A new massive double-lined spectroscopic binary system: The Wolf-Rayet star WR 68a*  
(Research Note)

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ABSTRACT

Double-lined spectroscopic binary systems, containing a Wolf-Rayet and a massive O-type star, are key objects for the study of massive star evolution because these kinds of systems allow the determination of fundamental astrophysical parameters of their components. We have performed spectroscopic observations of the star WR 68a as part of a dedicated monitoring program of WR stars to discover new binary systems. We identified spectral lines of the two components of the system and disentangled the spectra. We measured the radial velocities in the separated spectra and determined the orbital solution. We discovered that WR 68a is a double-lined spectroscopic binary with an orbital period of 5.2207 days, very small or null eccentricity, and inclination ranging between 75 and 85 deg. We classified the binary components as WN6 and O5.5-6. The WN star is less massive than the O-type star with minimum masses of 15 ± 5 $M_\odot$ and 30 ± 4 $M_\odot$, respectively. The equivalent width of the He II λ4686 emission line shows variations with the orbital phase, presenting a minimum when the WN star is in front of the system. The light curve constructed from available photometric data presents minima in both conjunctions of the system.

Key words. binaries: spectroscopic – stars: Wolf-Rayet – stars: individual: WR 68a – stars: fundamental parameters

1. Introduction

Observational works dedicated to the study of multiplicity among massive stars, e.g. Barbá et al. (2010), Sana et al. (2013), and many references there in, provide evidence that the fraction of O+OB systems is high, greater than 50%. This situation is not completely replicated by the available data for Wolf-Rayet (WR) stars. There are about 50 binary systems detected among the galactic WR stars (less than 10% of the known whole sample), and only 24 of them are known double-lined spectroscopic systems (SB2). These systems are key objects because they allow the determination of some fundamental astrophysical parameters for their component stars. Moreover, double-lined eclipsing systems allow the determination of stellar masses and radii in a direct and reliable way, thus providing strong constraints on stellar physics and evolutionary models. In this context, the discovery of these kinds of systems is highly relevant.

In an attempt to search for new binary systems among faint WR stars, a spectroscopic monitoring of southern galactic WR stars is underway. This survey was started in 2007 and its main results published to date are the discovery of the SB2 WR 62a, one of the most conspicuous radial-velocity (RV) variable stars in our sample (Collado et al. 2013, hereafter Paper I), and WR 35a (Gamen et al. 2014).

WR 68a (SMSNPL13, $v = 14.41$) was identified as a WR star by Shara et al. (1999). No other data or analysis on this star were found in the bibliography, thus it was included in our survey.

In this paper, we present the first spectroscopic and photometric analysis of WR 68a, demonstrating that this is an SB2 system. The paper is organised as follows: in Sect. 2, we describe the observations and data reduction. In Sect. 3, we present the spectral analysis of the system’s components, the measurement and analysis of radial velocities, and the study of the available photometry. In Sect. 4, we summarise our results.

2. Observations and data reduction

We obtained thirty-six spectroscopic observations of WR 68a between 2007 and 2013. The observations were carried out with the 2.15-m J. Sahade telescope at the Complejo Astronómico El Leoncito (CASLEO, Argentina), the 4-m V. Blanco telescope at Cerro Tololo Inter-American Observatory (CTIO, Chile), and the 2.5-m du Pont and the 6.5-m Magellan Baade telescopes at Las Campanas Observatory (LCO, Chile). See Table 1 for a summary of the observations. Immediately after or before the stellar
integration, at the same telescope position, we obtained comparison lamp spectra. We reduced the spectra using IRAF\(^1\) standard procedures.

### 3. Results and discussion

#### 3.1. The spectrum of WR 68a

The spectrum of WR 68a shows noticeable emission lines of helium, carbon, and nitrogen ions, and also several absorption lines of hydrogen and helium superimposed onto the emissions. As we prove below, these absorption lines move in anti-phase with respect to the emissions, indicating that WR 68a is a double-lined WR + OB binary system.

To separate the individual components in the spectrum of WR 68a, we applied a disentangling method similar to that developed by González & Levato (2006). Briefly, the method consists of shifting all the spectra to the common RV for one component and co-adding them so that the features of the other component are diluted. In a second step, the pure spectrum of one component (template) is subtracted to obtain a new RV decomposition. These steps are repeated in an iterative way. The method was only applied to the CTIO and LCO spectra because CASLEO data have lower signal-to-noise ratio (S/N). The spectral resolving power \((R = \lambda / \Delta \lambda)\) was measured using \(\Delta \lambda\) as the FWHM of calibration lamp emission lines.

#### 3.2. Measurement and analysis of radial velocities

The radial velocities (RVs) were determined by means of cross-correlation (using the IRAF FXCOR task) between the separated spectra of each component and the corresponding template. For each emission line, an appropriate spectral range was used to determine the RV thereof. In the case of the RVs of the absorption lines, we determined a mean RV using the spectral ranges of \(\text{H}\beta\), \(\text{H}\alpha\), and \(\text{He}\alpha\). The individual RVs of the measured emission lines according to the helio-centric Julian dates (HJD) of the observations, including \(\text{N}\text{iv}\lambda4058\), the blend \(\text{N}\text{iii}\lambda4686\) and \(\text{C}\text{iv}\lambda5812\) emissions, and the mean RV of \(\text{H}\beta\), \(\text{H}\alpha\), and \(\text{He}\alpha\) absorption lines are listed in Table 2.

We searched for periodicities in the RVs of the \(\text{He}\text{ii}\lambda4686\) emission line, using the method developed by Marraco & Muzzio (1980). This algorithm computes, for each trial period, the variances from the best-fitting straight line in each phase interval. The most probable period obtained is 5.22 d. Then, by means of the GBART\(^3\) code, we individually fit orbital solutions to the RVs for the emission and absorption lines. As all lines show a similar periodicity, we adopted the straight mean of the periods obtained from each data set, i.e. \(P = 5.2207 \pm 0.0005\) d, as the binary period. Thus, with the fixed period, we independently determined the orbital parameters for the emission and the mean of the absorption lines, and we show these in Table 3. The orbital solutions for each emission line are illustrated in Fig. 2.

As expected, each data set presents different systemic velocities, semi-amplitudes, times of periastron passage, and maximum RV. For example, the blend \(\text{N}\text{iv}\lambda4634\) presents the lowest semi-amplitude and the \(\text{C}\text{iv}\lambda5812\) emission appears to have the largest. This is a common behaviour in WN+OB systems, generally related to the fact that emission lines are formed.

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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.

2. The “o” means that no hydrogen is observed in the spectrum.

3. GBART is an improved version of the program for the determination of the orbital elements for spectroscopic binaries originally written by Bertiau & Grobben (1968), developed by F. Bareilles, and available at [http://www.ia.rup.it/-fede/pub/gbart](http://www.ia.rup.it/-fede/pub/gbart).

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### Table 1. Details of the observing material.

| Date-obs. UT | n | Sp. coverage [Å] | Observat. | Telesc. | Spectr. | Grating [l mm\(^{-1}\)] | Detector | Dispersion [Å pix\(^{-1}\)] | Resolving power |
|--------------|---|-----------------|-----------|--------|--------|------------------------|----------|-------------------------|---------------|
| 2007, Mar. 30 | 2 | 3650–6700 | CTIO | 4 | R–C | 632 | Loral 3k | 1.01 | 1300 |
| 2007, Apr. 1–3 | 4 | 3650–6700 | CTIO | 4 | R–C | 632 | Loral 3k | 1.01 | 1300 |
| 2008, Apr. 19–23 | 7 | 3650–6700 | CTIO | 4 | R–C | 632 | Loral 3k | 1.01 | 1300 |
| 2008, Jun. 16 | 1 | 3650–6750 | LCO | 6.5 | IMACS i/4 | 600 | STe (Mosaic 1) | 0.4 | 3300 |
| 2009, Mar. 24–27 | 7 | 4030–5590 | CASLEO | 2.15 | REOSC SD | 600 | Tek1024 | 1.63 | 1000 |
| 2009, Jul. 23 | 1 | 3890–5520 | LCO | 2.5 | B–C | 1200 | Marconi#1 | 0.79 | 2500 |
| 2009, Jul. 26 | 1 | 3540–6700 | LCO | 2.5 | B–C | 600 | Marconi#1 | 1.55 | 1200 |
| 2009, Jul. 27 | 1 | 3890–5520 | LCO | 2.5 | B–C | 1200 | Marconi#1 | 0.79 | 2500 |
| 2009, Aug. 14–17 | 3 | 4040–5700 | CASLEO | 2.15 | REOSC SD | 600 | Tek1024 | 1.63 | 1000 |
| 2010, Apr. 10–11 | 2 | 3930–5600 | CASLEO | 2.15 | REOSC SD | 600 | Tek1024 | 1.63 | 1000 |
| 2010, Aug. 2–8 | 4 | 3930–5600 | CASLEO | 2.15 | REOSC SD | 600 | Tek1024 | 1.63 | 1000 |
| 2011, Apr. 6–11 | 2 | 3930–5600 | CASLEO | 2.15 | REOSC SD | 600 | Tek1024 | 1.63 | 1000 |
| 2013, May 12 | 1 | 3930–5600 | CASLEO | 2.15 | REOSC SD | 600 | Tek1024 | 1.63 | 1000 |

Notes. “n”: number of spectra taken per run. (\(a\)): Details of the spectrographs can be found in the user manuals of the respective observatories. (\(b\)): The spectral resolving power \((R = \lambda / \Delta \lambda)\) were measured using \(\Delta \lambda\) as the FWHM of calibration lamp emission lines.
in asymmetric (not barycentric) regions at different depths in the expanding envelope (see e.g. Niemela & Moffat 1982; Niemela et al. 1995).

It is also noteworthy that the RVs of the absorption lines are anti-phased with respect to the emission lines, thus indicating that they belong to the O-type component of the system. The semi-amplitude of its orbit is lower than that of the WN (regardless of which emission line is used), which means that the O-type star is the more massive star in the system.

Eccentricities other than zero are not common in binary systems containing classical He-burning WN components. Only WR 97 is known to have a significant $e$ (0.1±0.04, Gamen 2004). We checked the robustness of the found $e$ with a test of significance given by Lucy & Sweeney (1971) and it resulted to be spurious in all of the emission lines (they do not reach the 5% level of significance for accepting eccentric orbits), but are significant in the absorption lines. This feature should be interpreted with tailored models appropriate to this context of close binaries, i.e. heating hemispheres by a hot companion, asymmetric emission-line forming regions, colliding wind zone, etc. On the other hand, as is shown below, the light curve presents two dips at 0.5 phase intervals, also pointing to a circular orbit. In the

**Table 3.** Orbital solutions corresponding to the radial velocities of the N	extsc{iv}, N	extsc{iii}, He	extsc{ii}, and C	extsc{iv} emission lines, and mean abs.

| Parameter | N	extsc{iv} | N	extsc{iii} | He	extsc{ii} | He	extsc{ii} | C	extsc{iv} | Mean abs. |
|-----------|-------------|--------------|-------------|-------------|-------------|-----------|
| $P$ [days] | 4057.76     | 4640.64      | 4685.68     | 5411.52     | 5811.98     | 5.2207 ± 0.0005 |
| $V_0$ [km s$^{-1}$] | $-159 \pm 7$ | $-245 \pm 5$ | $4 \pm 3$ | $22 \pm 5$ | $-373 \pm 4$ | $-146 \pm 4$ |
| $K$ [km s$^{-1}$] | $314 \pm 11$ | $307 \pm 7$ | $331 \pm 4$ | $331 \pm 7$ | $352 \pm 7$ | $158 \pm 6$ |
| $e$ | 0.05 ± 0.03 | 0.08 ± 0.02 | 0.05 ± 0.01 | 0.04 ± 0.02 | 0.06 ± 0.01 | 0.20 ± 0.04 |
| $w$ [degrees] | 350 ± 37 | 206 ± 17 | 111 ± 12 | 134 ± 30 | 157 ± 19 | 262 ± 9 |
| $T_{\text{Periastr}}$ [d$^*$] | 5036.9 ± 0.5 | 5039.7 ± 0.2 | 5038.4 ± 0.2 | 5038.8 ± 0.4 | 5039.4 ± 0.3 | 5038.4 ± 0.1 |
| $T_{\text{RVmax}}$ [d$^*$] | 5037.1 ± 0.5 | 5036.7 ± 0.2 | 5036.8 ± 0.2 | 5036.9 ± 0.4 | 5037.2 ± 0.3 | 5039.4 ± 0.1 |
| $T_{\text{WRinfront}}$ [d$^*$] | 5038.3 ± 0.5 | 5038.1 ± 0.2 | 5038.1 ± 0.2 | 5038.2 ± 0.4 | 5038.5 ± 0.3 | 5035.9 ± 0.1 |
| $a \sin i$ [R$_\odot$] | 32 ± 1 | 32 ± 1 | 34 ± 1 | 34 ± 1 | 36 ± 1 | 16 ± 1 |
| $\sigma$ [km s$^{-1}$] | 31.49 | 35.57 | 23.51 | 37.37 | 17.12 | 21 |

**Notes.** *(∗) HJD-2 455 000.*
Continuous curves represent the orbital solutions in Table 3.

A49, page 4 of 6

The He\textsuperscript{ii} different orbital phases. We found that the EW and FWHM of full width at half maximum (FWHM) of some lines at different phases. We shifted the RVs of emission lines by the difference between the barycentric velocities obtained for the individual solutions to match the lines of the O-type star component. We performed an iterative process to determine the orbital solution, rejecting those points whose O–C values were three times larger than the rms of the whole solution in each trial. The orbital parameters and the RV orbits are shown in Table 4 and Fig. 3, respectively.

The minimum mass derived for the O-type star is very similar to the theoretical value for an O 5.5–6 V star, as calibrated by Martins et al. (2005), 31–33 M\textsubscript{\odot}. Therefore, the orbital inclination should be close to 90 deg, and we can expect to observe photometric variability (eclipses, for instance).

3.3. Analysis of the emission-line profiles and available photometry

We analysed the behaviour of the equivalent width (EW) and full width at half maximum (FWHM) of some lines at different orbital phases. We found that the EW and FWHM of the He\textsuperscript{ii} λ4686, 5411 and N\textsuperscript{iv} λ4058 emission lines present some variability modulated by the orbital period, which is very noticeable in the He\textsuperscript{ii} λ4686 line (see Fig. 4). This line becomes fainter around phase φ = 0.0, i.e. when the WN star is in the front of the system. A similar effect has previously been observed in WR 62a (see Paper I) and in the intriguing LBV HD 5980 (Foellmi et al. 2008), and it has been explained as due to the emission line having an additional non-stellar component, which originates in the colliding wind region.

We also analysed the data collected by the All Sky Automated Survey (ASAS; Pojmanski 2001). We constructed
the light curve (see Fig. 6, where we also show the averaged points for each bin of $\phi = 0.05$), and noted two dips: one in phase 0.0 (when the WN-type component passes in front of the system) and the other, less pronounced, in phase 0.5. To prove it is not fortuitous, the ASAS data were searched for periodicities, applying the same algorithm used for the RVs. The most likely period found is $P = 5.22$ d, which is similar to the spectroscopic period (both periodograms are compared in Fig. 5).

The similarity between the light curves of WR 62a and WR 68a is notorious, however, the dip at $\phi = 0.0$ in the light curve of WR 68a is shallower and wider than that observed in WR 62a. The resemblance of these light curves to that of V444 Cyg, a WN5+O6 binary system, is also remarkable (see Fig. 2 of Eriş & Ekmekçi 2011). The photometric data of the ASAS survey are not suitable for a detailed analysis because of the faintness of WR 68a. Notwithstanding that, we adjusted a simple Wilson-Devinney (WD) model (Wilson & Devinney 1971) by means of the PHOEBE code (Prša & Zwitter 2005), to the RV of both stars and the photometric data together. We adopted the theoretical stellar mass and radii for an O 5.5-6 V star from Martins et al. (2005) and adjusted the stellar parameters of the WN6 component. We found that the light curve can be reasonably fitted with an orbital inclination ranging between 75 and 85 deg. These values imply for the WN component a radius between 4.5 and 7.4 $R_\odot$, comparable with those estimated for the WN5 component of V444 Cyg (Eriş & Ekmekçi 2011, and references therein).

### 4. Conclusions

We have discovered that WR 68a is a double-lined binary system composed of a WN6 star and an O 5.5-6 type component in a orbital period of 5.2207 d. We found that the O-type star is more massive than the WN component with minimum masses of $30 \pm 4 M_\odot$ and $15 \pm 5 M_\odot$ for the O-type and WN stars, respectively.

We also detected a minimum in the EW of the He II λ4686 emission when the WN star is in front of the system, likely due to the eclipse of an additional component of this line originated in the colliding winds region. From the analysis of the available photometric data (ASAS), we found a variability, i.e. two minima in the light curve during both conjunctions of the system, which we interpreted as eclipses.

WR 68a becomes in an important astronomical target, as accurate multi-band photometric and higher resolution spectroscopic follow-up observations will allow to determine the stellar parameters, as radius and masses, for both massive components. WR 68a is thus a target of choice to obtain direct properties of stars in a WR+O system, hence, to obtain valuable constraints to confront evolutionary models of massive stars.

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### References

Barbá, R. H., Gamero, A., Arias, J. I., et al. 2010, in Rev. Mex. Astron. Astrofis., 38, 39

Bertiau, F., & Grobben, J. 1968, Ric. Astr. Spec. Vat., 8, 1

Collado, A., Gamero, R., & Barbá, R. H. 2013, A&A, 552, A22

Eriş, F. Z., & Ekmekçi, F. 2011, Astron. Nachr., 332, 616

Feilhauer, C., Koenigsberger, G., Georgiev, L., et al. 2008, Rev. Mex. Astron. Astronofis., 44, 3

Gamen, R. 2004, Ph.D. Thesis, La Plata University

Gamen, R., Collado, A., Barbá, R., Chené, A.-N., & St-Louis, N. 2014, A&A, 562, A13

González, J. F., & Levato, H. 2006, A&A, 448, 283

Lacy, L. B., & Sweeney, M. A. 1971, AJ, 76, 544

Maiz Apellániz, J., Pellerin, A., Barbá, R. H., et al. 2012, 465, 201

Marraco, H., & Muzzio, J. 1980, PASP, 92, 700

Martins, F., Schaerer, D., & Hillier, D. J. 2005, A&A, 436, 1049

Niemela, V. S., & Moffat, A. 1982, Ap.J., 259, 213

Niemela, V. S., Cabanne, M. L., & Basso, L. P. 1995, Rev. Mex. Astron. Astrofis., 31, 45

Pojmański, G. 2001, in Small Telescope Astronomy on Global Scales, eds. B. Paczynski, W.-P. Chen, & C. Lemme, IAU Colloq. 183, ASP Conf. Ser., 246, 33

Prša, A., & Zwitter, T. 2005, Ap. 628, 426

Sota, A., Maiz Apellániz, J., Walborn, N. R., et al. 2011, ApJS, 193, 24

Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Table 2. Observed heliocentric radial velocities of WR 68a.

| HJD 2450000+ | Phase | N IV 4057.76 Å [km s⁻¹] | N III 4640.64 Å [km s⁻¹] | He II 4685.68 Å [km s⁻¹] | He II 5411.52 Å [km s⁻¹] | He II 5811.98 Å [km s⁻¹] | C IV 5513.8 Å [km s⁻¹] | Mean abs. 
|-------|-------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|-------|
| 4189.83 | 0.99 | −238 ± 2 | −173 ± 2 | 58 ± 1 | 46 ± 5 | −471 ± 3 | −113 ± 3 |
| 4189.85 | 0.99 | −239 ± 1 | −203 ± 2 | 41 ± 2 | 30 ± 1 | −491 ± 4 | −158 ± 3 |
| 4191.96 | 0.27 | 54 ± 2 | −85 ± 2 | 190 ± 1 | 274 ± 2 | −68 ± 5 | −290 ± 6 |
| 4192.95 | 0.58 | −450 ± 1 | −268 ± 4 | −162 ± 7 | −441 ± 3 | −110 ± 6 |
| 4193.67 | 0.72 | −425 ± 1 | −550 ± 2 | −309 ± 3 | −301 ± 3 | −702 ± 3 | 10 ± 9 |
| 4193.90 | 0.77 | −483 ± 2 | −542 ± 1 | −297 ± 1 | −327 ± 4 | −742 ± 3 | −15 ± 9 |
| 4575.90 | 0.94 | −297 ± 1 | −281 ± 2 | −64 ± 1 | −113 ± 3 | −571 ± 3 | −36 ± 3 |
| 4576.86 | 0.12 | 45 ± 2 | −17 ± 1 | 256 ± 1 | 243 ± 1 | −213 ± 3 | −209 ± 13 |
| 4577.75 | 0.29 | 150 ± 2 | −38 ± 2 | 272 ± 1 | 340 ± 1 | −32 ± 5 | −283 ± 17 |
| 4578.66 | 0.47 | −299 ± 3 | 6 ± 1 | 103 ± 1 | −230 ± 2 | −268 ± 7 |
| 4578.89 | 0.51 | −188 ± 4 | −365 ± 3 | −157 ± 2 | −70 ± 6 | −249 ± 2 | −161 ± 5 |
| 4579.61 | 0.65 | −365 ± 4 | −545 ± 2 | −303 ± 1 | −239 ± 1 | −587 ± 2 | −32 ± 10 |
| 4579.88 | 0.70 | −478 ± 5 | −592 ± 1 | −342 ± 1 | −306 ± 2 | −693 ± 3 | −2 ± 14 |
| 4633.69 | 0.01 | −213 ± 3 | −160 ± 3 | 66 ± 3 | 121 ± 3 | −411 ± 7 | −113 ± 21 |

Notes. Radial velocities errors listed in table are provided by the fxcor task of IRAF. The errors are calculated from the asymmetric noise of the cross-correlation function and of the fitted height of the peak. The mean FWHM and EW of each emission line were measured in the disentangled spectra.