend). We include both QHE models as well as non-homogeneous models. For the BEC tracks, QHE is reached via high initial rotation rates; the tracks shown in Fig. 17 are calcualted for $v_{\text{rot}, i} \approx 350 \, \text{km s}^{-1}$. The QHE BPASS tracks assume full homogeneity a priori; rotation is not consid-

³ bpass.auckland.ac.nz

⁴ The BONNSAI web-service is available at www.astro.uni-bonn.de/stars/bonnsai

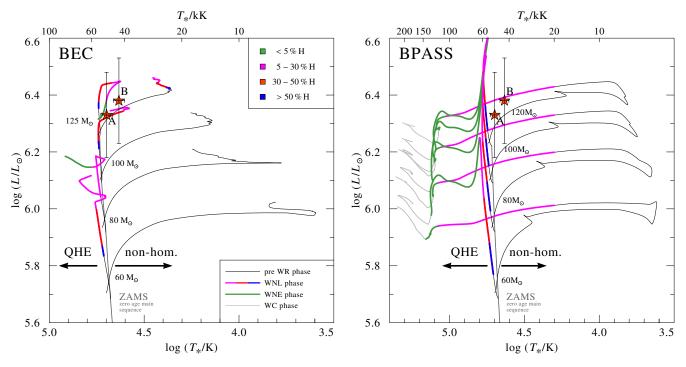


Fig. 17: The HRD positions of the primary (A) and secondary (B) components of R145 compared to BEC (left panel) and BPASS (right panel) evolution tracks calculated for (near-)homogeneous and non-homogeneous evolution for LMC metallicities. The WR phase is defined for $X_{\rm H} < 0.65$ and $T_* > 20$ kK. See text for details.

ered in the BPASS code. Note that the QHE BEC tracks are not fully homogeneous.

8.1.1. BEC tracks results

We first use the BONNSAI tool to find the initial parameters which best reproduce the observables T_* , L, $X_{\rm H}$, and $M_{\rm orb}$ of the primary, accounting for the errors as found in this study. As could be anticipated, only tracks with large initial rotations ($v_{\rm rot,\,i} \gtrsim 350\,{\rm km\,s^{-1}}$) can reproduce its HRD position (see left panel of Fig. 17); the non-homogeneous tracks terminate at low temperatures and do not return to high temperatures because hydrogen is then exhausted in the core. To obtain a consistent set of initial parameters for the secondary, we use the BONNSAI tool again to compare with the secondary's observables, but this time, we also use the primary's age (and associated errors), as obtained from the BONNSAI tool.

The resulting initial masses and age (as derived for the primary) are shown in Table 3. The Table also gives the current masses and hydrogen content of both components as predicted from the best-fitting evolutionary track. The initial rotations obtained by the BONNSAI tool for the primary and secondary are $v_{\rm rot,\,i}=410$ and $340\,{\rm km\,s^{-1}}$, respectively, while the predicted current rotational velocities are 240 and 260 km s⁻¹, marginally consistent with the upper bounds given in Table 2. Since the non-homogeneous BEC models do not reproduce the HRD positions of the system's components, we give only the corresponding QHE solution in Table 3.

8.1.2. BPASS tracks results

A similar procedure is performed with the BPASS tracks. We use a χ^2 minimization algorithm to find the best-fitting homogeneous and non-homogeneous tracks and ages which reproduce the prop-

erties of the primary (see eq. 3 in Shenar et al. 2016). Once a track and age for the primary is inferred, we repeat the procedure for the secondary, adopting the primary's age an associated error estimate which is based on the grid spacing. The corresponding initial parameters, ages, and current mass and surface hydrogen content, are given in Table 3. Because the BPASS tracks cover the whole evolution of the star, appropriate solutions can be found for the non-homogeneous case as well (see also right panel of Fig. 17). In Table 3, we also give the maximum radius $R_{\text{max}, 1}$ reached by the primary throughout its evolution. This should give an indication to whether or not the primary has exceeded its Roche lobe radius in the past.

8.1.3. Indication for QHE

Both the BEC tracks and the BPASS tracks imply very similar initial parameters and ages in the QHE case for both components. The tracks reproduce the observables reasonably well (compared to the errors), but the current masses predicted by the evolutionary tracks ($\approx 80-90~M_{\odot}$) are larger than the orbital masses derived here ($\approx 55~M_{\odot}$). Such masses would be obtained at an inclination of $\approx 33^{\circ}$, which is roughly consistent with our formal error on i given in Table 1. The QHE scenario would therefore suggest that the actual masses are $\approx 80-90~M_{\odot}$ per component.

For the non-QHE scenario, only the BPASS tracks can place meaningful constraints. In this scenario, the properties of the primary are reproduced when the evolution tracks "return" from the red to the blue, and He-core burning initiates. This scenario is consistent with much lower current masses, closer to those derived here. However, significant discrepancy is obtained for the hydrogen content. More importantly, a comparison between the maximum radius reached by the primary and the Roche lobe implies that, assuming the non-homogeneous tracks, the primary overfilled its Roche lobe in the past. Note that the separation increases with time due to mass-loss, making mass-transfer in-

evitable in the non-homogeneous case. In this scenario, binary interaction therefore has to be accounted for.

Table 3: Comparison with best-fitting evolution tracks

	BEC	BPASS		
	QHE ^a	non-hom.	QHE ^b	Binary ^c
$M_{\mathrm{i},1}$ $[M_{\odot}]$	105 ± 20	100 ± 20	100 ± 20	120 ± 20
$M_{ m i,2}~[M_{\odot}]$	91 ± 15	90 ± 20	90 ± 20	80 ± 20
$M_{\rm cur,1}~[M_{\odot}]$	77+30	48 ± 10	96	58
$M_{\rm cur,2}~[M_{\odot}]$	78+20	52 ± 10	85	113
Age [Myr]	2.3 ± 0.4	3.1 ± 0.3	2.1 ± 0.4	2.8 ± 0.4
$X_{\rm H,1}$ (mass fr.)	0.3 ± 0.1	0.1 ± 0.1	0.4 ± 0.1	0.1 ± 0.1
$X_{\rm H,2}$ (mass fr.)	$0.74^{+0}_{-0.25}$	0.1 ± 0.1	0.5 ± 0.1	-
$R_{\rm max, 1} [R_{\odot}]$	40	1500	20	-

Notes. Initial parameters and predictions of best-fitting evolution tracks calculated for single stars experiencing homogeneous/non-homogeneous evolution. (a) QHE in the BEC tracks is reached via an initial rotation velocity of $\approx 350\,\mathrm{km\,s^{-1}}$ for both components, which best-reproduces the observables. (b) These tracks are fully homogeneous a-priori; rotation is not accounted for in the BPASS tracks. (c) The tracks are identical to the non-homogeneous tracks, but include mass-transfer. The initial period defining the best-fitting track is $P_i = 100\,\mathrm{d}$.

8.2. Binary tracks

We now use set of tracks calculated with version 2.0 of the BPASS code (Eldridge et al. 2008) for Z=0.004 which are non-homogeneous and account for mass-transfer. Each track is defined by an initial period P_i , an initial mass ratio $q_i = M_{i,\,2}/M_{i,\,1}$, and an initial mass for the primary $M_{i,\,1}$, calculated at intervals of 0.2 on $0 < \log P[\mathrm{d}] < 4$, 0.2 on $0 < q_i < 0.9$, and $10 - 20\,M_\odot$ on $10 < M_{i,\,1} < 150\,M_\odot$. The tracks do not include the hydrogen abundance of the secondary, so only a comparison with the primary's $X_{\rm H}$ is possible.

To find the track which best reproduces the observables, we use a χ^2 minimization algorithm (see eq. 4 in Shenar et al. 2016). We account here for T_* , L, $M_{\rm orb}$ for both components, $X_{\rm H}$ for the primary, the current period P, and the current mass-ratio $q = M_2/M_1 = K_1/K_2$. Note that we include the mass ratio because it has a much smaller formal error ($q = 1.01 \pm 0.07$), as opposed to the actual masses.

The parameters of the best fitting binary track are given in the last column of Table 3. Even the best fitting track results in a mass ratio of almost 2. The reason is that in all relevant tracks, RLOF from the primary to the secondary occurs, which tends to result in mass ratios significantly different than 1. The binary track also fails to reproduce the large hydrogen mass fraction inferred for the primary. Binary evolution tracks therefore do poorly in reproducing the system's observables.

8.3. Outlook

To summarize, it appears that the system has evolved quasi-homogeneously, similarly to HD 5980 (Koenigsberger et al. 2014). This would suggest current masses of $\approx 80\,M_{\odot}$ and initial masses of $M_1\approx 105\,M_{\odot}$ and $M_2\approx 90\,M_{\odot}$. The current generation of evolution models can attain QHE only via rapid initial rotation $v_i\gtrsim 350\,\mathrm{km\,s^{-1}}$. Admittedly, one may argue that it is unlikely for both stars to be born with such high initial rotations (e.g.,

Ramírez-Agudelo et al. 2015). A possible resolution could lie in tidal interaction during periastron passage. The high eccentricity of the system yields a small separation between the components during periastron, which in turn may imply significant tidal mixing during periastron passage. As noted above, homogeneity can also be obtained by virtue of the large convective cores and strong mass-loss (Gräfener et al. 2011) of massive stars. Hence, the rotation which is needed for the BONN tracks may serve as a proxy for QHE rather than point at the actual physical mechanism responsible for homogeneity.

Assuming QHE indeed took place, there is no obvious reason to expect that the components would interact via RLOF in the future. This would be the case if the secondary would overfill its Roche lobe, which is currently hard to predict. If the components will indeed avoid interaction in the future, the system will likely evolve into a wind-fed high mass X-ray binary. With the help of fortunate kicks during core-collapse, the system could become close enough to merge within a Hubble time, emitting a gravitational wave event like those recently observed with LIGO (Abbott et al. 2016; Marchant et al. 2016).

9. Summary

We have performed an exhaustive analysis of the very massive system BAT99 119 (R145) in the LMC. Using high-quality FLAMES spectra, we detected and resolved for the first time lines from the secondary component and derived a first SB2 orbital solution for the system. The composite FLAMES spectral were disentangled to the constituent spectra of both components, and a spectral analysis was performed to derive the physical parameters of the components. This enabled us to confirm the primary's spectral type as WN6h, and to infer for the first time a spectral type for the secondary: O3.5 If*/WN7. A polarimetric analysis, as well as a WWC analysis, helped constrain the inclination of the system. Finally, a comparison with evolution tracks was conducted.

The system was previously speculated to host the most massive stars known ($M_1 > 300\,M_\odot$, S2009). From our orbital + polarimetric analysis, we derive $q = M_2/M_1 = 1.01 \pm 0.07$ and masses $M_1 \approx M_2 \approx 55^{+40}_{-20}\,M_\odot$. Thus, although the masses suffer from large uncertainties, we can exclude masses larger than $100\,M_\odot$ in the system.

We find clear evidence for WWC in the system. Interestingly, the signature of WWC is only clear in low-ionization transitions. We could only perform a rough quantitative spectroscopic analysis of the WWC spectral features because of the absence of very strong lines which are affected by WWC. The resulting inclination $(i=40^\circ)$ is consistent with that obtained from polarimetry $i=39^\circ$), and the half opening angle $(\theta=76^\circ)$ is consistent with the mass-loss rates and terminal velocities derived from the spectral analysis.

A comparison with quasi homogeneous and non-homogeneous BEC and BPASS evolution tracks, the latter accounting for mass transfer as well, implies that quasi-homogeneous evolution (QHE) best describes the system. In this scenario, the components remain compact throughout their evolution and do not fill their Roche lobes. Non-homogeneous evolution would imply mass transfer, and this in turn leads to mass ratios which are very different than found here (\approx 1), which is why we can exclude non-homogeneous evolution to a high degree of certainty. The high eccentricity found in this study ($e \approx 0.8$) is in line with the fact that the components did not interact via RLOF, which would tend to circularize the system. However, QHE is only consistent if the current masses are $\approx 80-90\,M_\odot$, which is roughly the upper limit of our derived

orbital masses. In any case, the initial masses of the stars are found to be $M_{1, i} \approx 105$ and $M_{2, i} \approx 90 M_{\odot}$.

Future spectroscopic and polarimetric observations are strongly encouraged to obtain more spectral phase coverage during periastron passage, which would constrain the orbital fit further and reduce uncertainties. A phase coverage of the red optical spectrum, as well as X-ray light curves, would be highly helpful in analyzing the WWC region to a much larger degree of accuracy, enabling an accurate derivation of the inclination, and a detailed study of WWC in this important system.

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Table A.1: RVs for primary (N $\ensuremath{\text{\tiny IV}}$) and secondary (Si $\ensuremath{\text{\tiny IV}}$) components

Spectrum	MJD	φ	N IV RV [km s ⁻¹]	Si IV RV [km s ⁻¹]
1	54794.18	0.27	230	302
2	54794.20	0.27	256	286
3	54794.24	0.27	220	298
4	54794.32	0.27	234	300
5	54798.29	0.29	234	288
6	54798.31	0.29	234	298
7	54804.07	0.33	266	288
8	54836.13	0.53	280	284
9	54836.16	0.53	280	278
10	54836.18	0.53	280	274
11	54836.20	0.53	280	274
12	54867.05	0.72	292	264
13	54867.07	0.72	296	260
14	55108.27	0.24	234	296
15	55108.29	0.24	234	298
16	56210.35	0.18	226	308
17	56210.37	0.18	220	306
18	56210.38	0.18	218	302
19	56217.33	0.23	234	300
20	56217.34	0.23	234	300
21	56217.35	0.23	234	294
22	56243.34	0.39	256	288
23	56243.35	0.39	252	300
24	56243.36	0.39	256	292
25	56256.26	0.47	270	278
26	56256.27	0.47	280	272
27	56256.28	0.47	276	268
28	56257.13	0.48	270	268
29	56257.14	0.48	270	278
30	56257.15	0.48	272	280
31	56277.31	0.61	282	268
32	56277.32	0.61	284	266
33	56277.33	0.61	276	262
34	56283.05	0.64	296	258
35	56283.06	0.64	268	298
36	56283.07	0.64	290	258
37	56294.20	0.04	302	258
38	56294.20	0.71	302	256
39	56294.23	0.71	294	252
40	56295.18		296	254
40	56295.19	0.72	294	258
42		1		
	56295.21	0.72	294	260
43	56304.24	0.77	294	250
44	56305.23	0.78	294	252
45	56305.24	0.78	294	244
46	56305.26	0.78	294	260
47	56306.22	0.79	294	238
48	56306.23	0.79	268	276
49	56306.24	0.79	294	246
50	56308.15	0.80	296	242

Section Sect	Spectrum	MJD	φ	N IV RV [km s ⁻¹]	Si IV RV [km s ⁻¹]
52 56308.18 0.80 280 244 53 56316.21 0.85 296 234 54 56316.23 0.85 296 226 55 56316.23 0.85 310 236 56 56347.01 0.04 222 326 57 56347.02 0.06 206 328 60 56349.03 0.06 208 328 61 56349.03 0.06 204 328 62 56352.02 0.08 224 342 63 56352.04 0.08 268 284 64 56352.05 0.08 214 334 65 56356.00 0.10 268 284 66 56356.03 0.10 202 322 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 <td< td=""><td></td><td></td><td>· ·</td><td></td><td></td></td<>			· ·		
53 56316.21 0.85 296 224 54 56316.22 0.85 296 226 55 56316.23 0.85 310 236 56 56347.04 0.04 222 326 58 56347.04 0.04 222 322 59 56349.03 0.06 206 328 60 56349.03 0.06 204 328 61 56349.05 0.06 204 328 62 56352.02 0.08 224 342 63 56352.05 0.08 214 334 65 56356.00 0.10 268 284 64 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56582.37 0.46 406 142 71 56582.37 0.53 280 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
54 56316.22 0.85 296 226 55 56316.23 0.85 310 236 56 56347.01 0.04 222 326 57 56347.03 0.04 232 326 58 56349.02 0.06 206 328 60 56349.03 0.06 204 328 61 56349.05 0.06 204 328 62 56352.04 0.08 268 284 64 56352.05 0.08 214 334 65 56356.00 0.10 268 284 64 56356.00 0.10 268 284 65 56356.00 0.10 192 332 67 56356.03 0.10 202 322 68 56571.35 0.46 272 288 70 56571.35 0.46 272 288 72 56582.37 0.53 280 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
55 56316.23 0.85 310 236 56 56347.01 0.04 222 326 57 56347.03 0.04 232 326 58 56347.04 0.04 222 322 59 56349.03 0.06 208 328 60 56349.05 0.06 204 328 61 56349.05 0.06 204 328 62 56352.02 0.08 224 342 63 56352.00 0.08 224 342 63 56352.00 0.08 214 334 65 56356.00 0.10 268 284 66 56356.02 0.10 192 332 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56582.34 0.53 280 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
56 56347.01 0.04 222 326 57 56347.03 0.04 232 326 58 56347.04 0.04 222 322 59 56349.03 0.06 206 328 60 56349.03 0.06 204 328 61 56349.05 0.06 204 328 62 56352.02 0.08 224 342 63 56352.05 0.08 214 334 65 56356.00 0.10 268 284 64 56352.05 0.08 214 334 65 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.35 0.46 270 286 72 56582.37 0.53 280 270 73 56582.25 0.55 280 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
57 56347.03 0.04 232 326 58 56347.04 0.04 222 322 59 56349.02 0.06 206 328 60 56349.03 0.06 204 328 61 56349.05 0.08 224 342 63 56352.04 0.08 268 284 64 56352.05 0.08 214 334 65 56356.00 0.10 268 284 66 56356.03 0.10 202 332 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.37 0.46 272 288 70 56571.37 0.46 406 142 71 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56586.25 0.55 280 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
58 56347.04 0.04 222 322 59 56349.02 0.06 206 328 60 56349.03 0.06 208 328 61 56349.05 0.06 204 328 62 56352.04 0.08 224 342 63 56352.05 0.08 214 334 65 56356.00 0.10 268 284 66 56356.02 0.10 192 332 67 56356.03 0.10 202 322 68 56571.35 0.46 264 284 69 56571.35 0.46 272 288 70 56571.37 0.46 406 142 71 56571.38 0.46 270 286 72 56582.34 0.53 280 274 74 56586.25 0.55 280 278 75 56586.27 0.55 280 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
59 56349.02 0.06 208 328 60 56349.03 0.06 208 328 61 56349.05 0.06 204 328 62 56352.02 0.08 224 342 63 56352.05 0.08 214 334 65 56356.00 0.10 268 284 66 56356.02 0.10 192 332 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.37 0.46 406 142 71 56571.37 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56586.25 0.55 280 280 75 56586.26 0.55 272 <td< td=""><td>57</td><td>56347.03</td><td>0.04</td><td>232</td><td>326</td></td<>	57	56347.03	0.04	232	326
60	58	56347.04	0.04	222	322
61 56349.05 0.06 204 328 62 56352.02 0.08 224 342 63 56352.04 0.08 268 284 64 56352.05 0.08 214 334 65 56356.00 0.10 268 284 66 56356.02 0.10 192 332 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.37 0.46 406 142 71 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56567.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56627.18 0.81 294 248 83 56620.28 0.76 294 262 84 56627.19 0.81 338 196 87 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56697.17 0.25 236 298 99 56653.10 0.22 234 304 94 56697.17 0.25 236 298 99 56653.10 0.22 234 304 94 56697.17 0.25 236 298 99 56697.17 0.25 236 298 99 56697.17 0.25 236 298 99 56697.17 0.25 236 298 99 56697.17 0.25 236 298 99 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56697.17 0.25 236 298 99 5670.31 0.22 234 304 94 56697.17 0.25 236 298 99 5670.31 0.22 234 304 96 56697.19 0.25 236 298 99 5670.31 0.22 234 304 96 56697.19 0.25 236 298 99 5670.31 0.22 238 306 95 56693.11 0.22 238 306 95 56693.13 0.22 240 304 96 56697.17 0.25 236 298 98 56697.19 0.25 236 298 99 5670.31 0.29 252 300 100 5670.314 0.29 252 288 103 56714.03 0.36 252 288 104 56714.03 0.36 252 288 105 56719.04 0.39 256 298 106 56719.03 0.39 256 298 107 56719.04 0.39 256 298 108 56723.17 0.41 268 284	59	56349.02	0.06	206	328
62 56352.02 0.08 224 342 63 56352.04 0.08 268 284 64 56352.05 0.08 214 334 65 56356.00 0.10 268 284 66 56356.02 0.10 192 332 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.37 0.46 406 142 71 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.26 0.55 272 270 77 5686.27 0.55 280	60	56349.03	0.06	208	328
63 56352.04 0.08 268 284 64 56352.05 0.08 214 334 65 56356.00 0.10 268 284 66 56356.00 0.10 192 332 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.27 0.55 280 28 77 56586.27 0.55 280 278 78 56597.24 0.62 276 262 80 56597.25 0.62 280	61	56349.05	0.06	204	328
63 56352.04 0.08 268 284 64 56352.05 0.08 214 334 65 56356.00 0.10 268 284 66 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.37 0.46 406 142 71 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 278 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.26 0.55 272 270 77 56586.27 0.55 280 28 79 56597.24 0.62 276 262 80 56597.25 0.62 280	62	56352.02	0.08	224	342
64	63	56352.04	0.08	268	284
65 56356.00 0.10 268 284 66 56356.02 0.10 192 332 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.26 0.55 272 270 77 56586.27 0.55 280 280 79 56597.23 0.62 236 298 79 56597.25 0.62 280 262 81 56620.27 0.76 294 262 82 56627.18 0.81 294 <td< td=""><td>64</td><td>56352.05</td><td></td><td></td><td>334</td></td<>	64	56352.05			334
66 56356.02 0.10 192 332 67 56356.03 0.10 202 322 68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.37 0.46 406 142 71 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.27 0.55 280 28 77 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.27 0.76 294					
67					
68 56571.34 0.46 264 284 69 56571.35 0.46 272 288 70 56571.37 0.46 406 142 71 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.37 0.53 280 274 74 56582.37 0.53 280 274 74 5658.25 0.55 280 280 76 56586.25 0.55 280 280 76 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 248 83 56620.27 0.76 294 248 84 56627.18 0.81 294					
69 56571.35 0.46 272 288 70 56571.37 0.46 406 142 71 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.37 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.26 0.55 272 270 77 56586.27 0.55 280 280 79 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 262 84 56627.18 0.81 294 246 85 56657.18 0.81 294 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
70 56571.37 0.46 406 142 71 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 262 84 56627.16 0.81 294 24 85 56627.18 0.81 294 24 86 56627.19 0.81 338 196 87 56645.04 0.92 340 1					
71 56571.38 0.46 270 286 72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 262 84 56627.16 0.81 294 24 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.07 0.92 340					
72 56582.34 0.53 280 270 73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.26 0.55 272 270 77 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56627.19 0.81 294 246 85 56627.18 0.81 294 246 86 56645.04 0.92 256 298 88 56645.07 0.92 338 <td< td=""><td></td><td></td><td>1</td><td></td><td></td></td<>			1		
73 56582.35 0.53 280 274 74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.26 0.55 272 270 77 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 248 83 56620.28 0.76 294 242 84 56627.18 0.81 294 246 85 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.07 0.92 338 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
74 56582.37 0.53 280 278 75 56586.25 0.55 280 280 76 56586.26 0.55 272 270 77 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56627.16 0.81 294 246 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.07 0.92 338 196 90 56653.28 0.97 408 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
75 56586.25 0.55 280 280 76 56586.26 0.55 272 270 77 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56627.16 0.81 294 246 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 408 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
76 56586.26 0.55 272 270 77 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56620.18 0.81 294 246 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.30 0.97 408 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
77 56586.27 0.55 280 278 78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56620.18 0.81 294 246 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.30 0.97 408 146 92 56693.11 0.22 234 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
78 56597.23 0.62 236 298 79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56627.16 0.81 294 234 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.30 0.97 408 146 92 56653.30 0.97 408 146 92 56693.11 0.22 234 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
79 56597.24 0.62 276 262 80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.28 0.76 294 248 83 56620.28 0.76 294 262 84 56627.16 0.81 294 234 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.13 0.22 234 304 94 56693.13 0.22 240 <td< td=""><td></td><td></td><td></td><td></td><td></td></td<>					
80 56597.25 0.62 280 262 81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56627.16 0.81 294 234 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 298		56597.23	0.62	236	298
81 56620.26 0.76 294 250 82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56627.16 0.81 294 234 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 298 98 56697.19 0.25 236 298	79	56597.24	0.62	276	262
82 56620.27 0.76 294 248 83 56620.28 0.76 294 262 84 56627.16 0.81 294 234 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56697.16 0.25 236 296 97 56697.17 0.25 236 298 98 56697.19 0.25 236 298 99 56703.13 0.29 252 302		56597.25	0.62		262
83 56620.28 0.76 294 262 84 56627.16 0.81 294 234 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 296 97 56697.17 0.25 236 298 98 56697.19 0.25 236 298 99 56703.14 0.29 246 292	81	56620.26	0.76	294	250
84 56627.16 0.81 294 234 85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 296 97 56697.17 0.25 236 298 98 56697.19 0.25 236 298 99 56703.13 0.29 252 302 100 56703.14 0.29 252 302	82	56620.27	0.76	294	248
85 56627.18 0.81 294 246 86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 296 97 56697.17 0.25 236 298 99 56703.13 0.29 252 300 100 56703.14 0.29 252 302 101 56703.16 0.29 246 292 102 56714.02 0.36 252 288	83	56620.28	0.76	294	262
86 56627.19 0.81 338 196 87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 296 97 56697.17 0.25 236 288 98 56697.19 0.25 236 298 99 56703.13 0.29 252 302 100 56703.14 0.29 252 302 101 56703.16 0.29 246 292 102 56714.02 0.36 252 288	84	56627.16	0.81	294	234
87 56645.04 0.92 256 298 88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 296 97 56697.17 0.25 236 298 98 56697.19 0.25 236 298 99 56703.13 0.29 252 302 100 56703.14 0.29 246 292 102 56714.02 0.36 252 288 103 56714.03 0.36 252 288 104 56719.02 0.39 256 286 <tr< td=""><td>85</td><td>56627.18</td><td>0.81</td><td>294</td><td>246</td></tr<>	85	56627.18	0.81	294	246
88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 296 97 56697.17 0.25 236 288 98 56697.19 0.25 236 298 99 56703.13 0.29 252 300 100 56703.14 0.29 246 292 101 56703.16 0.29 246 292 102 56714.02 0.36 252 288 103 56714.03 0.36 252 288 104 56719.02 0.39 256 298 <t< td=""><td>86</td><td>56627.19</td><td>0.81</td><td>338</td><td>196</td></t<>	86	56627.19	0.81	338	196
88 56645.05 0.92 340 194 89 56645.07 0.92 338 196 90 56653.28 0.97 414 152 91 56653.29 0.97 408 146 92 56653.30 0.97 406 142 93 56693.11 0.22 234 304 94 56693.12 0.22 238 306 95 56693.13 0.22 240 304 96 56697.16 0.25 236 296 97 56697.17 0.25 236 288 98 56697.19 0.25 236 298 99 56703.13 0.29 252 300 100 56703.14 0.29 252 302 101 56703.16 0.29 246 292 102 56714.02 0.36 252 288 103 56714.03 0.36 252 288 104 56719.02 0.39 256 298 <t< td=""><td>87</td><td>56645.04</td><td>0.92</td><td>256</td><td>298</td></t<>	87	56645.04	0.92	256	298
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