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The very massive X-ray bright binary system Wack 2134 (= WR 21a)*

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ABSTRACT

From the radial velocities of the N IV λ4058 and He II λ4686 emission lines, and the N V λ4604-20 absorption lines, determined in digital spectra, we report the discovery that the X-ray bright emission line star Wack 2134 (= WR 21a) is a spectroscopic binary system with an orbital period of 31.673 ± 0.002 d. With this period, the N IV and He II emission and N V absorption lines, which originate in the atmosphere of the primary component, define a rather eccentric binary orbit ($e = 0.64 \pm 0.03$). The radial velocity variations of the N V absorptions have a lower amplitude than those of the He II emission. Such a behaviour of the emission line radial velocities could be due to distortions produced by a superimposed absorption component from the companion. High-resolution echelle spectra observed during the quadrature phases of the binary show H and He II absorptions of both components with a radial velocity difference of about 541 km s^{-1}. From this difference, we infer quite high values of the minimum masses, of about 87 and 53 M$_{\odot}$ for the primary and secondary components, respectively, if the radial velocity variations of the He II emission represent the true orbit of the primary. No He I absorption lines are observed in our spectra. Thus, the secondary component in the Wack 2134 binary system appears to be an early O-type star. From the presence of H, He II and N V absorptions, and N IV and C IV emissions, in the spectrum of the primary component, it most clearly resembles those of Of/WNLha-type stars.

Key words: binaries: spectroscopic – stars: Wolf-Rayet – stars: individual: Wack 2134 – stars: individual: WR 21a.

1 INTRODUCTION

The X-ray source 1E 1024.0−5732, detected with *Einstein*, was identified by Caraveo, Bignami & Goldwurm (1989) with the emission line star 2134 in the Wackerling (1970) catalogue, and suggested to be a binary system composed of an O star with a compact companion. Further X-ray data of this source obtained with *ROSAT* were analysed by Mereghetti et al. (1994), who described the optical spectrum to be of Wolf–Rayet type, and proposed that the X-rays could arise in the colliding winds of a WN+OB binary system. Thus, the star was added to the Catalogue of Galactic Wolf–Rayet Stars (van der Hucht 2001) as WR 21a. Recent interferometric radio observations detected a weak non-thermal source at the position of Wack 2134, which was also interpreted as due to a colliding wind region in a WN+OB binary (Benaglia et al. 2005).

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Table 1. Details of the different observing runs.

Telescope	Observatory	Inst. conf.	Spectral range (Å)	Dispersion (Å pixel^{-1})	Resolution (Å)	Velocity resolution (km s^{-1})	S/N	*n*
1.9-m	SAAO	ITS+SITe CCD	4 200–5 000	0.5	1.5	96	16	6
1.9-m	SAAO	ITS	3 800–7 800	2.3	6.0	386	90	1
2.15-m	CASLEO	REOSC+Tek1024	3 800–5 500	1.6	4.2	269	80	24
2.5-m	LCO	Echelle+Tek5[a]	3 650–10 150	0.1	0.14	8	40	8
4-m	CTIO	R-C+Loral3K	3 650–6 700	0.95	3.8	243	100	13
3.58-m	La Silla	EMMI	4 150–7 700	0.2	0.6	38	80	1[b]

Note. SAAO: South African Astronomical Observatory; CASLEO: Complejo Astronómico El Leoncito (CASLEO is operated under agreement between CONICET, SECYT and the National Universities of La Plata, Córdoba and San Juan, Argentina); LCO: Las Campanas Observatory, Chile;
CTIO: Cerro Tololo Inter-American Observatory, Chile.
[a]The CCD was binned 2 × 2 to increase the S/N.
[b]Spectrum retrieved from the ESO data base.

However, indications of orbital binary motion had not been found thus far. Here we present a radial velocity (RV) study of Wack 2134, showing it to be a binary system with an orbital period of 31.673 ± 0.002 d and a rather high eccentricity, $e = 0.64 \pm 0.03$.

2 OBSERVATIONS

We have obtained optical spectroscopy of Wack 2134 between 1994 and 2007 at various observatories. A description of the instrumental configuration of each observation is shown in the Table 1. Resolution was determined by measuring the full width at half-maximum (FWHM) of comparison-arc emission lines, and the velocity resolution was calculated at 4686 Å.

The spectra obtained at CASLEO (Complejo Astronómico El Leoncito), LCO (Las Campanas Observatory), ESO (European Southern Observatory) and CTIO (Cerro Tololo Inter-American Observatory) were processed with IRAF[1] routines, and those obtained at SAAO (South African Astronomical Observatory) with FIGARO supported by STARLINK.

We have determined the RVs of Wack 2134 by fitting Gaussian profiles to the observed lines using the IRAF routine NGAUSSFIT (in the STSDAS package). This routine provides an estimation of errors for each fitted parameter. For example, in the fitting of the He II 4686 Å emission lines, we obtained errors in line position of about 11 and 6 km s^{-1}, for the CASLEO and echelle spectra, respectively.

The spectra were first normalized to the continuum and, to standardise the RV measurements in the broad lines, we used the position of the core of the line; this procedure has the advantage of being less dependent on the errors in the definition of the continuum.

We do not have any target in common among the different instruments, which could be used as a comparison star to investigate possible wavelength zero-point differences. The different spectral coverages prevented a suitable characterization of any such differences by means of interstellar lines. However, as will be shown in Section 4, we did not detect any significant shifts within our measurement errors.

3 THE SPECTRUM OF WACK 2134

Fig. 1 shows a low-resolution optical spectrum of Wack 2134, obtained at SAAO. Note that C IV emission is present in the spectrum, as well as N IV and He II. N III is faint, and N V is observed in absorption. Faint absorption lines of H and He II are also present. The observed optical spectrum of Wack 2134 resembles that of HD 93162 (≡WR 25), a WN 6ha-type star and the second brightest X-ray source in the Carina Nebula (NGC 3372), which has also been recently unveiled as a massive binary system (Gamen et al. 2006). The spectrum of Wack 2134 presents intrinsic H and He II absorptions (see below), as well as the C IV and N IV emissions with comparable intensities. An effort to classify this star has been made by Reig (1999). He found spectral evidence for a WN+Of classification, i.e. a very broad, high-intensity He II λ4686 emission line but nitrogen (N V λ4604 and λ4620) and hydrogen absorption lines. However, the FWHM of the He II λ4686 emission line is narrower than 30 Å and, in the following section, we demonstrate that the observed absorption lines move in phase with it, so they belong to the same star. Thus, we prefer to classify Wack 2134 as O3 f*/WN 6ha, i.e. as a massive star in an intermediate evolutionary stage between an O-type and a Wolf–Rayet star similar to those found in the R136 cluster (at the centre of the 30 Doradus nebula in the Large Magellanic Cloud), cf. Melnick (1985), Walborn & Blades (1997), Massey & Hunter (1998). Many strong interstellar features are observed in the spectrum, indicating that it is a heavily reddened star.

Spectral lines of the secondary component are observed in our high-resolution echelle spectra obtained during both quadratures of the binary system (see below). These lines correspond to absorptions of H and He II. He I lines are not visible in our spectra. Therefore, the secondary component certainly is an early O-type star, probably as early as O4. The spectral type of the secondary may not be much earlier than this, since we observe single N V absorptions when H and He II appear clearly double. The RV of the N V absorptions corresponds to the WN component (as is shown below).

4 THE RADIAL VELOCITY ORBIT

In all of our spectra we have determined RVs of the spectral features by fitting Gaussians to the line profiles. Only the strongest emission line, He II λ4686, could be measured in all spectrograms. Weaker features were also measured in those spectra with higher signal-to-noise ratio (S/N). Of these, N V absorptions as well as N IV and C IV emissions show RVs which follow the orbital motion of He II λ4686, and thus originate in the atmosphere of the primary WN component. The RVs of the absorption lines of H and He II show much scatter, and are separated into two components only in our high-resolution echelle spectra. The RV measurements of He II λ4686 emission

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

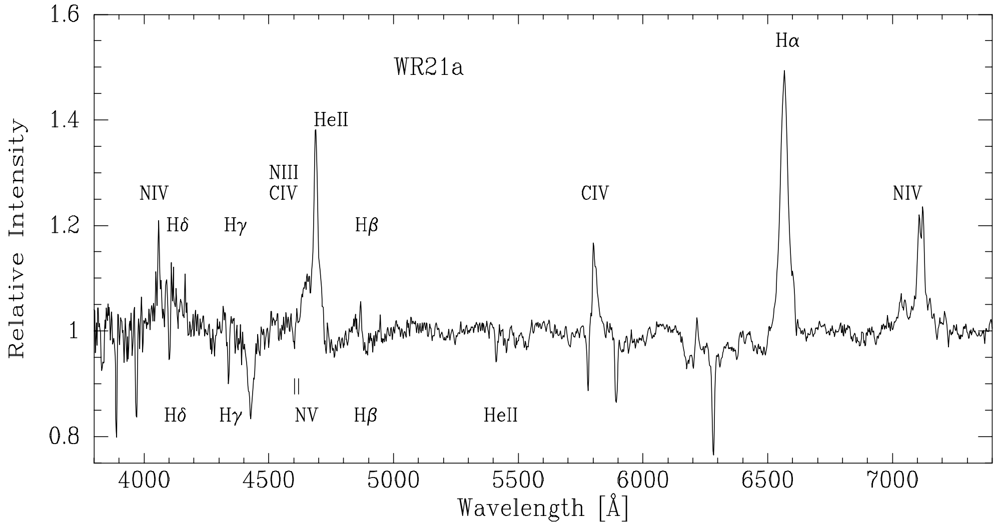

Figure 1. Continuum rectified spectrum of Wack 2134 obtained at SAAO in 1998 February. Absorption and emission lines are identified below and above the spectrum, respectively. The stellar emission lines identified are the blend of He II with Hα, Hβ, Hγ and N III+Hδ; N IV λ4058, λ7103-22; N III λ4511-15, λ4634, λ4640-42; C IV λ4658, λ5801-12; He II λ4686; and the absorptions are N V λ4604, λ4620; He II λ5411 and Hβ, Hγ and Hδ. Strong unidentified absorptions are mostly of interstellar origin.

of the mean of N V λ4604-20 absorptions and of the N IV λ4058 emission are presented in Table 2.

We introduced the He II emission line RVs into a Lafler & Kinmann (1965) period search routine. The RVs from our spectra do not show large variations from one night to the next, but considerable variations are present between data obtained during different observing runs, thus suggesting a binary period longer than 10 d. The best period found was 31.67 d, with some aliases, i.e. 40.68, 45.64, 63.34 d. An inspection of the distribution of the RVs phased with each of those periods readily indicated that the most suitable is 31.67 d and that the orbit of Wack 2134 is very eccentric.

The period of 31.67 d was then introduced as an initial value into a routine for defining the orbital elements of the binary. To this end we used an improved version of the program originally written by Bertiau & Grobben (1969). Taking into account the different instrumental configurations involved in our data set but also the spectral S/N, we decided to weight the spectra such that echelle data were assigned a value of 1 and the lowest resolution spectrum 0.1. Thus, SAAO data were weighted with 0.1, CASLEO with 0.4 and CTIO with 0.8. We inspected the individual O − C values derived by the program looking for systematic RV shifts, but in all cases the mean of the O − C (of each data set) remained below 30 km s^{-1}, which we considered as a conservative internal error. Thus we did not apply any zero-point corrections to the data.

We calculated the orbital elements of Wack 2134 independently with the RVs of the He II and N IV emissions and the N V absorptions. We adopted the period determined with the most numerous set of RVs from the He II emission also for the orbit of the N V absorptions and N IV λ4058 emission. We obtained eccentric orbital solutions, $e = 0.64 \pm 0.03$ for the three data sets. Similar times of periastron and of maximum RV found in each data set indicate that these lines move together, thus belonging to the same component. A similar conclusion is reached for the C IV emission lines, confirming that C and N lines are formed in the same envelope. The orbital elements for the different data sets of RVs are listed in Table 3. Fig. 2 illustrates the RV orbits of Wack 2134 as defined by the He II λ4686 and N IV λ4058 emission lines, and the N V absorptions. In this figure we labelled each instrumental-configuration data set with a different symbol in order to show that there are not systematic shifts among their RVs.

We note that the RV orbit defined by the He II emission has a higher amplitude when compared with the RV orbit defined by the N V absorptions. The higher amplitude of the RV variations of the He II emission in principle could arise from distortions of the emission line by a superimposed absorption moving in antiphase, i.e. a He II absorption originating in the atmosphere of the secondary component. However, our spectra do not show any clear evidence for an absorption line originating in the secondary component. On the other hand, if the secondary component were of earlier spectral type, i.e. an O3 star which also shows N V absorptions in its spectrum, then blending of both components could explain the lower amplitude of the RV variations of these absorption lines. Spectra of higher S/N and resolution are needed to verify these hypotheses.

Our high-resolution echelle spectra obtained during orbital phases close to the quadratures ($\phi \sim 0.93$ and 0.05) show double absorption lines of H and He II, most clearly seen in He II λ5411, as illustrated in Fig. 3. Measuring the component of the He II λ5411 absorption line belonging to the assumed O companion in the echelle spectra taken during quadratures (four spectra obtained during maximum RV but only one presenting minimum RV), we obtained a difference in RVs of about 541 km s^{-1} between quadratures. When we did the same with the absorption lines from the WN component, we obtained a RV difference of about 352 km s^{-1}, which means an orbital semi-amplitude of 174 km s^{-1}, in good agreement with the N IV and He II emission lines. Assuming that the RV orbit defined by the He II λ4686 emission represents the orbital motion of the primary (WN) component, and the RVs of the He II λ5411 absorption line (corrected by the difference between the systemic velocities of both components) show the secondary orbital motion, we performed a fit of the orbital solution. The new SB2 orbital solution implies very high minimum masses for the binary components, namely $87 \pm 6\,M_\odot$ for the primary WN-type component, and $53 \pm 4\,M_\odot$ for the O4-type secondary component. This solution is depicted in Fig. 4. If the RV orbit of the N V absorptions represents the true

Table 2. RVs of some lines in the spectrum of Wack 2134.

HJD[a]	He II λ4686 em (km s^{-1})	N V λ4604-20 abs (km s^{-1})	N IV λ4058 em (km s^{-1})	C IV λ5801 em (km s^{-1})
0179.427	272			
0621.234	248			
0623.269	213	35		
0850.557	129			48
0879.420	184	−22		
1189.580	323			
1484.854	139	−90		
1653.528	3	−189	−45	
1654.516	4	−171	−68	
1655.519	27	−211	−78	
2009.574	282		130	
2011.589	285		47	
2013.561	240	20	75	
2298.747	251			
2299.688	191	−64	158	
2353.527	161	17		54
2384.512	53		−79	
3076.798	33	−228	−73	
3077.790	20		−88	
3145.540	202	−128	41	
3146.483	282	15	186	
3150.519	246	29	0	
3151.476	246		40	
3154.477	163	−39	85	
3155.463	185	−24	−4	
3156.479	187		52	
3169.453	64			
3170.449	0			
3171.453	30	−189	−215	
3172.459	32		−263	
3481.536	145	−66	−62	−14
3482.538	119			−57
3489.501	28	−132	−117	−68
3490.540	18	−156	−143	−85
3491.540	20	−160	−143	−74
3741.788	3	−179	−153	
3747.790	325		82	
3772.701	24	−125	−112	−88
3875.510	311	188	255	196
4188.714	−11	−209	−200	−48
4188.724	−8	−216	−160	−32
4189.508	41	−209	−52	−28
4189.517	49	−167	−194	−15
4189.769	−1	−187	−156	−50
4189.778	11	−196	−184	−53
4190.525	124	−129	−47	21
4190.801	258	−16	12	47
4191.510	297	41	76	146
4192.489	345	126	179	202
4192.765	345	124	130	211
4193.479	363	122	165	193
4193.794	332	121	99	175
4200.583	226	8	64	60

[a]Heliocentric Julian Date: 245 0000+.

orbital motion of the primary, then the minimum masses of the primary and secondary components would be 83 ± 22 and 47 ± 14 M$_\odot$, respectively. Similar values were obtained when we used both components of the He II λ5411 absorption line as representing the orbital motion of each star in the system.

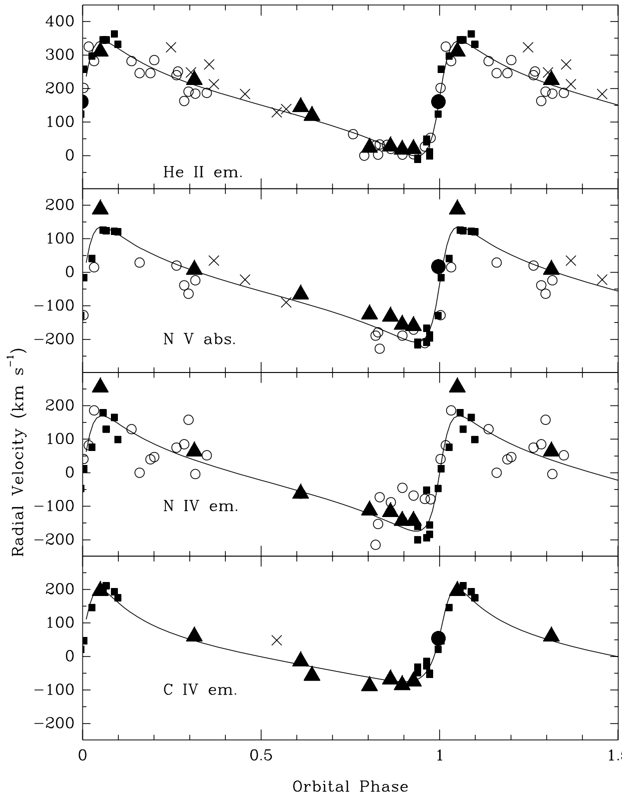

Figure 2. RV variations of the He II λ4686 emission, N V λ4604-20 absorption, N IV λ4058 emission and C IV λ5801 emission lines in the Wack 2134 binary system, phased with the period of 31.673 d. We distinguished the RVs measured in the different data sets: SAAO spectra (×), EMMI spectrum (•), CASLEO (○), CTIO (■) and LCO (▲). Note that there are no systematic shifts among the data obtained with different instrumental configurations. The continuous curves represent the orbital solutions from Table 3.

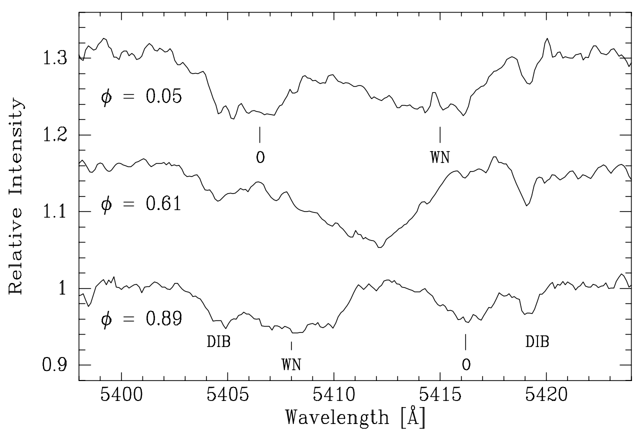

Figure 3. He II λ5411 absorption lines of both primary (WN) and secondary (O) components in the Wack 2134 binary system observed in our high-resolution echelle spectra during the quadrature phases of the orbital motion. We also show (in the middle) a spectrum taken at nearly conjunction when the lines from both components are blended. Note that the RVs are more extreme in the O-type star, thus indicating a lower mass. Diffuse interstellar bands (DIB), which are blended with the stellar lines in lower resolution spectra, are also indicated.

Table 3. Orbital solutions corresponding to the RVs of the He II λ4686 emission line, the mean of the N V λ4604-20 absorption lines, the N IV λ4058 emission line and the C IV λ5801 emission line in the spectrum of Wack 2134. Symbols have the canonical meanings. The last three correspond to, respectively, the mass function, a standard deviation of the fit (parameter defined by Bertiau & Grobben 1969) and the number of data points involved.

	He II λ4686 em	N V λ4604-20 abs	N IV λ4058 em	C IV λ5801 em
P (d)	31.673 ± 0.002	31.673 (fixed)	31.673 (fixed)	31.673 (fixed)
V_0 (km s^{-1})	157 ± 3	−51 ± 7	−17 ± 9	20 ± 5
K (km s^{-1})	172 ± 3	159 ± 6	163 ± 8	138 ± 4
e	0.64 ± 0.02	0.64 ± 0.03	0.64 ± 0.03	0.64 ± 0.02
ω (°)	276 ± 3	281 ± 6	287 ± 7	303 ± 4
$T_{\rm Periast}$ (d)[a]	190.68 ± 0.08	191.0 ± 0.2	191.1 ± 0.2	191.5 ± 0.1
$T_{\rm RVmax}$ (d)[a]	192.39 ± 0.08	192.5 ± 0.2	192.4 ± 0.2	192.5 ± 0.1
$a \sin i$ (R$_\odot$)	82.2 ± 0.5	76 ± 5	78 ± 7	66.2 ± 3
$F(\mathcal{M})$ (M$_\odot$)	7.6 ± 0.1	6 ± 1	6.4 ± 2	4 ± 0.6
σ (km s^{-1})	16.4	26.6	34	12.5
n	52	36	40	23

[a]Heliocentric Julian Date: 245 4000+.

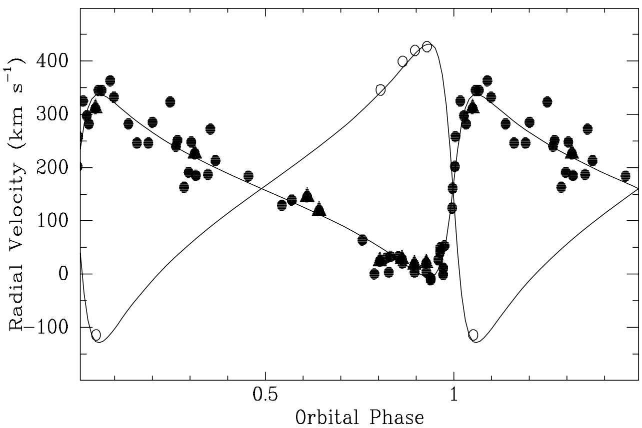

Figure 4. RV variations of the He II λ4686 emission and He II λ5411 absorption line, in the Wack 2134 binary system, phased with the period of 31.673 d. Filled symbols represent the RVs of the emission (WN component), and open ones depict the RVs of the absorption (O component). Curves show the orbital motion of each component.

With the high minimum masses found from our RV orbit, we would expect to observe eclipses. Wack 2134 has been monitored in V magnitude by the All Sky Automated Survey (ASAS) (cf. Pojmański 2001). We have examined the public ASAS data of this star. No obvious variations were found in the V magnitudes when we folded them at the spectroscopic binary period of 31.673 d. However, as Wack 2134 is near the faint magnitude limit of the ASAS survey, the V magnitudes show rather high noise. More accurate photometry is needed to rule out, or confirm, the eclipsing nature of this binary.

5 CONCLUSIONS

From the RV variations of the He II λ4686 emission line in the spectrum of the WN-type star Wack 2134, we found a most probable period $P = 31.673 \pm 0.002$ d, thus revealing Wack 2134 as an eccentric binary system ($e = 0.64 \pm 0.03$).

Our higher resolution spectra taken during quadratures show H and He II resolved into two components. We could obtain an orbital solution for the secondary component measuring the He II λ5411 absorption line in those spectra, but this orbit has only one measurement at one of the quadratures (see Fig. 4). Using the He II λ4686 emission line and the He II λ5411 absorption line to follow the motion of the WN and O component, respectively, we obtained very high minimum masses $M_{\rm WN} \sim 87$ M$_\odot$ and $M_{\rm O} \sim 53$ M$_\odot$.

In spite of the high minimum masses obtained, no light variations indicative of eclipses are found in the photometry performed by ASAS.

These minimum masses have to be considered as preliminary, as more high resolution and S/N spectra are needed to confirm these values. Furthermore, more precise photometry could shed light on this new massive binary system.

Although we prefer to be cautious, the WN component in the Wack 2134 system could be amongst the most massive stars ever measured from binary motion in the Galaxy, as both WN6ha components in the binary system WR 20a (83 + 82 M$_\odot$; Rauw et al. 2004; Bonanos et al. 2004), located about 16 arcmin from Wack 2134, and those in the new Wolf–Rayet binary system NGC 3603-A1, which has masses of 116 + 89 M$_\odot$ (Schnurr et al. 2008; Moffat et al. 2004).

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REFERENCES

Benaglia P., Romero G. E., Koribalski B., Pollock A., 2005, A&A, 440, 743
Bertiau F., Grobben J., 1969, Ric. Spec. Vaticana, 8, 1
Bonanos A. Z. et al., 2004, ApJ, 611, 33
Caraveo P. A., Bignami G. F., Goldwurm A., 1989, ApJ, 338, 338
Gamen R. C. et al., 2006, A&A, 460, 777
Lafler J., Kinmann T., 1965, ApJS, 11, 216

Massey P., Hunter D. A., 1998, ApJ, 493, 180
Melnick J., 1985, A&A, 153, 235
Mereghetti S., Belloni T., Shara M., Drissen L., 1994, ApJ, 424, 943
Moffat A. F. J., Poitras V., Marchenko S. V., Shara M. M., Zurek D. R., Bergeron E., Antokhina E. A., 2004, AJ, 128, 2854
Pojmański G., 2001, in Pacynski B., Chen W.-P., Lemme C., eds, ASP Conf. Ser. Vol. 246, IAU Colloq. 183, Small Telescope Astronomy on Global Scales. Astron. Soc. Pac., San Francisco, p. 53
Rauw G. et al., 2004, A&A, 420, 9
Reig P., 1999, A&A, 345, 576
Schnurr O., Moffat A. F. J., St-Louis N., Casoli J., Chené A.-N., 2008, MNRAS, 389, L38
van der Hucht K. A., 2001, New Astron. Rev., 45, 135
Wackerling L. J., 1970, Mem. R. Astron. Soc., 73, 153
Walborn N. R., Blades J. C., 1997, ApJS, 112, 457

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