

A Detailed Spectroscopic Study of the WN6ha + O5 Colliding-wind Binary WR 25

Eric GOSSET^{1,2,*}, Roberto GAMEN^{3,4}, Laurent MAHY⁵, Nidia MORRELL⁶, Hugues SANA⁷
and Rodolfo H. BARBÁ^{8,†}

¹ Honorary Research Director F.R.S.-FNRS (Belgium)

² Space sciences, Technologies and Astrophysics Research (STAR) Institute, Université de Liège, Allée du 6-Août, 19c, Bât. B5c, B–4000 Liège, Belgium

³ Instituto de Astrofísica de La Plata, CONICET-UNLP, Paseo del Bosque S/N, B1900FWA La Plata, Argentina

⁴ Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, La Plata, B1900, Argentina

⁵ Royal Observatory of Belgium, Avenue Circulaire/Ringlaan, 3, B–1180 Brussels, Belgium

⁶ Las Campanas Observatory, Carnegie Observatories, Casilla 601, La Serena, Chile

⁷ Institute of Astronomy, KU Leuven, Celestijnenlaan, 200D, B–3001 Leuven, Belgium

⁸ Departamento de Física y Astronomía, Universidad de la Serena, La Serena, Chile

† Deceased 2021

* Corresponding author: eric.gosset@uliege.be

Received: 22 September 2025 – Accepted 22 April 2026

This work is distributed under the Creative Commons CC BY 4.0 Licence.

Abstract

Massive stars have a major dynamical as well as chemical impact on their environment in their host galaxy. Despite their importance, many details of their life and evolution remain poorly constrained. Observational determinations of their physical parameters are therefore required to better constrain evolutionary models. In particular, the mass and the mass-loss rate—two key parameters—are known to be more reliably determined through the study of binary stars. In this context, the binary system WR 25 ($\equiv$ HD 93162) whose dominant spectral type is that of a nitrogen sequence Wolf–Rayet star, is of particular interest. It exhibits the highest known hydrogen content among the Milky Way Wolf–Rayet stars, as well as additional absorption lines. It is therefore most probably an object still on the main-sequence or close to leaving it. We acquired new high-resolution spectra of this extremely interesting object. Following a detailed analysis, we present an improved version of the SB1 orbital solution for the motion of the WN component. We confirm the detection of the previously reported probable O companion and definitively prove that it is indeed gravitationally bound to the WN star. A first SB2 solution is presented, and a mass-ratio WN/O of 2.02 ± 0.36 (1σ) is derived. Following a spectral disentangling procedure, we identify the companion as an O5(f⁺) star belonging to either the main-sequence (V) or giant (III) luminosity classes. The spectral type of the companion, together with the above-mentioned mass ratio, points to a very massive primary WN star of at

least $55 M_{\odot}$. This confirms that WR 25 belongs to the family of very massive WNLh objects, a very poorly populated class in the Milky Way. We demonstrate that the absorption component in the P-Cygni profile of the He II $\lambda 4859 + H\beta$ line of WR 25 is mainly due to the O-type companion, and we propose to adopt a WN6ha spectral type for the WN component of the system. On the basis of the extracted disentangled spectra, we derive approximate physical parameters through a detailed CMFGEN analysis, given the difficulty in constraining both the extinction towards WR 25 and the definitive brightness ratio between the components. Finally, we propose the presence of a third component contributing to the spectrum of WR 25.

Keywords: binary stars:spectroscopic, stars:early-type stars:Wolf–Rayet, star:individual:WR 25

1. Introduction

Massive stars are very important objects in galaxies. Through their strong winds and their associated high mass-loss rates, they exert a marked influence on their surroundings and are able to carve out and shape the interstellar medium, thereby affecting the local dynamical evolution. In addition, they can modify the characteristics of local star formation (see, e.g., Li et al., 2014; Tsang and Milosavljević, 2018, and references therein). During their lifetime, and at its end, massive stars play a major role in the chemical enrichment of the interstellar medium. Despite their importance, the physical parameters of these stars, including the most fundamental ones governing their evolution—namely the mass and the mass-loss rate (and its history)—remain poorly constrained. The evolutionary details of massive stars are still to be understood. The main-sequence O stars are supposed to evolve towards a Wolf–Rayet stage, with or without going through a Luminous Blue Variable stage (see Mahy et al., 2016, 2022a, for discussions and references).

It is therefore necessary to improve our theoretical understanding and to strengthen the constraints on evolutionary models. This can only be achieved through an extensive observational effort aimed at reducing the uncertainties on stellar physical parameters. One of the best ways to determine the physical parameters of massive stars is, as elsewhere in the Hertzsprung–Russell diagram, through the study of binary systems. The minimum masses of both objects of a binary system can be derived from the Keplerian laws through the analysis of the orbital motion. The determination of the inclination (through photometry and/or astrometry) then provides access to the true masses. Photometric variations, as well as the total luminosity, could also place constraints on the stellar radii. In the case of massive stars, the stellar winds are usually strong and radiatively driven (Puls et al., 2008). In massive binary systems, the winds of both components collide, and the collision zone emits strong X-rays. The study of this phenomenon provides valuable information on the respective mass-loss rates, and in some cases, on the inclination (Stevens et al., 1992; Cherepashchuk, 1976; Prilutskii and Usov, 1976; Luo et al., 1990; Parkin and Gosset, 2011). The detailed and comprehensive study of massive binary stars is therefore an important scientific objective. Because massive stars are rare, the study of a unique, important object can be considered as a breakthrough in the field. Interest in massive multiple stars has further increased in recent years following the long-awaited detection

of the first Gravitational-Wave signal (GW; Abbott et al., 2016). Indeed, a large fraction of the detected GW events have been attributed to mergers of massive binary black holes.

Binary systems can also be used to investigate the stellar evolution, although a caveat is of order here. The evolution of a massive binary star does not necessarily correspond to the independent evolutions of two single stars. This approximation may hold for very wide systems where the two stars evolve independently. In closer systems, however, tidal forces could have some influence, and, even more dramatically, mass transfer can take place through Roche Lobe Overflow (RLOF). Sana et al. (2012, 2014) presented the binary characteristics of Galactic O-type stars and revealed that O binary systems are very common. They further demonstrated that approximately 70% of all stars born as O-type stars exchange mass with their companion during their lifetime and therefore undergo an evolution strongly affected by binary interaction: binary interaction actually dominates the evolution of massive stars. These results obtained for the Galactic O stars have since been confirmed for early B stars—which dominate the core-collapse supernovae progenitors (Banyard et al., 2022)—and at sub-solar metallicity (Sana et al., 2013, 2025; Dunstall et al., 2015; Villaseñor et al., 2025). This consequently has implications for the population of core-collapse supernovae. For sufficiently young stars, mass transfer may not yet have taken place, offering the possibility, similarly to wide systems, to derive interesting constraints in a safe but cautious analysis.

In the 1990s, WR 22 was presented by Rauw et al. (1996) as the first observational example of a WR + O binary system, in which, by far, the most massive object was the WN star. Although the existence of such objects had been anticipated by Crowther et al. (1995), the detailed analysis of WR 22 inaugurated the class of highly luminous objects containing an important amount of residual hydrogen and supposed to be core-hydrogen-burning objects disguised as WR stars (Rauw et al., 1995). These stars turned out to be massive stars still on the main-sequence (Rauw et al., 1996; Schweickhardt et al., 1999). Since then, similar other objects have been identified in the Milky Way (such as WR 29: Gamen et al., 2009; WR 20a: Rauw et al., 2005; WR 21a: Niemela et al., 2008; Tramper et al., 2016; Gosset and Nazé, 2016; Barbá et al., 2022). These objects, previously classified as WN7+abs, are now classified as late WN objects with residual hydrogen: WNLh. Because they are very massive and still located on the main-sequence, they are particularly important to study.

Another object of this kind is the WN6ha + O binary WR 25 ($\equiv$ HD 93162, Hen 3-478, *Gaia* DR3 5350357519345171200). WR 25 is a bright Wolf–Rayet star ($V \approx 8.1$; van der Hucht, 2001) located in the region of the Carina Nebula south-west of η Carinae. This star is known as the WR star of the Milky Way with the highest hydrogen content (see, e.g., Hamann et al., 2019). WR 25 was among the first massive stars recognised as an X-ray emitter with an abnormally high flux (Seward and Chlebowski, 1982; Seward et al., 1979, using *Einstein* observations). This flux was usually attributed to the presence of a colliding-wind region in a binary system, although the object had not yet been identified as a true binary system at that time. Gamen et al. (2006) were the first to report the detection of orbital motion and to definitively prove that WR 25 was indeed a binary system. They presented a preliminary orbital solution of type SB1 (i.e., a spectroscopic binary where the spectral signature of only one component is

detected) for the WR component. Gamen et al. (2008) subsequently reported new observations that revealed the first traces of the O companion at a particular phase corresponding to the maximum radial-velocity separation.

In the present paper, we report on a new and more accurate orbital solution of type SB2 and further discuss its implications. We also present a detailed analysis of the individual spectra and discuss the properties of the system. A preliminary account of this work can be found in Gosset et al. (2023).

The paper is organised as follows. Section 2 details the spectroscopic observations and the data reduction procedures, including a particular method for the normalisation to the continuum. Section 3 explores the spectrum of the WN star and analyses the various possibilities for adequately measuring the radial velocities (RVs) of the essential spectral lines in order to accurately derive the orbital motion. A reassessment of the period is then performed in Sect. 4, and a new improved SB1 orbital solution is deduced from the carefully selected measurements in Sect. 5. Section 6 investigates all possible detections of the O-type companion in the WR 25 spectrum and prepares the derivation of the SB2 orbital solution, which requires the use of spectral disentangling techniques applied in Sect. 7. Section 8 presents additional considerations and derived results, whereas Sect. 9 presents a first CMFGEN analysis of the disentangled spectra. The conclusions are presented in Sect. 10.

2. Observations and Data Reduction

Since the discovery paper by Gamen et al. (2006), we have organised several observing campaigns to improve the phase coverage and the signal-to-noise (S/N) ratio of the spectroscopic data. These different campaigns have provided various data sets, which are described below. The main effort took place in data set I.

2.1. Data set I

Data set I consists of spectra obtained during the FEROS observation campaigns carried out between 2006 and 2009. It forms the backbone of the present study.

2.1.1. Instrumental configuration

The Fiber-fed Extended Range Echelle Optical Spectrograph (FEROS; Kaufer et al., 1999) is a two-fiber bench-mounted cross-dispersed echelle spectrograph currently installed at the MPG/ESO 2.2 m telescope at ESO La Silla (Chile). The two fibers have a 2'' aperture and are separated by 2.9' on the sky. The science target is observed through one fiber, while the sky contribution is recorded simultaneously through the other fiber. The instrument covers 39 orders in a fixed cross-dispersed format, providing an effective coverage from 3700 Å to 9200 Å. The resolving power is around 48 000. The detector is an EEV 2K × 4K CCD with a square pixel size of 15 μm. All observations used the 225 Kps-fast, low-gain read-out mode and the 1 × 1 binning. FEROS is equipped with an atmospheric dispersion corrector (ADC) that can

be inserted into the light path to reduce the losses due to atmospheric refraction. However, the ADC significantly reduces transmission below 4000 Å and, given the interest of this domain, we usually did not use the ADC.

ESO has implemented a detailed Calibration Plan that provides sufficient support to calibrate the night observations (Pritchard, 2005). These calibrations consist of five daily bias frames and one dark exposure allowing to estimate the bias level, the read-out noise, the dark current, and to detect CCD cosmetic defects as well as hot pixels. Flat-field exposures were also acquired (10 exposures of 2.4 s each) to correct for the blaze function and pixel-to-pixel sensitivity variations. The flat-field lamp consisted of two bulbs. However, residual fringing above 6500 Å was not fully corrected using these data. Wavelength calibration (WLC) was performed via the acquisition of lamp spectra producing emission lines. Two lamp types were available: ThArNe and ThAr+Ne. In practice, a series of two frames with exposure times of 3, 15 and 30 s are obtained on a daily basis with each lamp. In addition, Solar and flux standard-star spectra are also acquired and the linearity of the detector is regularly monitored. Usually, observers acquire additional flat-field and WLC frames in the afternoon prior to the night in order to initiate the data reduction system (DRS) and to further improve the quality of the reduction procedure. In most cases, we also acquired an O-type star spectrum close to the WR 25 exposure. Its usefulness will be clarified in the following sections.

The twenty-seven WR 25 spectra constituting data set I were collected between March 01, 2006 and March 31, 2009. The exposure time typically ranged between 23 and 30 min. The ADC was generally not used, except on three occasions. In 12 cases, a 60-s ThAr WLC has been obtained immediately after the WR 25 observation, using the ThAr+Ne lamp. The detailed journal of the observations is provided in Table A.1.

2.1.2. Data basic reduction

Data reduction was performed using a modified version of the FEROS DRS working under the eponymous context in ESO-MIDAS. For each night, a master bias frame was created by averaging the individual bias frames with the appropriate binning and read-out mode. The master bias was used to check the homogeneity of the read-out noise and the cosmic defects of the detector throughout the campaign. However, the master bias frame is not used to subtract the bias level. Instead, this latter was determined using the overscan on each individual frame. During the data reduction process, detected bad columns were replaced over their full length by the average of the two adjacent columns. This procedure usually provides a satisfactory approximation, except for columns 1299 and 1300, which both suffer from more severe cosmetic defects.

When available, dark frames were bias-subtracted and used to monitor the dark current. The contribution of the latter was found to be negligible and it has been neglected throughout the data reduction. A daily master flat-field frame was created by averaging all 2.4-s frames available for a given night (i.e., taken both before and after the observing night). It was used to detect the location of orders on the detector and to determine the blaze function, as well as the relative pixel-to-pixel response. The order localisation step uses a cross-order profile, which

is required to accurately trace the order positions by cross-correlating, starting from an initial guess solution at the centre of each order. The adopted cross-order profile and guess starting values were determined using the June 2006 campaign data (Sana, 2009). They were found to be suitable for the reduction of the whole WR 25 data set.

The instrument’s diffuse light was estimated for each frame by fitting a 2D polynomial using the zero inter-order regions. Prior to this step, residuals from bad column corrections and individual bad pixels were removed using additional filtering. The spectra from the SKY and OBJECT fibers are then extracted using the order locations determined on the master flat-field frame. To reduce contamination arising from a narrower inter-order separation in the red part of the spectrum, we used different extraction window widths for different order ranges. A window width of 13, 15, and 17 pixels has been used for order ranges 35–39, 32–34, and 1–31, respectively (as in Sana et al., 2006). The same procedure is applied to both calibration and nighttime observations.

The wavelength calibration proceeds through two alternative approaches, depending on whether an attached 60 s ThAr+Ne frame is actually available. When such a frame is available, it is used with the specific extraction windows described above; otherwise, a series of 3×2 ThArNe exposures is used. The full procedure is described in Sana (2009). Different integration time exposures are used to calibrate different spectral orders: frames with individual integration times of 3, 15, and 30 s are used to calibrate orders 30–39, 10–29, and 1–9, respectively. In all cases, saturated lines are excluded from the wavelength calibration solution. Finally, a two-pass 3σ clipping is applied to reject remaining discordant lines. The resulting WLC residuals are systematically better than $0.003 \text{ \AA}$ when using the ThArNe series. Comparable performance is obtained with ThAr+Ne exposures, although values as high as $0.006 \text{ \AA}$ have occasionally been reached. For the observation at HJD = 2,454,092.827, the attached ThAr+Ne exposure failed to provide an acceptable WLC and the ThArNe series was used instead.

Finally, the blaze function and the WLC are applied to nighttime observations. During this process, the final spectra are remapped onto a linear wavelength scale with a step size of $0.03 \text{ \AA}$. This corresponds to sampling the resolution element with the Nyquist frequency at $3000 \text{ \AA}$ and with twice that sampling rate at $6000 \text{ \AA}$. Because of the long time base of our observations, and because of the different WLC approaches, the Na I $\lambda 5896$ interstellar line in the spectrum of WR 25 was used to check the consistency of our wavelength calibration. The adopted line presents multiple components. Although the four main ones are fitted simultaneously (see below), the solution is tested on the basis of the strongest red-shifted component, which is indeed less affected by the uncertainty of the deblending. The average velocity measured for this component is $4.014 \pm 0.097 \text{ km s}^{-1}$; the maximal deviation from the average value is 0.127 km s^{-1} . The dispersion of the measurements is in perfect agreement with the measurement uncertainties obtained from the multi-Gaussian fitting. No systematic uncertainties seem to affect the calibration, which is therefore fully consistent throughout the entire duration of the data set I campaign.

2.1.3. Normalisation to the continuum

Even after all these reduction steps, the continuum of the spectra still presents oscillations due to the global response function of the spectrograph. The latter may vary from one epoch to another, due to imperfect corrections of the blaze function, and to variations in the flux of the flat-field lamps depending on their temperature. The accurate normalisation of the WR spectra to the continuum is a very difficult step. To verify the consistency of our results, we used a twofold approach. A first possibility consists in fitting a (relatively) low-degree polynomial to the mean flux value over a set of selected narrow windows. The observed spectrum is then approximated order by order and normalised by dividing the spectrum by the resulting local polynomial. Although this technique is usually good, the true spectrum of a WR star generates some problems. Indeed, the broad underlying lines and their wings are usually mistakenly identified as part of the continuum. The zones affected by these lines are thus clearly modified, generally leading to a weakening of the emission lines.

The second possible approach consists in determining a relative response by using a continuum star obtained as close as possible (both in time and on the sky) to the science observation. This star, preferentially an O-type star, is reduced in exactly the same way as the science exposure. However, this is not always possible, and sometimes the continuum star was observed several hours apart and/or under quite different airmass or observing conditions. On other occasions, no suitable continuum star could be found, so that the approach is not universally applicable. The quality of the response curve can be well tested by merging the individual orders of the continuum star. However, even if this merging is excellent for the continuum star (i.e., better than a fraction of a percent), the transposition to the science object (here WR 25) is not necessarily as good. When successful, the division by the response function derived from the continuum reference star leaves a linear trend in the data that results from the temperature difference between the two objects. An additional division by a straight line could still be necessary. This method could also be more efficient and has the major advantage of preserving the broad spectral lines. Its main benefit is to better handle broad line regions with little or no continuum spanning several consecutive orders. The possibility of having two stars (science and continuum) of the same brightness greatly improves the quality of the normalisation. In the following, this procedure is referred to as the *global* normalisation by opposition to the first approach, which is termed *local* normalisation.

Generally, after order merging, both approaches provide similar results in relatively straightforward spectral regions, with dispersions over the continuum well below one percent. In some more difficult regions, the global approach may be better suited to detecting very extended spectral emission regions. Therefore, for data set I, we have produced two versions of the reduced spectra: I_{loc} and I_{glo} , for the local and global procedures, respectively. A comparison of the dissimilarities between the results from the two methods used to define the continuum is illustrated in Fig. 1 where we present selected wavelength domains for which the difficulty to trace the continuum is evident. To demonstrate the stability of the reduction obtained with the global approach, Fig. 2 displays a selected portion of the WR 25 spectrum for all 21 spectra

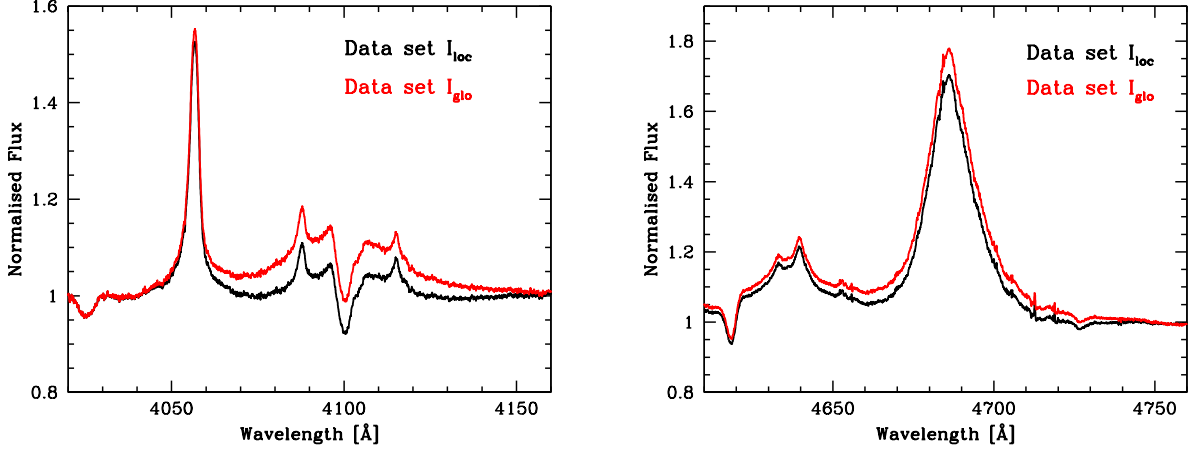


Figure 1: Illustration of the spectrum of WR 25 and of the dissimilarities between the normalisations to the continuum in the local (black) and in the global (red) reduction mode. (*Left*) Region of the N IV $\lambda 4058$ and the He II $\lambda 4100$ +H δ lines. (*Right*) Region between the N V $\lambda 4619$ transition and the He II $\lambda 4686$ line.

included in I_{glo} . Indeed, only 21 of the 27 spectra from I_{loc} had a suitable reference O-type star available for the global normalisation procedure.

2.2. Data set II

Data set II consists of a single observation obtained at a critical phase for which very few observations are available (see below). The spectroscopic observation was acquired in February 2007 with the Magellan Inamori Kyoceros Echelle (MIKE) high-throughput double-echelle spectrograph mounted on the Magellan II Clay Telescope located at Las Campanas Observatory. The MIKE spectrograph has two arms: a blue one (3350–5000 Å) and a red one (4500–9500 Å). The two $2\text{K} \times 2\text{K}$ detectors were both used with a 2×2 binning and in slow read-out mode. The reading noise was about $3.5 e^-$. The resolving power was approximately 33 000. The spectrum was processed with IRAF standard echelle routines. Wavelength calibration was performed with ThAr lamp exposures taken before or after the stellar spectrum at the same telescope position. Continuum normalisation was carried out in the local mode, by polynomial fitting. The details and the journal of the observations are provided in Table A.2.

2.3. Data set III

The third data set consists exclusively of FEROS spectra previously analysed by Gamen et al. (2006). Some 15 spectra acquired between 2001 and 2004 were found to be of sufficient quality to be included in our sample. The first ones were still acquired with the ESO 1.5-m telescope, whereas the remaining ones (obtained after 2002) were acquired with the MPG/ESO 2.2-m telescope. The reduction procedure has been described in Gamen et al. (2006). The normalisation to the continuum was performed in local mode only as no suitable continuum-star observations were acquired during the same nights. The details and the journal of the observations are provided in Table A.3.

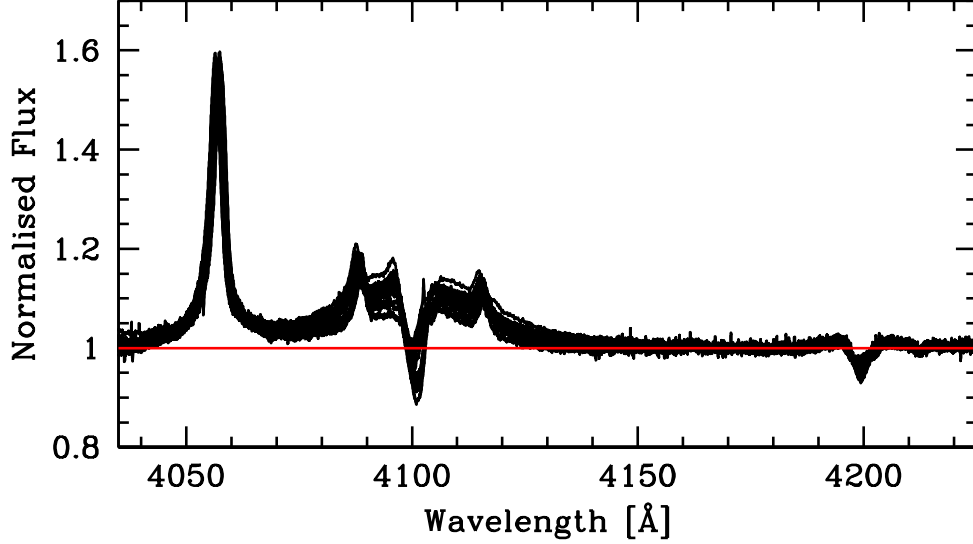


Figure 2: The 21 spectra of the I_{glo} data set overplotted to illustrate the stability of the global reduction procedure in this spectral region.

2.4. Data set IV

The fourth data set consists of spectra acquired in 2006 and 2007 with the 2.5-m Irénée du Pont Telescope at Las Campanas Observatory, Chile. One of these spectra was used to illustrate the detection of the companion reported in Gamen et al. (2008). The telescope was equipped with an echelle spectrograph providing spectra in the range $\sim 3700 \text{ \AA}$ to $7000 \text{ \AA}$ with a resolving power of about 40 000. The detector was a TeK5 2K by 2K CCD with a pixel size of $24 \mu\text{m}$. We used a 1 by 4 pixel slit and the typical S/N ratio was at least 100. Some 10 spectra were acquired in 2006 and two (acquired during the same night) in 2007. Spectra were processed following the same standard procedure described above (see Sect. 2.2). The normalisation to the continuum was performed in local mode only as no suitable continuum-star observations were acquired during the same nights. The details and the journal of the observations are provided in Table A.4.

3. The WR Spectrum and Related RV Measurements

The visible spectrum of WR 25 is dominated by the He II $\lambda 4686$ line and the He II $\lambda 6560$ +H α blend. The N IV $\lambda 4058$ line also stands out. This is precisely the line that was used to reveal the binarity of the system (Gamen et al., 2006). As expected for a WN object, several other nitrogen lines are detected: the N V $\lambda \lambda 4604\text{--}4619$ doublet, the N IV lines around 6220 and $7110 \text{ \AA}$ and others. Numerous N III lines are also present. The Si IV $\lambda \lambda 4089\text{--}4116$ doublet is observed in emission and is blended with the He II $\lambda 4100$ +H δ lines.

The main objective of the work described in this section is to measure the RVs of the WR star in order to derive its orbital motion. We therefore focus on spectral lines that are expected to best trace the true motion of the star. Lines such as He II $\lambda 4686$ and He II $\lambda 6560$ +H α are too broad and too complex, and may further contain (variable) contributions from the wind-collision region. As a result, these features do not provide sufficiently reliable RV measurements. Lines that could

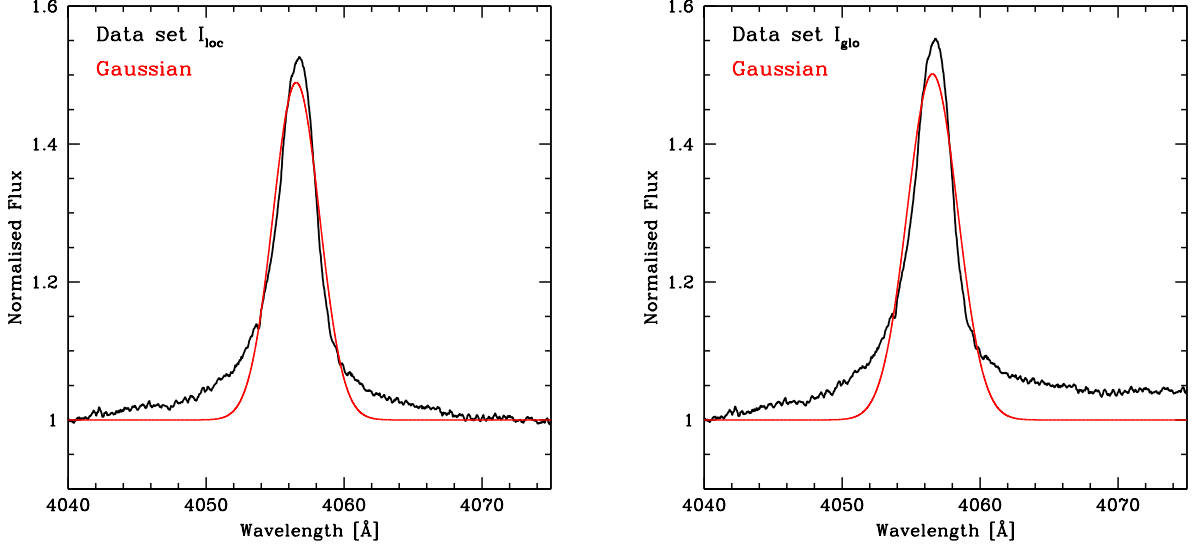


Figure 3: Single-Gaussian fit to the N IV $\lambda 4058$ line in WR 25 illustrated for a spectrum acquired at HJD 2,453,868.628. The black curve represents the observed spectrum, whereas the red curve corresponds to the fitted profile. (*Left*) Spectrum reduced using the local normalisation procedure. (*Right*) Same spectrum reduced using the global normalisation procedure.

be hampered by the presence of the companion (e.g., Balmer lines) should also be avoided. The N IV $\lambda 4058$ is certainly much more suitable and reliable to use. In the following, we measured the positions and RVs of a series of lines in each individual spectrum and carefully examined their behaviour. The line positions were estimated on the basis of single- or multiple-Gaussian fitting and the method is detailed below for each line individually.

3.1. Data set I

3.1.1. The N IV $\lambda 4058$ line

A major and particularly important line in the spectra of WN stars is N IV $\lambda 4058$, essentially as a result of its strength and relative narrowness. It arises from a highly ionised element and is expected to form deep within the stellar wind. This line is often used to derive radial velocities (Gamen et al., 2006). We adopted a typical laboratory wavelength $\lambda_0 = 4057.90$ Å for this line, as proposed by Conti et al. (1977). We first fitted this line with a single Gaussian curve. An example is shown in Fig. 3, illustrating the best fits for both data sets I_{loc} and I_{glo} , and for the same spectrum acquired at HJD 2,453,868.628. Although a single Gaussian does not provide an entirely satisfactory representation of the line profile, it nevertheless provides some valuable estimate of the RV. The observed profile presents excess flux, particularly in the blue wing, although the broad part of the line is detected on both wings. Further to the red, a contribution from the blend of the He II $\lambda 4100$ +H δ wings is also visible in the I_{glo} data.

We also performed two-Gaussian fits, including an additional trend component in the case of the globally normalised spectra. In the following, this additional component is referred

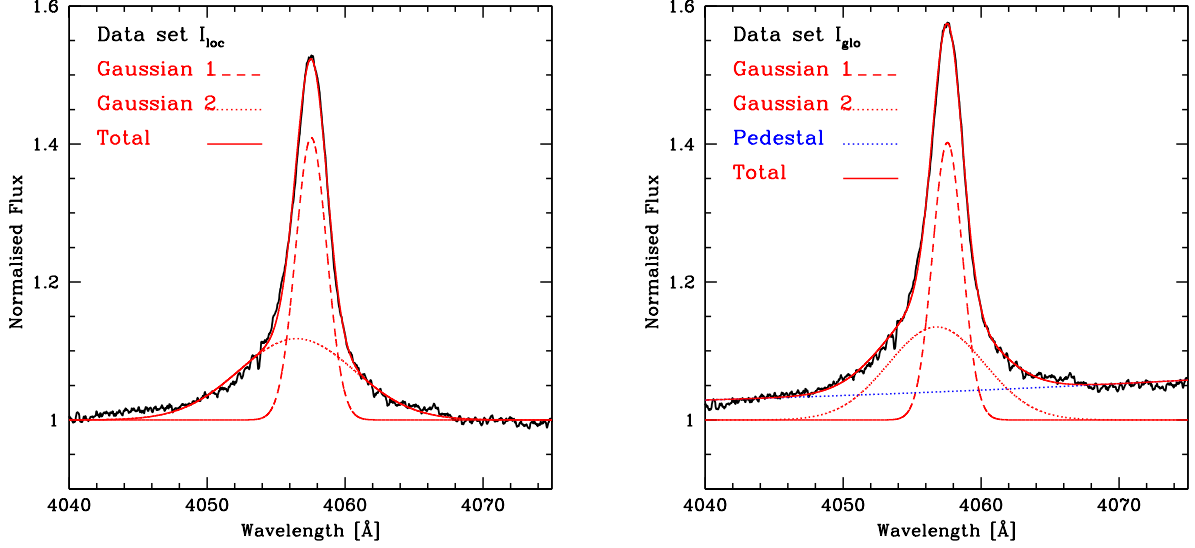


Figure 4: Two-Gaussian fits to the N IV $\lambda 4058$ line in WR 25 illustrated for a spectrum acquired at HJD 2,453,901.587. The black curve represents the observed spectrum, whereas the red curve corresponds to the fitted profile. (*Left*) Spectrum reduced using the local normalisation procedure. (*Right*) Same spectrum reduced using the global normalisation procedure. This latter fit required the introduction of an additional pedestal component, shown in blue. Gaussian 1 was adopted for the RV measurement.

to as the *pedestal*. Examples of these fits are shown in Fig. 4 for the spectrum acquired at HJD 2,453,901.587. They demonstrate that the two-Gaussian fits provide a significantly better representation of the profile. The primary Gaussian (Gaussian 1) reproduces the position of the main emission peak more accurately. Only very minor residuals remain. However, the two fitting approaches do not necessarily yield compatible absolute RV values. Figure 5 compares the RVs obtained from the dominant component (the single Gaussian in the one-component fit and Gaussian 1 in the two-Gaussian fit) for the two kinds of continuum-normalisation methods (local versus global). The two types of reduction clearly have no significant impact on the RV measurement in the single-Gaussian case, whereas a small but systematic effect is present for the two-Gaussian fit. To first order, the two RV determinations differ only by a constant, but the slope of the relation is preserved. This means that the absolute positions (and therefore the absolute RVs) of the emission line are determined only up to an arbitrary constant, whereas the relative positions—and thus the relative variations of the positions and consequently of the RVs—are fully determined. This behaviour appears to be a general property of the WR spectra: absolute RV measurement cannot be reliably obtained. The absolute wavelengths of blends of emission lines remain unknown, as they may depend on the physical conditions in the line-formation zone. In addition, the line profiles can be strongly asymmetric, and the relation between the centroid of the line (as derived, for example, by a Gaussian fit) and the absolute zero-velocity position of the line remains unknown. The position of the line could also be affected by systematic effects. Since we preferentially measure narrow lines expected to trace the orbital motion more closely,

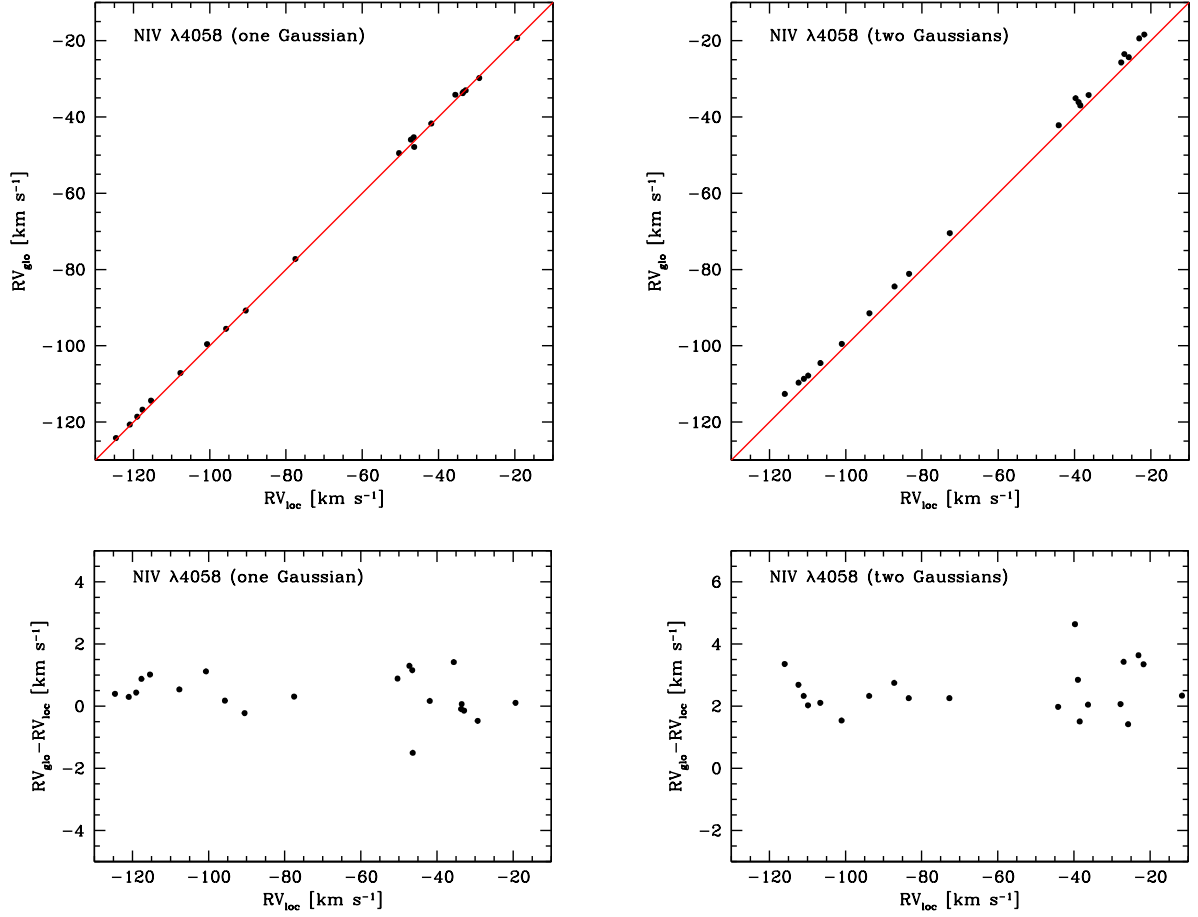


Figure 5: Comparison between the RVs derived from the globally normalised spectra and those measured from the locally normalised spectra. (*Upper left*) Results obtained from single-Gaussian fits. (*Upper right*) Results obtained from two-Gaussian fits, adopting Gaussian 1 for the RV measurements. The red line indicates the perfect one-to-one relation. The agreement is particularly good, especially when allowing for a constant offset between the two determinations. (*Lower panels*) Same comparison, with the ordinate now representing the differences between the two RV measurements.

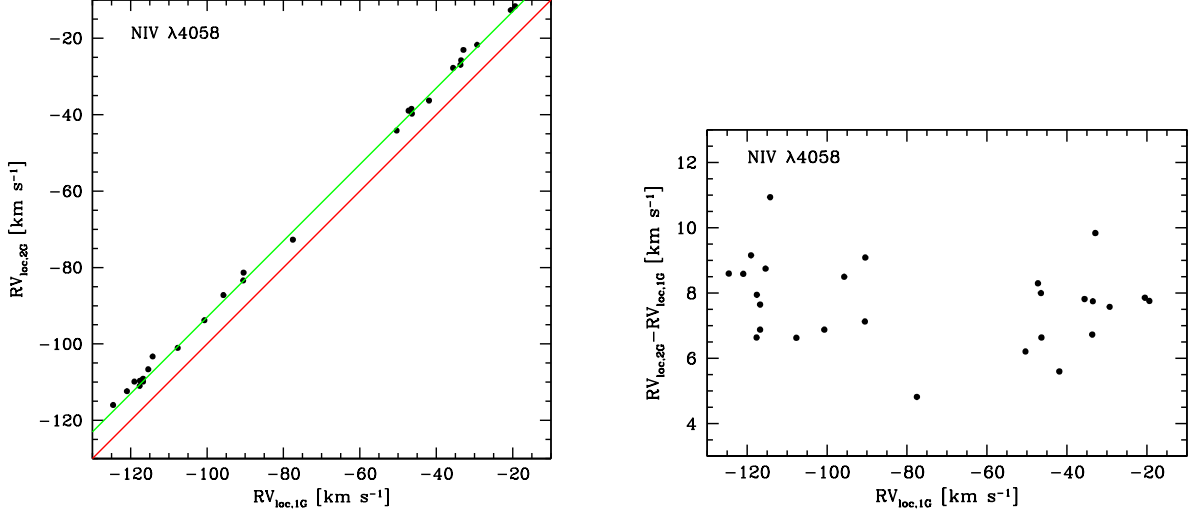


Figure 6: (*Left*) Comparison between the RVs derived from the single-Gaussian fits (1G) and those associated with Gaussian 1 from the two-Gaussian fits (2G); both measurements correspond to the locally normalised spectra. The red line indicates the one-to-one relation, whereas the green line is an arbitrary line drawn parallel to it. This illustrates that the two RV sets differ by a mere constant. (*Right*) RV differences for the same data set.

these lines are likely formed close to the stellar core, and occultation effects could thus induce line shifts. As a consequence, the orbital motion can be accurately determined, but not the systemic velocity. If we accept this conclusion, the precise choice of laboratory rest wavelengths becomes less critical. However, it demonstrates that we can reach a good precision on the orbital motion provided other spectroscopic lines agree with the observed motion. The RVs derived from the N IV $\lambda 4058$ line are listed in Appendix B.

Figure 6 compares the RVs obtained from the single-Gaussian fits with those measured from the two-Gaussian fits, adopting Gaussian 1 for the RV measurement. We restrict the comparison to the I_{loc} data set. Here again, the two RV sets essentially differ only by a single offset.

Figure 7 compares the RVs associated with Gaussian 1 and Gaussian 2 (i.e., respectively the major and the weaker). Although some dispersion is present, the separation between the two Gaussian components remains approximately constant to first order. Thus, to first order, the two Gaussians are considered necessary for a satisfactory representation of the physical line profile. However, they vary essentially in concert, and the relative motion of the star can be reliably associated with the dominant component, Gaussian 1. The same conclusion is reached when using the globally normalised data set.

Since some spectra are not included in the I_{glo} data set, we decided to adopt the RV measurements derived from the two-Gaussian fits to the I_{loc} data set, using the RVs associated with the dominant component (Gaussian 1).

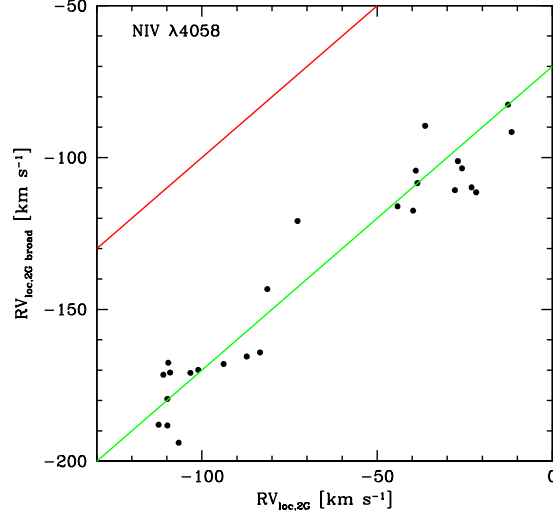


Figure 7: Comparison between the RVs associated with Gaussian 1 and those associated with Gaussian 2, the latter representing the broader component of the profile. Despite the observed dispersion, both components vary essentially together and differ primarily by a constant offset, confirming that the combination of two Gaussians provides an adequate representation of the line profile.

3.1.2. The N v $\lambda\lambda 4604$ -4619 doublet

This doublet consists primarily of the N v $\lambda 4604$ transition, which presents a P-Cygni profile, and the N v $\lambda 4619$ transition, which is observed mainly in absorption. In numerous objects, both lines present P-Cygni profiles. However, in the case of WR 25, the second line is seen essentially in absorption and with a very weak emission, if any. The two lines of the doublet are not blended with each other. To the red, a broad blend of several lines is present (see Fig. 1) and the N III $\lambda\lambda 4634$ -4641 triplet emission is rather close and induces a marked slope in the apparent continuum. The contamination is significant even in the locally normalised version of the spectra. It is therefore necessary to include a pedestal component in the fitting procedure. We only used the local version because the corresponding fit is much more stable.

The spectral region has been fitted with three Gaussians together with a pedestal. Here and throughout the following analysis, the parameters of each Gaussian (position, amplitude, and width) were allowed to vary freely and independently. For this spectral region, the RVs associated with the N v $\lambda 4604$ line were adopted, but the N v $\lambda 4619$ line was fitted simultaneously to improve the stability of the procedure. Gaussian 1 was assigned to the absorption part of the N v $\lambda 4604$ transition profile, Gaussian 2 to the emission part and Gaussian 3 to the absorption of the other line. An example of the fit is illustrated in Fig. 8. Because the slopes of the P-Cygni profile differ strongly on the blue side, on the red side, and between the absorption and emission components, Gaussians 1 and 2 strongly interact; we nevertheless consider that this remains the best way to proceed. In contrast to the case described in the previous section, several possible reference points can be adopted here. We investigated the position of the absorption component (Gaussian 1), the position of the emission component (Gaussian 2), and

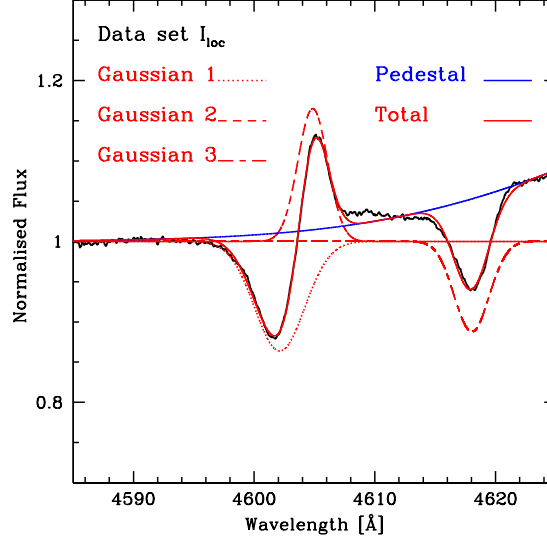


Figure 8: Determination of an RV associated with the N v $\lambda\lambda 4604\text{--}4619$ doublet for a spectrum acquired at HJD 2,454,912.516. Three Gaussian components were used to fit the spectral region: one for the absorption of the N v $\lambda 4604$ transition (Gaussian 1), one for the corresponding emission component (Gaussian 2), and one accounting for the absorption of the N v $\lambda 4619$ transition (Gaussian 3). The surrounding spectral region further required the introduction of a pedestal component (shown in blue). The position of Gaussian 2 has been adopted as the reference RV.

the wavelength corresponding to the intersection of the total fitted profile with the normalised flux level of unity. The position derived from the absorption turned out to be noisier, whereas the two other options yielded quite equivalent results, differing mainly by a constant offset. We therefore decided to report the RV value corresponding to the emission component (Gaussian 2). As before, the derived RVs are not intended to provide absolute velocity measurements. In all cases, we adopted $\lambda_0 = 4603.73 \text{ \AA}$ for the laboratory wavelength. Figure 9 compares the RVs derived from the N iv $\lambda 4058$ line with those obtained here. The two RV series are in good agreement despite a huge—and expected—difference that is essentially constant. Both lines therefore tend to trace the same relative motion.

3.1.3. The N iv $\lambda 5737$ line

The N iv $\lambda 5737$ line is quite isolated, and the continuum in its vicinity is the same in data sets I_{glo} and I_{loc} . Therefore, the measured positions of the lines in both the globally and locally normalised data sets are strongly similar and, in practice, almost identical. Although the line is comparatively isolated, a diffuse interstellar band (DIB) at $\lambda 5747.81$ is present near its red side. We therefore adopted a single-Gaussian fit for this line, as illustrated in Fig. 10. The shape of the DIB is too complex to justify the introduction of an additional fitting component, which would introduce unwanted arbitrariness in the process. The adopted laboratory wavelength for this line is $\lambda_0 = 5736.93 \text{ \AA}$. The Gaussian profile provides a good representation of the observed

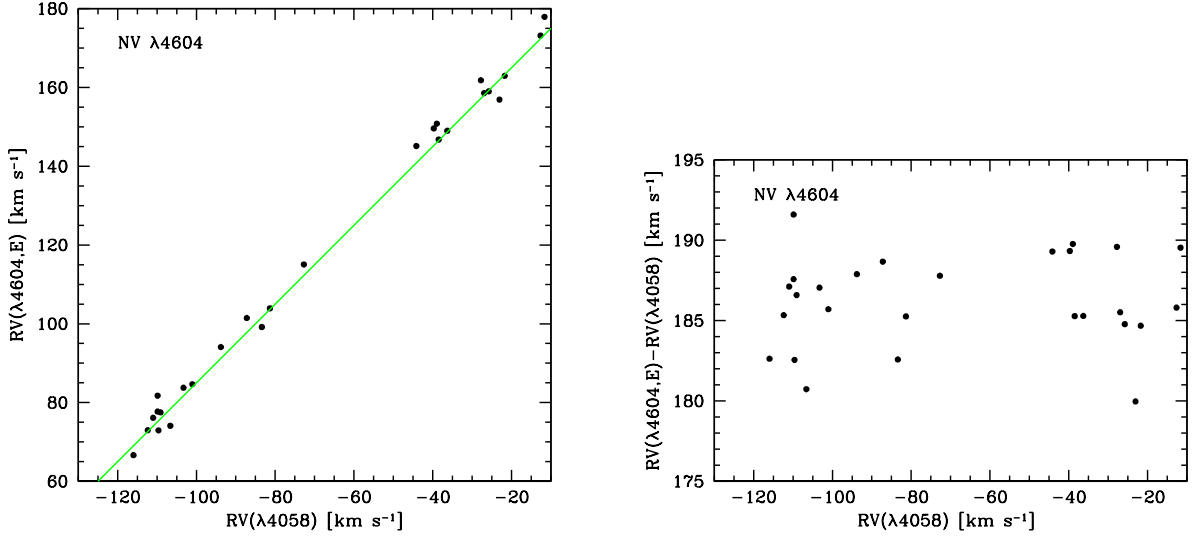


Figure 9: (*Left*) Comparison between the RVs associated with Gaussian 2 in Fig. 8 and those derived from the N IV $\lambda 4058$ line. The one-to-one correlation line lies outside the plotted range. The green line is an arbitrary line parallel to it. The large—but essentially constant—difference between the RVs of the two data sets is not unexpected owing to the particular choice of the profile component adopted as the RV reference. (*Right*) Same comparison shown in terms of RV differences.

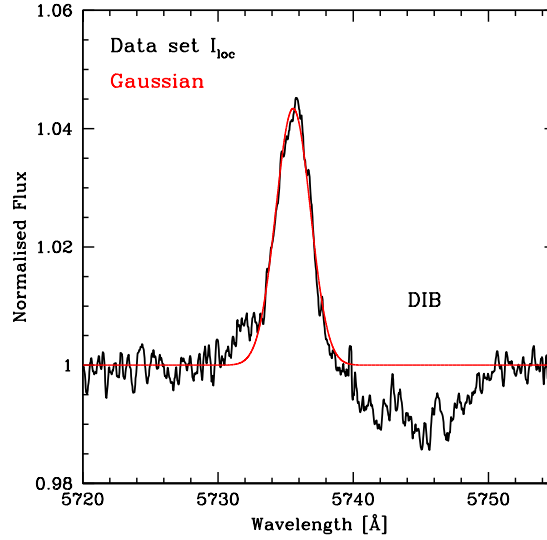


Figure 10: Example of the RV determination based on the fit of the N IV $\lambda 5737$ line. The spectrum shown here was acquired at HJD 2,453,864.483.

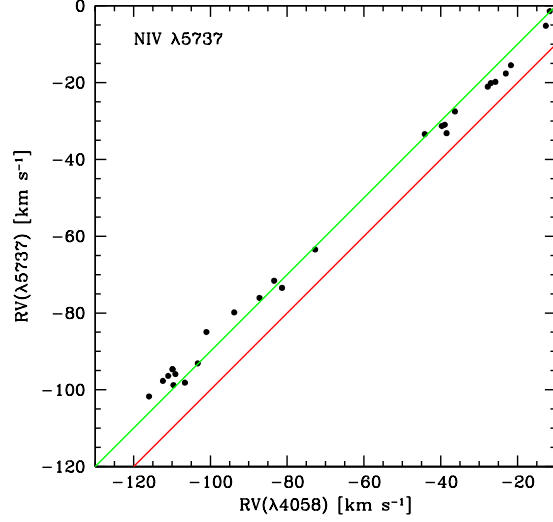


Figure 11: Comparison between the RVs derived from the N IV $\lambda 5737$ and N IV $\lambda 4058$ lines. The red line represents the one-to-one correlation, whereas the green line is drawn parallel to it.

line shape. A comparison between the RVs derived from this transition and those obtained from N IV $\lambda 4058$ is presented in Fig. 11. Once again, the two RV series differ primarily by a constant offset, while exhibiting very similar slopes. An extremely slight difference may still be present, but it remains below the level of dispersion of the measurements. Here, the offset is very small, since both compared lines are defined through the position of their main emission peak. The N IV $\lambda 5737$ line is therefore a good indicator of the relative orbital motion. It also originates from a highly ionised species.

3.1.4. The N V $\lambda 4945$ line

The N V $\lambda 4945$ feature appears as a single emission line, composed of several blended triplets in a complex spectral region. It is relatively faint, reaching only slightly more than 2% above the continuum level. In general, we fitted it with a single Gaussian profile, as illustrated in Fig. 12. Despite the complexity of the surrounding spectral environment, the deduced RVs appear to be useful. We adopted a laboratory wavelength of $\lambda_0 = 4944.56 \text{ \AA}$. Figure 13 compares the RVs derived from N V $\lambda 4945$ with those obtained from N IV $\lambda 4058$. The green line drawn parallel to the red one-to-one relation, indicates that the two RV series merely differ by a constant offset. This spectral line may therefore also be regarded as an interesting tracer of the orbital motion.

3.1.5. The N IV $\lambda \lambda 6212\text{--}6215\text{--}6220$ triplet

A blend of three lines is present in this spectral region. The dominant component of this triplet in WR 25 is the feature located near $6220 \text{ \AA}$ (see Fig. 14). A DIB is also present in the blue wing of the blend. To determine an RV for this group of lines, we decided to use the dominant component, for which a laboratory wavelength of $\lambda_0 = 6219.89 \text{ \AA}$ was adopted. To obtain the position of this line, the full region was fitted using three Gaussian components (Gaussians 1–3);

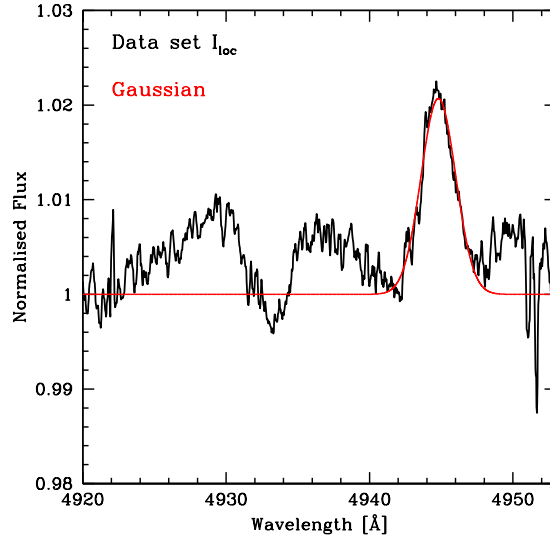


Figure 12: Same as Fig. 10, but for the N v $\lambda 4945$ line. The spectrum was acquired at HJD 2,453,897.469.

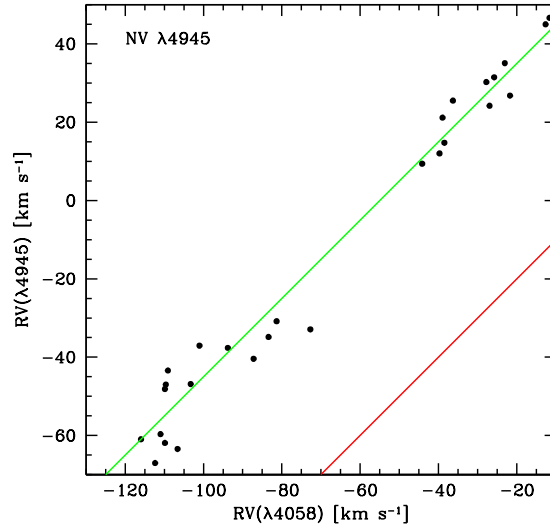


Figure 13: Same as Fig. 11, but for the N v $\lambda 4945$ line.

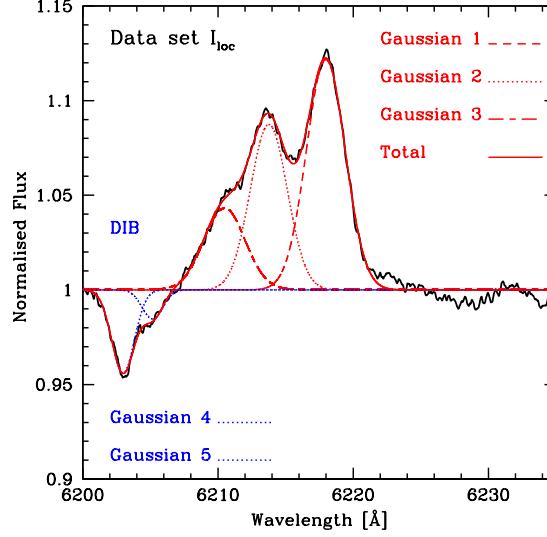


Figure 14: Illustration of the RV determination based on the N IV $\lambda\lambda 6212$ - 6215 - 6220 triplet. The three Gaussian components fitted to the emission lines are shown in red and the two Gaussians that account for the neighbouring DIB feature are shown in blue. This spectrum was acquired at HJD 2,454,918.588. Gaussian 1 was adopted as the RV reference.

the DIB could be adequately represented by two additional Gaussian components (Gaussians 4 and 5). These five Gaussians were fitted simultaneously, without imposing constraints on any of their parameters, including those associated with the DIBs. The position of Gaussian 1 was adopted as the RV reference for this multiplet. The RV variations derived from the N IV $\lambda 6220$ feature and the N IV $\lambda 4058$ line can, to first order, be represented by a straight line relation, although the results in this case are somewhat noisier. As in the previous figures, this behaviour is represented in Fig. 15 by the green line drawn strictly parallel to the red one-to-one relation. The residual deviations may either correspond to higher-order effects that could possibly be ignored, or simply reflect noise. This spectral feature can also be considered as a useful tracer of the orbital motion.

3.1.6. The N IV multiplet around 7100–7120 Å

The emission multiplet in this spectral region is rather complex, although it presents neither absorption components nor strong neighbouring DIBs (see Fig. 16). It appears as the blend of four apparent emission lines, the reddest one being visible only as a small bump in the red wing of the dominant component. This weak line is essentially associated with the transition at 7127.25 Å whereas the dominant one corresponds to the transition at 7122.98 Å. On the far blue side, the transition at 7103.24 Å is present. The second-strongest line arises from two fully blended transitions at 7109.35 and 7111.28 Å. This blended feature was selected as the reference line for precise RV measurements. We adopted a laboratory wavelength of $\lambda_0 = 7109.99$ Å for this unresolved pair and refer to the feature hereafter as the 7110 line. The dominant line was deliberately avoided because it seems to be affected by very weak, most likely telluric, absorption

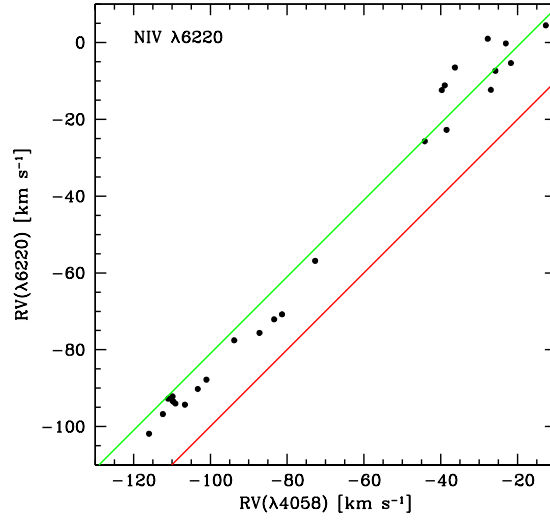


Figure 15: Same as Fig. 11, but for Gaussian 1 from Fig. 14.

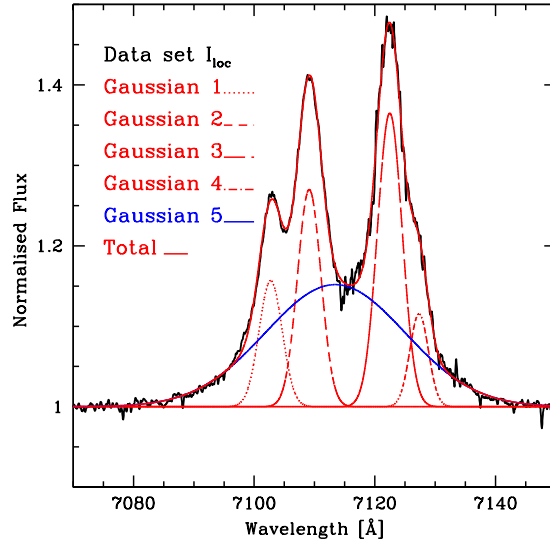


Figure 16: Illustration of the RV determination based on the N IV transitions in the 7100–7120 Å spectral region. Fitting this purely emission-line blend requires five Gaussian components: four narrow Gaussians (shown in red) together with one broader (in blue). This spectrum was acquired at HJD 2,453,837.576. The Gaussian 2 was adopted as the RV reference.

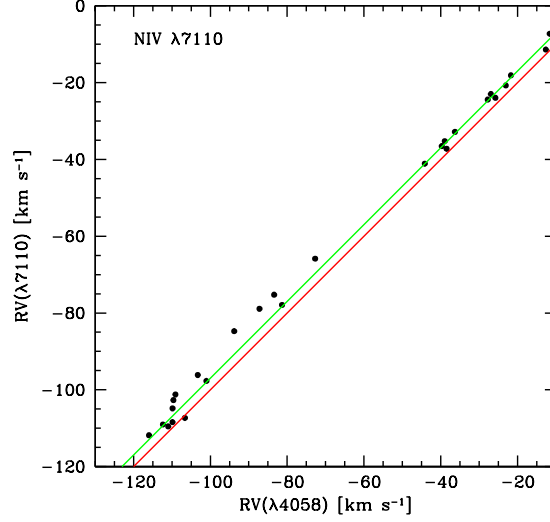


Figure 17: Same as Fig. 11, but for Gaussian 2 from Fig. 16.

lines. Moreover, at certain orbital phases, it exhibits a very strange behaviour characterised by additional absorption components. By contrast, this effect does not appear to affect the selected 7110 line, which is therefore better suited for the RV measurements. Additional wings are visible on both sides of the full blend, requiring the inclusion of a broad Gaussian to the fit. In addition to this broad Gaussian, four narrower Gaussians were used to reproduce the complete profile. For each epoch, the RV associated with Gaussian 2 was adopted as the reference value.

Figure 17 compares the RVs derived from this feature with those obtained from the N IV $\lambda 4058$ line. The agreement is very good, despite a small systematic offset. This line thus constitutes an excellent tracer of the orbital motion.

3.1.7. The N III $\lambda 4905$ line

A weak emission line is present near 4905 Å and we will refer to it accordingly. Inspection of the NIST Atomic Spectra Database (<https://www.list.gov/pml/atomic-spectra-database>) suggests the existence of a line at $\lambda_0 = 4904.78$ Å, part of a triplet whose two bluer components are not detected. The spectral region is shown in Fig. 18, where it appears that the feature can be well fitted by a single Gaussian profile. The continuum on the blue side of the line is somewhat depressed in flux, which may complicate the placement of the continuum. This depression probably results from the presence of some DIBs and the onset of the flux rise due to the far red wing of He II $\lambda 4859 + \text{H}\beta$. We performed RV measurements for all individual spectra of the I_{loc} data set. More recently, we noted that the University of Kentucky Atomic Line List database (van Hoof, 2018, <https://linelist.pa.uky.edu>), lists an N III triplet at 4907.04, 4907.30, and 4907.30 Å. This blend may therefore also contribute, partially or even predominantly, to the observed feature. This would not pose a problem a priori, provided that both contributors do present the same relative variations, since our work focuses on relative motions. Figure 19 compares the RVs derived from this feature with those obtained from the N IV $\lambda 4058$ line. In addition to a global offset, which could be partly due to the N III triplet just mentioned, the line clearly shows a significant dependency of the RV shift on the measured RV itself. This

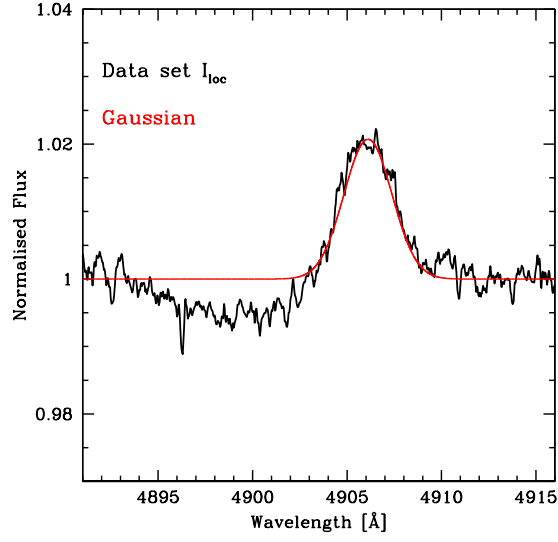


Figure 18: Same as Fig. 10, but for the N III $\lambda 4905$ line. The spectrum was acquired at HJD 2,453,897.469.

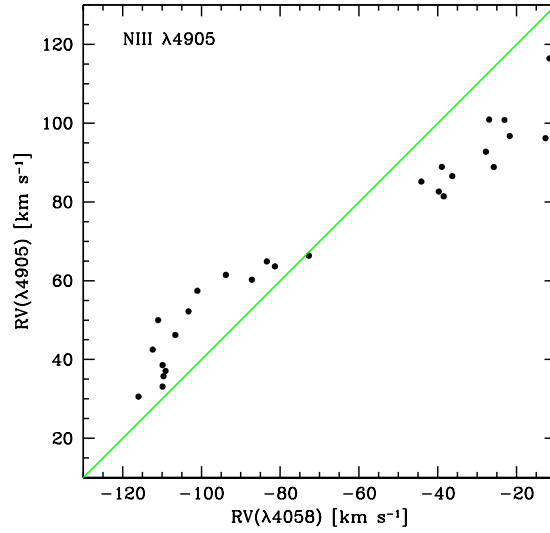


Figure 19: Comparison between the RVs determined from the N III $\lambda 4905$ feature and those obtained from the N IV $\lambda 4058$ line. The two sets of RVs are clearly inconsistent.

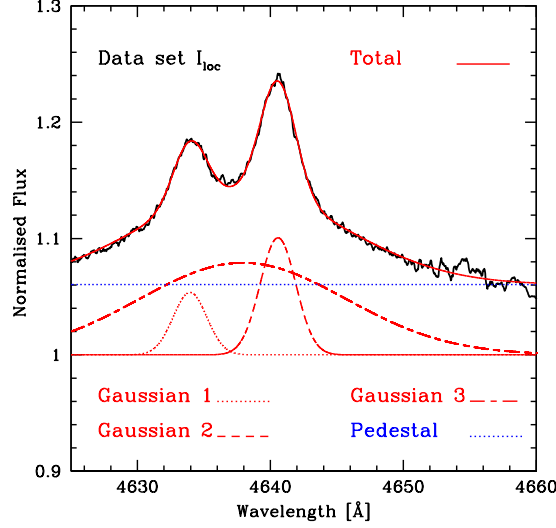


Figure 20: RV measurements based on the well-known N III $\lambda\lambda 4634$ - 4641 triplet. The spectrum was acquired at HJD 2,453,918.499. Reproducing the full profile of the spectral region requires three Gaussians: two narrow and one broad. The measurement shown here yields essentially the same results when using the globally normalised data set instead of the locally normalised one.

behaviour may be linked to the continuum depression mentioned above, although no definitive interpretation is currently available. In any case, this feature does not provide reliable RVs and does most probably not trace the orbital motion of the WR component. We therefore excluded it from further orbital analysis.

3.1.8. The N III $\lambda\lambda 4634$ - 4641 triplet

This N III triplet transition is well known to be present in the spectra of certain O stars displaying the “f” classification suffix, as well as in WN stars, where it is usually strong. The observed profile consists of the two main emission peaks: one corresponding to the transition at $4634.12 \text{ \AA}$, and the other to the transition at $4640.64 \text{ \AA}$ blended with the weaker line at $4641.85 \text{ \AA}$. Figure 20 illustrates this spectral region. The usual lines are clearly visible. We fitted the profile using two narrow Gaussians corresponding to the two apparent emission peaks. It was immediately clear that an additional broad Gaussian was required to represent the excess emission in the surrounding region. We thus fitted three Gaussians simultaneously. We considered the position of Gaussian 2 to provide the best representative reference point and therefore adopted it for the RV measurements, using the arbitrarily chosen laboratory wavelength $\lambda_0 = 4640.64 \text{ \AA}$. The resulting RVs are compared in Fig. 21 with those derived from the N IV $\lambda 4058$ line. The total disagreement between the two RV sets is evident, with differences occasionally reaching 30 km s^{-1} , well above the typical random dispersion (noise), which is estimated to be lower than 10 km s^{-1} . This transition should therefore not be used to trace the orbital motion of the WN star. The line being bright, the observed discrepancy clearly reflects a systematic effect. A straightforward explanation for this phenomenon is given in Sect. 6.3.

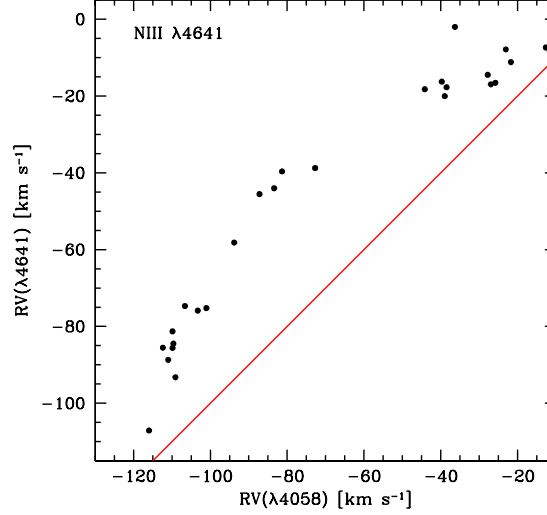


Figure 21: Comparison between the RVs derived from Gaussian 2 in Fig. 20 and those obtained from the N IV $\lambda 4058$ transition. The two RV sets are clearly inconsistent, with particularly large discrepancies.

3.1.9. The Si IV $\lambda\lambda 4089$ -4116 lines

The silicon doublet is a well-known feature in the spectra of late WN stars. The two lines correspond to transitions located at 4088.862 Å and 4116.103 Å. They are well separated and should, in principle, be of interest for RV measurements. However, the spectral region is affected by other lines, notably He II $\lambda 4100$ +H δ and the N III $\lambda\lambda 4097$ -4103 doublet. Figure 22 offers a view of this spectral region. In the adopted fit, Gaussian 1 and Gaussian 3 correspond to the silicon lines, whereas the broad Gaussian 4 represents the Balmer-line emission. Gaussian 2 accounts for an absorption component of the transition. The nitrogen lines are not visible in the figure because they are much weaker. The RV measurement for Si IV $\lambda 4089$ can be performed using four Gaussians. Additional Gaussians are occasionally required for RV measurements of the Si IV $\lambda 4116$ line, depending on orbital phase. This complexity is partly due to the interaction between the structure of the He II $\lambda 4100$ +H δ line and the nitrogen lines, which affect the broad component. Furthermore, at very particular phases, the red wing of the Balmer profile becomes more complex, as will be detailed in Sect. 6.1. Figure 23 compares the RVs derived from the Si IV $\lambda 4089$ with those obtained from N IV $\lambda 4058$. Apart from a small offset, the two lines clearly exhibit the same behaviour. We therefore consider Si IV $\lambda 4089$ to be a reliable tracer of the orbital motion and we will retain it as a basic indicator. In contrast, the Si IV $\lambda 4116$ measurements are much more corrupted, most likely because the fitting procedure requires a larger number of Gaussians. The corresponding RV comparison is shown in Fig. 24. We decided to exclude this line from the list of reliable orbital tracers.

3.1.10. The N III $\lambda\lambda 4511$ -4515 multiplet

The two dominant emission lines of this N III multiplet are clearly present in our WR 25 spectra. They are actually part of a broader blend composed of the two dominant lines together with extended surrounding wings. The feature typically reaches a peak intensity of about 4%

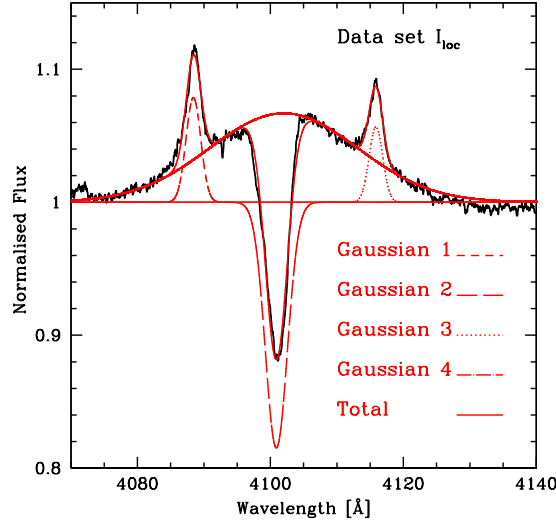


Figure 22: Illustration of the RV measurement of the Si IV $\lambda 4089$ line and of the surrounding blend consisting of the Si IV $\lambda 4116$ line and the He II $\lambda 4100 + \text{H}\delta$ feature. Four Gaussians are required to reach a good total fit: Gaussians 1 and 3 (relatively narrow) reproduce the two silicon emission lines, Gaussian 2 represents a slightly broader absorption for the He II $\lambda 4100 + \text{H}\delta$ transitions and Gaussian 4 accounts for its much broader emission component. Fitting the full spectral region yields a very robust RV determination for the Si IV $\lambda 4089$ line. The situation is more complicated for the Si IV $\lambda 4116$ line (see text). The spectrum shown here was acquired at HJD 2,453,833.528.

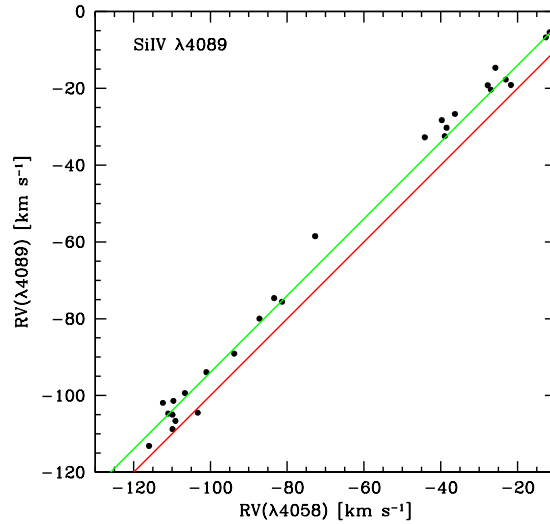


Figure 23: Comparison between the RVs derived from Gaussian 1 in Fig. 22 and those obtained from the N IV $\lambda 4058$ transition. The two RV sets are nicely consistent, differing only by a small constant offset.

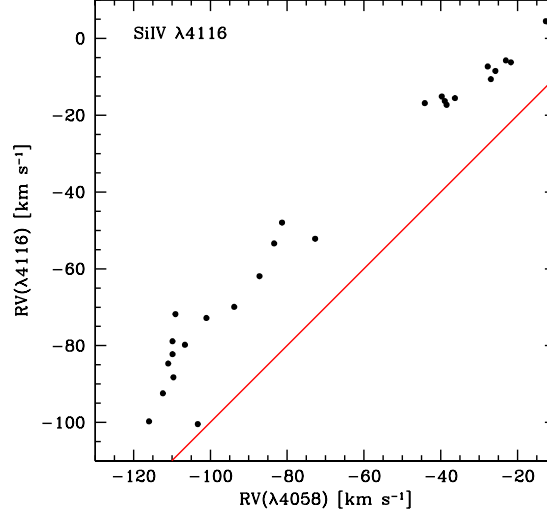


Figure 24: Comparison between the RVs derived from Gaussian 3 (Si IV $\lambda 4116$) in Fig. 22 and those obtained from the N IV $\lambda 4058$ transition. The measurement of this line may require additional Gaussians (see text). The two RV sets are not fully consistent in this case.

above the continuum level. We attempted to derive RV measurements from these lines; however, the blue wing is affected by a strong nearby DIB. As a result, our efforts to obtain reliable RVs from these transitions were unsuccessful. Direct measurements (by cursor) of the line positions yield RVs that vary similarly to those derived from the N IV $\lambda 4058$ line, although the data are dispersed around this trend, as expected. Consequently, these RVs cannot be used to improve our knowledge of the orbital motion. However, the blend moves in phase with the N IV line and must therefore be associated with the WN star, which is not unexpected.

3.1.11. The N III $\lambda 4379$ line

This emission line is actually a tight triplet and reaches an intensity of approximately 3.5% above the continuum. The profile was fitted either with a single Gaussian or with the combination of one narrow and one broad Gaussian. This non-uniform fitting procedure inevitably introduces additional dispersion into the RV measurements. The resulting RVs were compared with those obtained from the N IV $\lambda 5737$ line. Despite some scatter, the N III $\lambda 4379$ feature clearly follows the motion of the WN star and can be securely attributed to it. However, the observed level of dispersion indicates that this line is not sufficiently reliable to serve as an efficient tracer of the orbital motion.

3.1.12. The N III $\lambda 4321$ line

An emission line is detected in the blue wing of the He II $\lambda 4339 + \text{H}\gamma$ line. The corresponding fit was performed using a single Gaussian, together with a second Gaussian accounting for the proximity of the broad feature. (The spectral region is illustrated in the He II $\lambda 4339 + \text{H}\gamma$ panel of Fig. 31—see Sect. 6.1.) The RVs derived from this fit exhibit clear changes reminiscent of the orbital motion of the WN star. This line must therefore be associated with the WN star. We

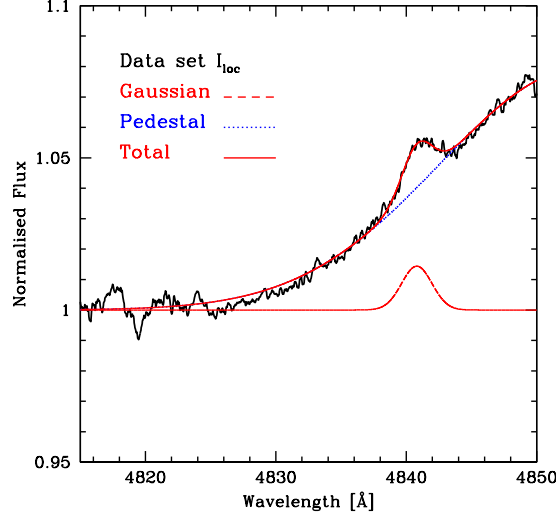


Figure 25: Example of the fit applied to the unidentified line on the blue side of $H\beta$ (near 4841 Å). A single Gaussian is sufficient to reproduce the line profile but a pedestal is necessary to account for the influence of the neighbouring $\text{He II } \lambda 4859 + H\beta$ feature. The spectrum shown here was obtained at HJD 2,454,918.588.

tentatively identify it with the $\text{N III } \lambda 4321$ transition and label it accordingly. This identification should nevertheless be treated with caution (see Appendix E). Because of the substantial scatter in the RV distribution, we do not consider this line to provide a sufficiently reliable tracer of the orbital motion, despite its clear association with the WN star.

3.1.13. Two unknown lines on both sides of $H\beta$

Two weak emission features are present on either side of the $\text{He II } \lambda 4859 + H\beta$ line. To the best of our knowledge, these lines have not previously been reported in the spectrum of a WR star. The one on the blue side is located near 4841 Å and reaches approximately 1.5% above the continuum, whereas that on the red side is situated near 4883 Å and reaches only about 1% above the continuum. We measured the relative RVs for both lines, as the laboratory wavelengths are unknown. Figure 25 illustrates the Gaussian fit to the line near 4841 Å which requires a pedestal to mitigate the influence of the neighbouring $\text{He II } \lambda 4859 + H\beta$ line. These unidentified lines approximately follow the RV variations of the WN object. It is tempting to propose the following N III transitions as identifications for these lines (see the University of Kentucky Atomic Line List database (van Hoof, 2018), accessible at <https://linelist.pa.uky.edu>):

$$1s^2 2s 2p (^3P^o) 4f ^4D_{5/2} - 1s^2 2s 2p (^3P^o) 5d ^4D_{3/2}^o \quad \text{at } 4841.87 \text{ Å},$$

and

$$1s^2 2s 2p (^3P^o) 3p ^4D_{5/2} - 1s^2 2s 2p (^3P^o) 3d ^4F_{3/2}^o \quad \text{at } 4881.78 \text{ Å},$$

$$1s^2 2s 2p (^3P^o) 3p ^4D_{7/2} - 1s^2 2s 2p (^3P^o) 3d ^4F_{7/2}^o \quad \text{at } 4884.14 \text{ Å}.$$

The latter feature may additionally be affected by the presence of a DIB at 4880.1 Å. These identifications remain highly tentative and require further confirmation. In particular, other

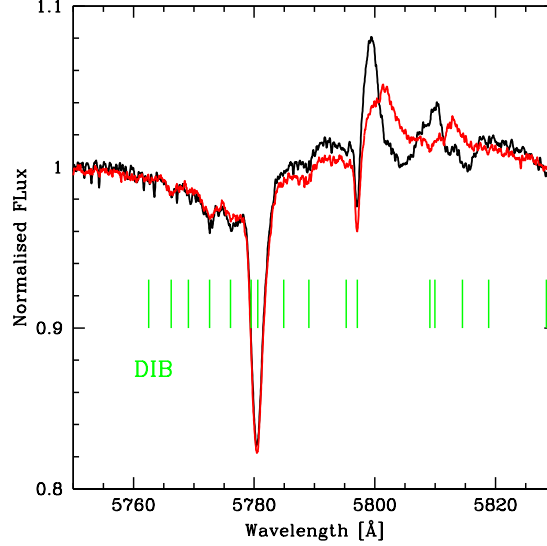


Figure 26: Spectral region around the C IV $\lambda\lambda 5801$ - 5812 doublet for two spectra acquired at HJD 2,453,800.671 (red) and HJD 2,454,916.541 (black). At the epoch corresponding to the black spectrum, the WN star was shifted towards the blue, whereas at the epoch of the red spectrum, it was shifted to the red. The carbon lines thus follow the motion of the WN star. However, the large number of DIBs present in this spectral region prevents these features from being used as reliable tracers of the WN orbital motion.

transitions in multiplets that these lines also belong to are not detected, which may argue against the proposed identifications. It is nevertheless noteworthy that these features are also observed in weak emission in the spectra of WR 24 and WR 78 (see also Sect. 6.2).

3.1.14. Carbon lines

The C IV $\lambda\lambda 5801$ - 5812 doublet, although rather faint, is clearly present in the spectrum of WR 25, as can be seen in Fig. 26, where the region is shown at two different epochs. At the epoch corresponding to the spectrum plotted in red, the WN star has a relative shift to the red (according to the behaviour of the N IV $\lambda 4058$ line as described in Sect. 3.1.1). The C IV lines therefore clearly belong to the WN star. Unfortunately, they are rather faint and the spectral region moreover contains a plethora of DIBs, preventing any reliable RV measurements without the use of a special dedicated analysis method, which would inevitably introduce additional uncertainties. We therefore chose not to include this doublet in our selected set of RV tracers.

The C III $\lambda 5696$ line is also detectable, although it is very faint, and it is hard to associate it with either component of the binary system. This line will be addressed further in Appendix E.

3.2. The other data sets (II, III and IV)

An analysis similar to that described in Sect. 3.1 was also carried out for the remaining data sets. We will not describe them here in detail. The spectrum from data set II was reduced only

using the local normalisation procedure and is slightly noisier than the spectra from data set I. For data set III, all the lines were carefully remeasured using the local normalisation approach, as no simultaneously observed O-type star was available as reference for the continuum determination. We also measured the positions of the N IV $\lambda 4058$ line in the spectra from data set IV, since this line is crucial for the determination of the orbital period (values are provided in Appendix B). An extended version of Fig. 7, including data sets II and III, is likewise presented in Appendix B.

3.3. The radial velocities

We finally selected seven lines that are expected to follow the orbital motion of the WN star with the best accuracy. These lines are N IV $\lambda 4058$, N V $\lambda 4604$, N IV $\lambda 5737$, N V $\lambda 4945$, N IV $\lambda 6220$, N IV $\lambda 7110$, and Si IV $\lambda 4089$. It should be emphasised that we do not have absolute positions for these lines, as different features were measured using Gaussians fitted to profiles that were not necessarily symmetric. Moreover, this lack of absolute value makes the measurements effectively independent of the adopted zero velocity (laboratory) wavelength. We therefore focus exclusively on the relative motion. To improve the precision of the RV determinations, we computed the mean RV from these seven transitions after subtracting the individual zero-point offsets. The resulting modified RVs constitute what we refer to hereafter as the “gold sample”. The absolute velocities measured on the dominant Gaussian fitted to the N IV $\lambda 4058$ line together with the gold sample RVs derived from the seven selected spectroscopic lines are listed in Appendices B and C, respectively.

4. Period Reassessment

The first and only determination of the orbital period of the WR 25 system dates back to the discovery paper of Gamen et al. (2006), who reported a period of 207.85 ± 0.02 d. The new data presented here are of higher precision; it is therefore natural to attempt a refinement of this value. Although the precision of the RV measurements is important, the time span covered by them is even more so. Data sets I to IV cover the interval from HJD 2,452,037 to HJD 2,454,921, and comprise 27 measurements from data set I, one from data set II, 15 from data set III and 12 from data set IV. We considered it useful to extend this combined data set with the N IV $\lambda 4058$ RV measurements reported by Gamen et al. (2006). We therefore complemented our combined data set (I+II+III+IV) with RVs from the high-resolution spectra (i.e., labelled HRS) published by Gamen et al. (2006), from which we removed the FEROS data already included in data set III. The latter are already part of the combined data set and were thus remeasured in the present work (see Sect. 2.3). The RVs from spectra not included in data set III were not remeasured, but directly taken from Table 2 of Gamen et al. (2006). These additional data are thus made up of previously determined RVs and could therefore belong to a slightly different reference system. The first such observation dates back to HJD 2,450,505; the additional data set adds 35 measurements. Although these data are of lower quality and were measured using a different method, they extend the observed interval, increase the number of measurements by 35, and could thus improve upon the previous result. We redetermined the period on the basis of this complete data set, which contains 90 measurements distributed over a time span of about

Table 1: Values of the frequencies ν corresponding to the largest peak in the periodogram as a function of the number of harmonics included in the considered method. The corresponding periods P are also given. The last line corresponds to a harmonic content identical to that of a Keplerian motion.

Periodogram	ν [d ⁻¹]	P [d]
ν	0.47697×10^{-2}	209.660
$\nu + 2\nu$	0.48159×10^{-2}	207.646
$\nu + 2\nu + 3\nu$	0.48205×10^{-2}	207.447
$\nu + 2\nu + 3\nu + 4\nu$	0.48162×10^{-2}	207.633
Keplerian	0.48161×10^{-2}	207.638

4416 d. We first analysed the time-series with a Fourier-type technique; the peaks in the Power Spectrum have a typical width of $\delta\nu = 2.3 \times 10^{-4} \text{ d}^{-1}$. We used the Heck–Manfroid–Mersch (HMM) method, which is particularly suited for the Fourier analysis of unevenly sampled data (Heck et al., 1985; Gosset et al., 2001). There is one peak standing out in the periodogram; the corresponding frequency ν is given in Table 1 together with the associated period.

This value definitively confirms the existence of the period previously reported by Gamen et al. (2006). Since the RV curve of WR 25 is known to be eccentric, the position of the peak could be slightly inaccurate due to an interaction between the exact shape of the curve and the actual temporal distribution of the data points. Therefore, we need to estimate the period with a method that is less sensitive to the shape of the curve. The inclusion of harmonics allows us to reduce the dependence on the shape (and thus on the true harmonic content) of the curve. We used the formalism of the multifrequency extension of the HMM method, as introduced in the appendix of Gosset et al. (2001, equations (A13)–(A19)) to construct a super-periodogram. This super-periodogram gathers within each peak the power of the trial fundamental frequency as well as that of the related harmonics. The positions of the main peak in the periodogram as a function of the number of harmonics are reported in Table 1. Increasing in the number of included harmonics leads to a form of convergence of the derived period value. We also used a version of the periodogram based on the harmonic content of a Keplerian orbit, similarly to Gosset et al. (2025). We finally adopted the value $P = 207.638 \text{ d}$. The determination of the uncertainty on the period is not an easy task. We can obtain a very conservative upper limit by adopting a value equal to one-tenth of the natural width of the peaks; this corresponds to $\sigma_\nu = 2.3 \times 10^{-5} \text{ d}^{-1}$, which in turn corresponds to $\sigma_P = 0.97 \text{ d}$. We could also use the analytical formula of Lucy and Sweeney (1971). In this case, we obtain $\sigma_\nu = 1.3 \times 10^{-6} \text{ d}^{-1}$, i.e. $\sigma_P = 0.06 \text{ d}$. This analytical value is often considered to be slightly underestimated. If we consider the three values of the period for the super-Fourier with two, three and four harmonics, their convergence suggests an uncertainty of $\sigma_P = 0.11 \text{ d}$. The correct value should be somewhere between 0.06 and 0.11. It is interesting to note that the value associated with the inspection of the objective function for the Keplerian fit gives an uncertainty of $\sigma_P = 0.093 \text{ d}$, which is the value we finally adopt.

Table 2: Orbital elements derived from the fit of a Keplerian model to the two selected data sets of the present work, compared with the previous results reported in Gamen et al. (2006).

Parameter	Value (Gamen et al.)	Value (N IV $\lambda 4058$)	Value (“gold sample”)
P [d]	207.85 (0.02)	207.638 (0.093)	207.638 (fixed)
e	0.50 (0.02)	0.570 (0.011)	0.595 (0.013)
ω_{WN} [degree]	215 (3)	214.05 (2.21)	212.04 (1.59)
T_0 (2,400,000+)	51598.0 (1.0)	51184.33 (5.06/0.59)	51184.08 (0.46)
K_{WN} [km s $^{-1}$]	44.0 (2.0)	52.83 (0.82)	53.18 (0.82)
γ_{WN} [km s $^{-1}$]	−34.6 (0.5)	−34.63 (0.59)	0.00 (0.60)
$\rho(\omega_{\text{WN}}, T_0)$	—	0.7	0.8
σ_{fit} [km s $^{-1}$]	4.7	4.86	3.39
N	124	90	43
$f(M)$ [$M_{\odot}$]	1.2 (0.2)	1.765 (0.097)	1.687 (0.098)
ϕ (lower conj.)	—	0.039	0.038
ϕ (upper conj.)	—	0.843	0.859
ϕ (min. RV)	—	0.978	0.981

Notes: the listed parameters are the period P , the eccentricity e , the argument of periastron ω_{WN} associated with the WN star, the time of passage at periastron T_0 , the semi-amplitude K_{WN} , and the apparent systemic velocity γ_{WN} . Additional information is also provided, such as the correlation coefficient ρ between ω_{WN} and T_0 , the σ of the fit, the number of data points in the analysed time-series, the mass function $f(M)$, as well as the phases ϕ of the two conjunctions and of the minimum RV for the WN (i.e., phase of maximum RV separation). The figures in parentheses give the 1σ uncertainties on the parameters as estimated from the fit. For T_0 , two values are presented in the third column: one corresponding to the fit with the period being adjusted and the other for the period kept fixed.

Since the shape of the RV curve could be problematic, we also applied the method of Renson (1978), which is expected to be more robust with respect to the exact shape, although it makes locating the extremum of the statistic more difficult. The value obtained with the Renson method is about 207.6 d, which provides further support for our Fourier analysis. As an additional check, we also performed a detailed analysis of the I+II+III+IV data sets ($N = 55$) which yielded results in good agreement with the value obtained from the $N = 90$ data set. We therefore finally adopted the value $P = 207.638$ d with $\sigma = 0.093$ d.

5. The New SB1 Solution for the WN Star

5.1. The SB1 model

The period having been determined, we can now perform a fit of the Keplerian motion of the WN star in the SB1 mode. First, we performed the fit on the basis of the general data set of 90 RVs associated with the N IV $\lambda 4058$ line. The results of this first fit are given in Table 2. For this data set, the period is not fixed but is naturally identical to the adopted value, since we selected the period obtained from the Keplerian model. Compared to the preliminary solution of Gamen

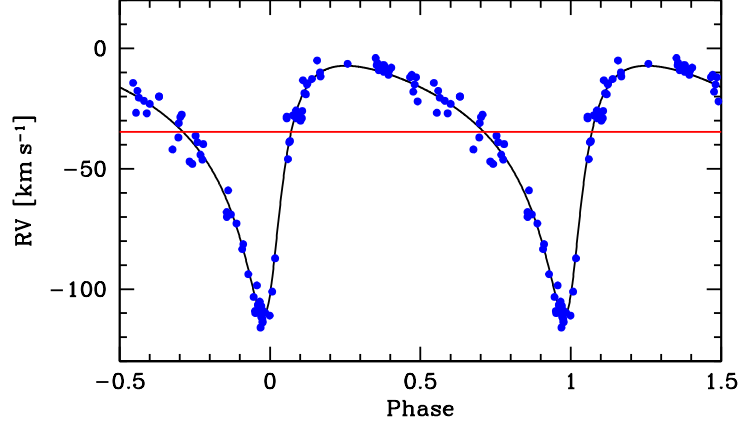


Figure 27: RV curve of WR 25. The blue points represent the 90 individual RVs associated with the position of Gaussian 1 fitted to the N IV $\lambda 4058$ line. The phase was computed on the basis of the orbital elements given in the third column of Table 2. The solid black curve corresponds to the fitted Keplerian solution derived from these elements; the red line represents the apparent systemic velocity associated with the spectroscopic line considered.

et al. (2006), the eccentricity is slightly but significantly larger. The corresponding solution is compared with the RV data in Fig. 27. The data points are rather well distributed in phase, and the new data provided in the present work strongly alleviate, and indeed solve, the uncertainty problem around the minimum previously reported by Gamen et al. (2006). The typical dispersion of the residuals can be characterised by $\sigma_{\text{fit}} = 4.86 \text{ km s}^{-1}$, which is quite satisfactory for a WN star. As a final check, we renormalised the individual residuals corresponding to each data point by σ_{fit} and plotted the histogram of these normalised residuals in Fig. 28. We compared them with the Gaussian probability density function (PDF) expected for Gaussian behaviour (with $\sigma = 1$). The histogram is consistent with the expected Gaussian distribution, and we therefore detect no significant anomaly.

Secondly, we analysed the gold data set of 43 RVs obtained from the combination of the seven lines exhibiting a well-defined and coherent behaviour. For this fit, we fixed the period to the adopted value. The resulting fitted parameters are given in Table 2, and the fit is illustrated in Fig. 29. As expected, this fit produces smaller residuals. Both fits reported in Table 2 provide orbital parameters that are fully compatible with each other. Each value lies well within three times the uncertainty associated with the corresponding parameter in the other solution. Due to the general compatibility of the two solutions, we decided to adopt the second one as the preferred solution. The systemic velocity is here equal to zero by construction of the gold data set. However, the zero value reported was not fixed during the fit, which allows us to estimate the associated uncertainty. It should be noted that the time of periastron passage (T_0) has a smaller uncertainty in this second fit because the period was fixed and because the period and T_0 parameters are correlated. The second uncertainty on T_0 in the third column refers to the uncertainty expected when the period is fixed. The ephemerides adopted here were used to determine the phases of the individual observations; these phases are reported in Appendix A.

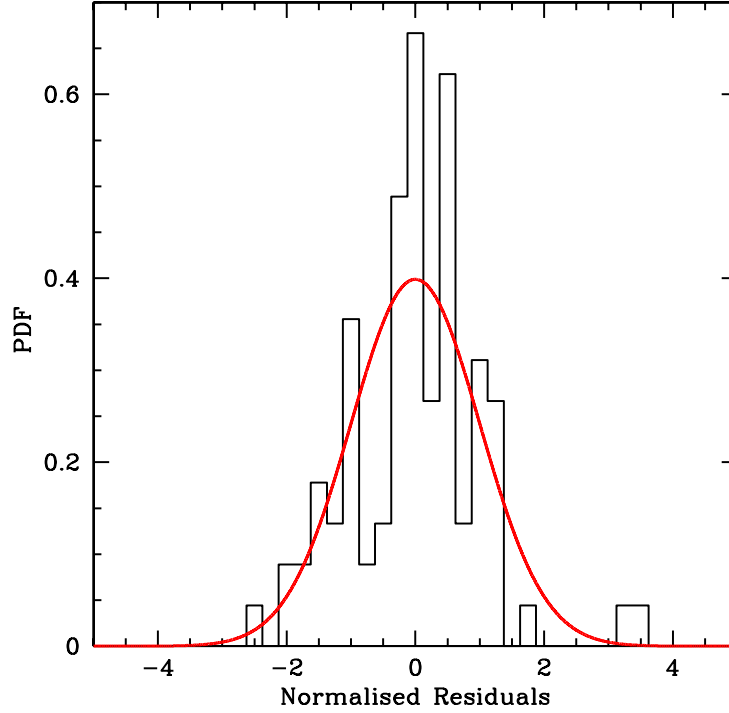


Figure 28: Histogram of the residuals of the fit shown in Fig. 27. The residuals have been normalised by the $\sigma_{\text{fit}} = 4.86 \text{ km s}^{-1}$. The histogram counts have been normalised so that they can be directly compared with the expected probability density function (PDF), assumed here to be a Gaussian.

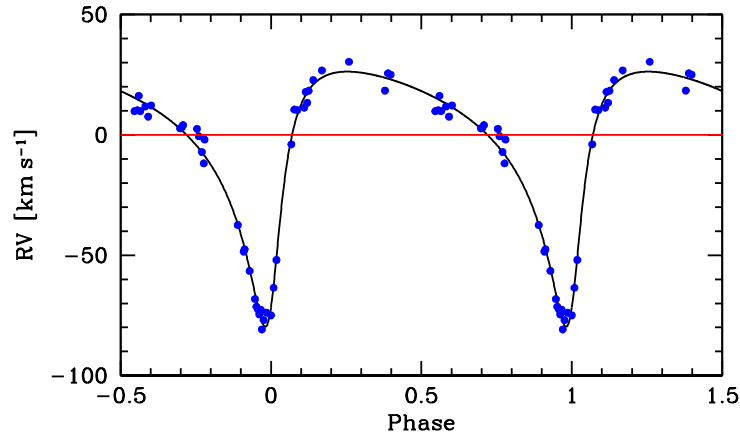


Figure 29: Final RV curve of WR 25. The blue points represent the 43 individual RVs obtained from the combination of the seven lines that best trace the orbital motion (“gold sample”). The phase is computed using the final elements given in the fourth column of Table 2. The solid black curve corresponds to the fitted Keplerian solution derived from these elements. The red line represents the artificial systemic velocity, which is zero by construction.

For a better understanding of the following discussion, we also report in Table 2 the SB1 mass function, as well as the phases corresponding to the lower conjunction (the WN star being closer than the centre of mass) and upper conjunction (the WN star being behind the centre of mass).

5.2. Soft X-ray eclipse and validation

In the absence of confirmed photometric variations, it is difficult to validate the spectroscopic orbital solution, despite the early claim by Gosset et al. (1994) of a possible period longer than 200 d. In contrast, the X-ray domain may provide additional support. WR 25 was first recognised as variable in the X-ray domain by Pollock and Corcoran (2006), although this preceded the report of the discovery of the periodic spectral variations (Gamen et al., 2006). This latter work provided confirmation and triggered subsequent X-ray monitoring of WR 25, leading to several published analyses (Pandey et al., 2014; Arora et al., 2019; Pradhan et al., 2021). Based on *Swift* data, Arora et al. (2019) performed a time-series analysis of the X-ray flux and found a period of 207.8 ± 3.4 d, thereby independently confirming the period of the system. A similar analysis based on *XMM-Newton* data provided a value of 208.3 ± 2.2 d. These results definitively confirm the period value, although they are not sufficiently precise to discriminate between the period reported by Gamen et al. (2006) and the value proposed here. In any case, this difference between the two values is not significant.

We retrieved the fluxes from the *Swift* satellite as measured by Arora et al. (2019, see their Tables 2 and 3). The observed *Swift* spectra, binned in phase, were fitted by these authors in the energy range 0.5–10.0 keV using a two-temperature thermal plasma model with a free absorbing column in the foreground. The latter consists of a free local column density, to which is added the interstellar column density fixed at $N_{\text{H}}(\text{ISM}) = 3.7 \times 10^{21} \text{ cm}^{-2}$ (equivalent hydrogen-column density). Solar chemical abundances from Anders and Grevesse (1989) were adopted. The plasma temperatures were fixed at 0.268 keV and 2.75 keV for all fits. In their Table 3, Arora et al. (2019) present the observed fluxes, the fluxes corrected for interstellar extinction, and the intrinsic fluxes, corrected for both the interstellar extinction and the assumed local wind absorption.

Unfortunately, the work of Arora et al. (2019) was performed using phase binning based on the ephemerides of Gamen et al. (2006). The slight modification of the period proposed here implies a corresponding shift in phase. Even assuming that the grouping of the various exposures remains unchanged, the *Swift* data span 15 orbital cycles of the binary system, which leads to a phase uncertainty of about 0.02 solely due to the revised period. In Fig. 30, we show the run of the X-ray flux corrected for interstellar extinction in the soft band (0.3–2.0 keV) as a function of phase. The data points are horizontally elongated to illustrate this uncertainty of 0.02. Although our discussion is based on the flux corrected for interstellar extinction (taken from Arora et al. 2019), the conclusions remain unchanged if the observed fluxes are considered instead. The blue vertical line indicates the position of the conjunction with the WN star in front (see Table 2). The observed soft X-ray eclipse confirms and therefore supports our ephemerides. However, due to the possible phase error, the observations also remain generally consistent with the earlier orbital solution of Gamen et al. (2006). A full reanalysis of the X-ray data to resolve this ambiguity is, however, beyond the scope of this paper.

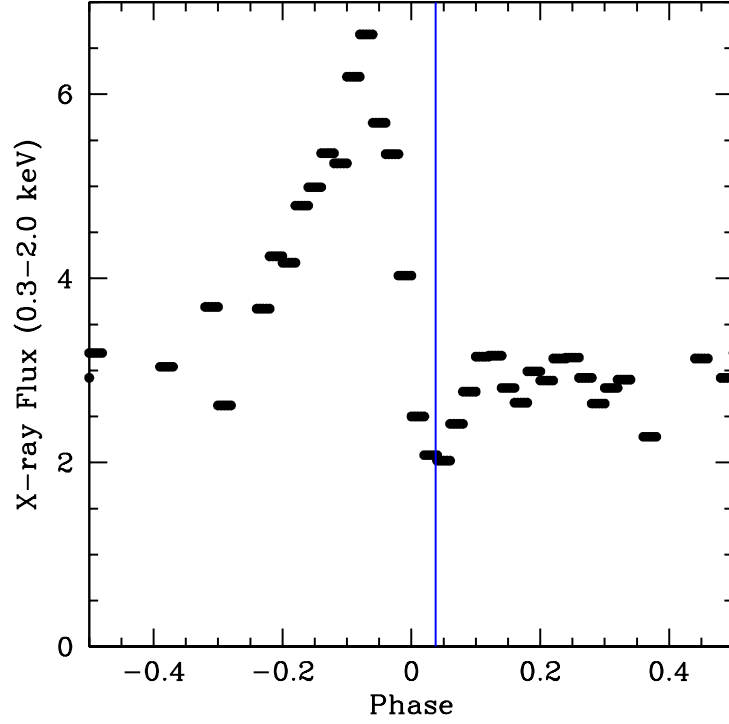


Figure 30: Run of the soft X-ray flux of WR 25 as a function of phase (see Table 2). The fluxes plotted here are corrected for extinction by the interstellar medium and are expressed in units of $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. The measured fluxes are taken from Arora et al. (2019). The soft band corresponds to the 0.3–2.0 keV energy range. The data points are horizontally elongated to illustrate the phase uncertainty of 0.02 (see text). The blue vertical line indicates the time of conjunction with the WN star in front according to the ephemerides presented here.

The eccentricity reported by Gamen et al. (2006) could be slightly underestimated, as first suggested by Pradhan et al. (2021). This is not surprising given the lack of good spectroscopic data around phase 0.98 in that early study. The eccentricity derived here ($e = 0.595$) implies a conjunction phase of 0.038 whereas an eccentricity of ~ 0.5 would imply a conjunction phase of ~ 0.05 . The conjunction therefore occurs 7.9 d after periastron instead of 10.5 d, respectively. If the time of conjunction in Fig. 2 of Pradhan et al. (2021) is shifted accordingly, the agreement between the conjunction and the soft X-ray eclipse appears to improve somewhat.

6. The O-Component Detection and Motion

6.1. The detection of the O component

Now that the SB1 orbital solution of the WN star in WR 25 has been determined, it is time to investigate the orbit of the companion. Shortly after the paper by Gamen et al. (2006) which reported the discovery of the binarity of WR 25, we had the opportunity to complement our data set with a spectrum acquired in May 2006 that observed the star at the epoch of maximal radial-velocity separation, a phase not previously covered by our high- and medium-resolution spectra. The detection of the companion was illustrated in Fig. 1 of Gamen et al. (2008) on the basis of the He II $\lambda 4542$ line, indicating that the companion is an O-type star. This spectrum is included in data set IV. To further illustrate the detection of the companion, we show in Fig. 31 two spectra: one displayed in black (phase 0.98), where the WN component is shifted towards the blue and the O-star component towards the red, corresponding to the phase of maximum radial-velocity separation; and a second spectrum displayed in red, acquired at phase 0.14, which approximately corresponds to the opposite configuration. The actual extremum occurs at phase 0.256. Both spectra are part of data set I_{glo}. Six different wavelength regions are shown, each illustrating different spectroscopic lines. At phase 0.98, the He II $\lambda 4542$ line clearly exhibits an additional weaker component shifted towards the red that can be associated with the O companion, thereby confirming the results of Gamen et al. (2008). As the system evolves towards the phase 0.14 configuration, the O-star component shifts towards the blue and the WN absorption towards the red. The relative motion of the WN star can be seen in the short-wavelength wing of the WN absorption line. At phase 0.14, both absorption lines have merged. A very similar behaviour is observed for the He II $\lambda 4200$ transition. The He II $\lambda 5412$ line exhibits the same behaviour, although the situation is more complex due to the effect of a marked P-Cygni profile in the WN spectrum: at phase 0.98, the O-star absorption component is superimposed on the emission component of this WN P-Cygni profile.

In the panel of Fig. 31 showing the behaviour of the H γ line, the blue-to-red shift of the WN star is visible in the unrelated N III $\lambda 4321$ line, which has no contribution from the O star. The same shift is also visible in the short-wavelength wing of the central absorption line and in the overall displacement of the centre of this same line. The case of H δ is also similar, although the displacement of the short-wavelength wing of the central absorption is almost invisible, probably due to the additional presence of the N III lines. The spectroscopic line He I $\lambda 4026$ (with a contribution also from He II) is not deblended at phase 0.98, and thus never deblends. The line is simply broader at this phase. The strengths (equivalent widths) of the absorption

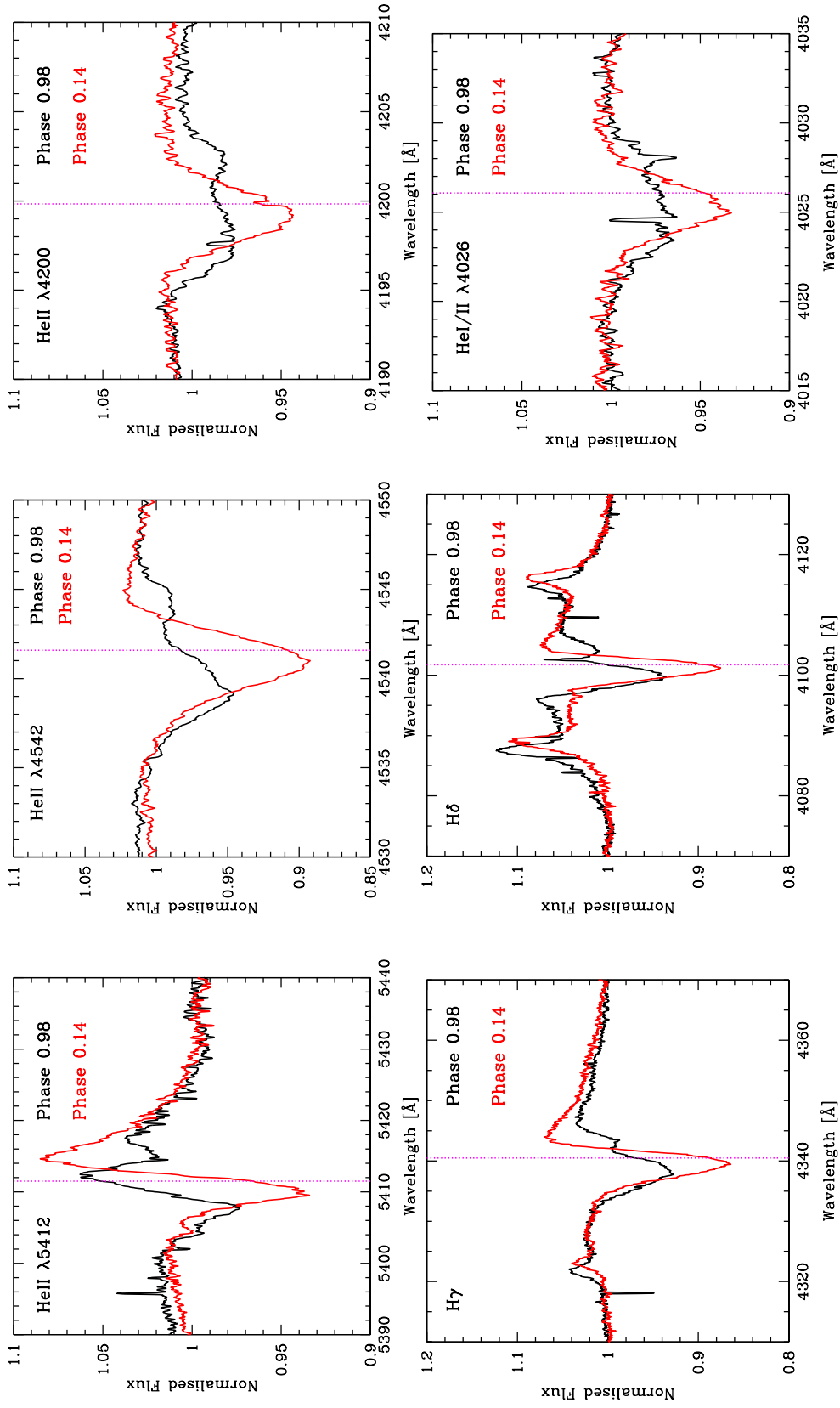


Figure 31: Comparison of the shape and position of selected spectroscopic lines at two orbital phases: 0.14 (red) and 0.98 (black). These phases correspond to the maximum RV separation (phase 0.98, WN star shifted towards the blue) and to the approximate opposite extreme separation (phase 0.14, WN star shifted towards the red). The panels show the He II $\lambda 5412$, He II $\lambda 4542$, He II $\lambda 4200$, H γ , H δ , and He I-II $\lambda 4026$ lines.

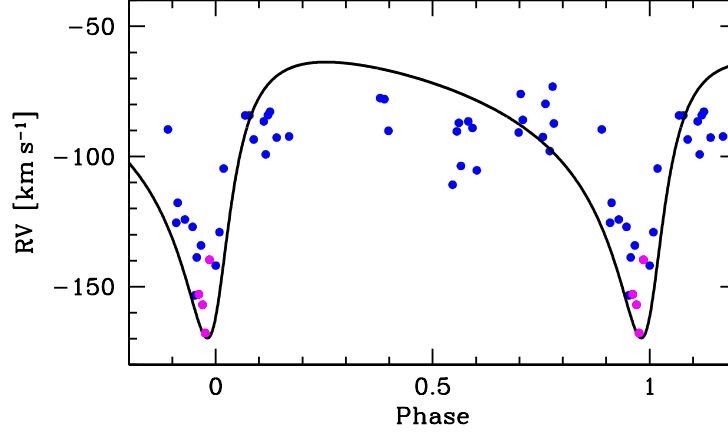


Figure 32: Phase diagram showing the RVs associated to the main absorption component of the $H\gamma$ profile. The blue points represent the RVs for the phases where only one absorption component is visible, whereas the few magenta points correspond to phases where two absorption components are visible and can be separated (the RVs associated solely with the O star are not shown here). The continuous line represents the adopted WN orbital solution from Sect. 5.1 (see Fig. 29), with the zero systemic velocity shifted by an arbitrary -90 km s^{-1} for illustration purposes.

components associated with the WN star and the O one are here very similar. The $\text{He I } \lambda 5876$ line (not shown here) also never becomes deblended. The depth of the WN absorption at phase 0.14 is always greater than at phase 0.98, but the difference is very roughly comparable to the contribution of the O star. This suggests that we are essentially observing a simple merging of the absorption components of the two objects. Consequently, at phase 0.14, the contribution of the O star to the total absorption is not negligible for these lines.

From the inspection of all these lines, it is clear that the spectral components of the two objects can be separated only for the He II and H lines and even then only over a narrow range of phases around 0.98. This indicates that we should search for other spectroscopic lines of the O star that are significantly narrower and for which the influence of the WN component is much more limited.

In order to further illustrate the behaviour of the absorption components in the above-mentioned transitions, we focus on the case of $H\gamma$. The absorption lines in $H\gamma$ were fitted with one or two Gaussians. The resulting RVs are displayed in the phase diagram shown in Fig. 32. The majority of the data points (in blue) correspond to a single-Gaussian fit, whereas a very few data points (in magenta) correspond to a simultaneous fit with two Gaussians, one for the WN component and one for the O-star component (not shown here). The magenta points associated with the WN component are concentrated at the most negative velocities when the two lines are separated. In contrast, the blue points at phases between approximately 0.5 and 0.8 are located at less negative velocities. This indicates that the absorption component broadly follows the motion of the WN star, although not perfectly. This provides definitive evidence that

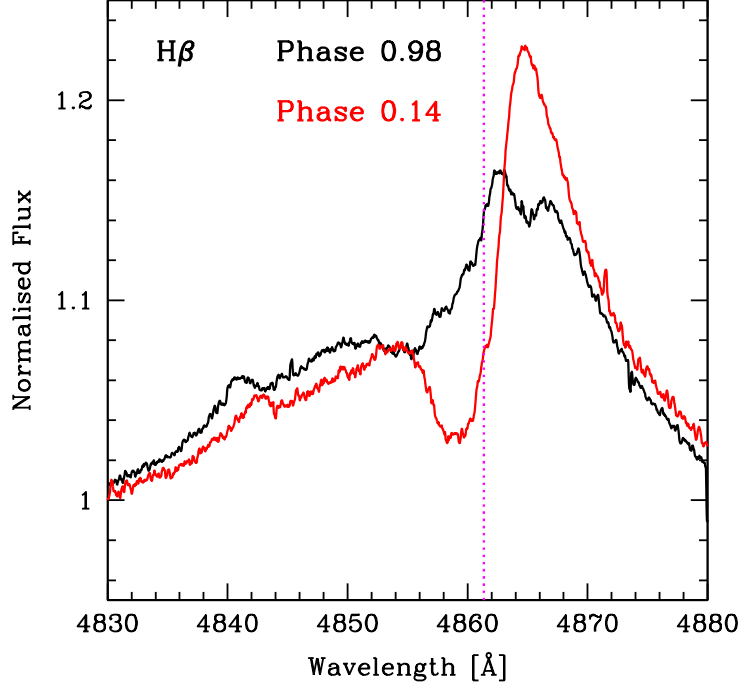


Figure 33: Illustration of the He II $\lambda 4859 + \text{H}\beta$ profile in WR 25 at the two usual extreme phases, 0.98 (black) and 0.14 (red). The dotted magenta line indicates the position of the laboratory wavelength of this spectral feature. The small emission line to the blue side of He II $\lambda 4859 + \text{H}\beta$ is attributed (see Sect. 3.1.13) to the transition N III $\lambda 4842$.

WR 25 contains absorption lines associated with both stars. The same phenomenon is observed in the other lines discussed in the present section. At phases between 0.75 and 0.92, the RVs are shifted towards less negative velocities. This is an effect of the blending between the WN absorption line and the line of the O star. At phases between 0.1 and 0.7, the RVs do not change dramatically. If an orbital fit is performed on these data, an eccentricity of 0.7 is obtained, which is not consistent with the orbital motion derived for the WN component. Two effects could play a role: either the WN absorption line does not perfectly follow the orbital motion because of distortions in the line-formation region, or the absorption component of the O star in H γ shifts the apparent position of the blended absorption profile. From an observational point of view, it is difficult, if not impossible, to disentangle these two effects. We nevertheless consider that the RVs at phases just below 0.98 strongly suggest that the second effect is indeed present.

6.2. The particular case of H β

Similarly to what was done in Sect. 6.1, we show in Fig. 33 the spectrum of WR 25 in the vicinity of the He II $\lambda 4859 + \text{H}\beta$ line at phases 0.14 and 0.98. At phase 0.14, the WN spectrum is close to its maximum shift towards the red, as can be seen from the N III $\lambda 4842$ line. The spectrum is then characterised by a P-Cygni profile. The presence of such a marked absorption component has been reported in several stars by Crowther and Walborn (2011), prompting them to introduce the composite spectral type O2.5f*/WN6, for which WR 25 was selected as the

archetype. The main and sole defining criterion for this spectral type is the presence in $H\beta$ of a P-Cygni profile with a strong absorption component (see Table 2 of Crowther and Walborn, 2011).

At phase 0.98, when the WN star is at its maximum shift towards the blue, and the O star is expected to be at its maximum shift towards the red, the above-mentioned absorption component is no longer prominent. In addition, the emission component of the global P-Cygni profile is strongly attenuated. This effect is actually caused by the $H\beta$ absorption of the O star. At this phase, the absorption feature is located almost exactly at the centre of the emission component, producing the observed double-subpeak structure and the associated flux deficit. We note that the area between the red and black lines around $4864 \text{ \AA}$ is similar, but of opposite sign, to the area between the same two lines at the position of the absorption feature near $4859 \text{ \AA}$. It is tempting to attribute the absorption component observed at phase 0.14 to the O component. However, this interpretation would require a velocity shift substantially larger than that observed for the $\text{He II } \lambda 4200$ line. To investigate this issue further, we illustrate the behaviour of the $\text{He II } \lambda 4859 + H\beta$ line near phase 0.98 in Fig. 34. Several selected spectra of WR 25 are shown for phases between 0.91 and 0.02 (or 1.02). None of these spectra exhibits a pronounced P-Cygni absorption. Clearly, the region between 4850 and $4860 \text{ \AA}$ shows significant variability, but none of the phases exhibits the P-Cygni absorption visible at the other phases (as illustrated in this paper by phase 0.14). Around the dotted magenta line, a small level of variability is also present, but this is essentially due to an imperfect subtraction of the narrow nebular $H\beta$ line, which is ubiquitous in the Carina nebula region. The spectrum at phase 0.95 (dotted line) differs markedly from that at phase 0.96 in the region around $4850\text{--}4855 \text{ \AA}$. This provides additional evidence for variability in this region, since the two spectra were acquired only one day apart.

As indicated by the blue vertical line, the absorption component superimposed on the P-Cygni profile is located approximately at the position of this line around phase 0.98. In contrast, before and after this phase, the absorption shifts towards the blue (left-hand side), thereby tracing the RV motion of the O star. For comparison, we also show in Fig. 34 an arbitrarily rescaled spectrum of the $\text{He II } \lambda 4859 + H\beta$ profile of WR 24 (in green). At these phases, the $\text{He II } \lambda 4859 + H\beta$ profile of WR 25 is very similar to that of WR 24, which has the spectral type WN6ha (Crowther and Walborn, 2011).

The variability observed between 4850 and $4860 \text{ \AA}$ at phases around 0.98 is most probably due to instabilities in the wind of the WN component. The origin of the P-Cygni absorption component visible between phases 0.14 and 0.80 is more difficult to assess. It appears to be related to the absorption line of the O component, although further modelling is required to confirm this interpretation. In any case, the pronounced absorption component observed in WR 25 is only visible at certain phases. To illustrate this further, we define an $H\beta$ index corresponding to the minimum normalised flux in the vicinity of $4860 \text{ \AA}$. The run of this index as a function of phase is shown in Fig. 35. The phase dependence of the absorption component is striking. Even if the effect is not entirely caused by the spectrum of the O star itself, it is certainly linked to the presence of the O-star companion and therefore to the binary nature of the system. Consequently, the selection of WR 25 as the archetype of the O2.5f*/WN6 spectral

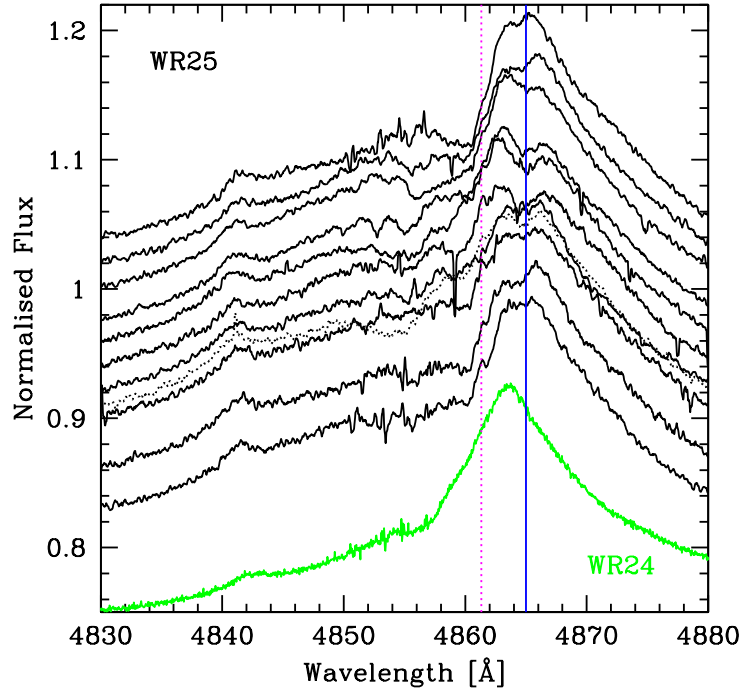


Figure 34: Selected WR 25 spectra (black) at phases close to 0.98. For illustrative purposes, the spectra have been vertically shifted relative to the continuum level at 1 by an amount equal to twice the difference between phase zero and the phase of the corresponding spectrum. From *top to bottom*, the phases are 0.018, 0.009, 0.000, 0.986, 0.976, 0.966, 0.956, 0.952 (dotted), 0.947, 0.929, and 0.912. The magenta vertical line indicates the laboratory wavelength, whereas the blue vertical line marks the maximum redward excursion of the O component. An arbitrarily rescaled spectrum of WR 24 (green) is also shown to facilitate comparison between the two stars.

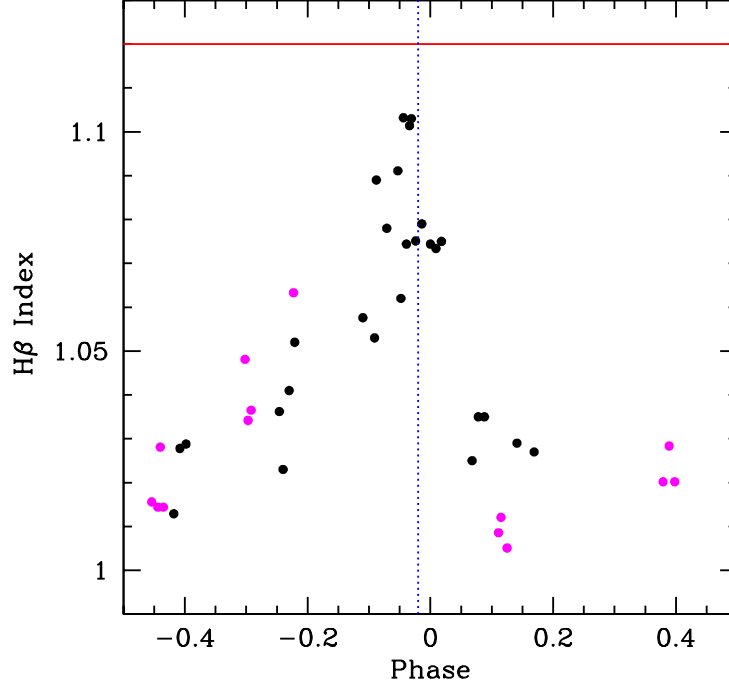


Figure 35: Run of the $H\beta$ index as a function of orbital phase. The black points correspond to the spectra from the I_{loc} data set, while magenta points represent data set III. The blue dotted vertical line indicates the phase of minimum radial velocity of the WN star. The horizontal red line marks the maximum flux level possible in the region around $4860 \text{ \AA}$.

type, defined by the presence of a strong absorption component in the $\text{He II } \lambda 4859 + H\beta$ profile, appears somewhat unfortunate.

6.3. The anomaly of $\text{N III } \lambda 4641$

In this section, we further investigate the anomaly reported in Sect. 3.1.8. Figure 36 shows the spectrum of WR 25, in the region of the $\text{N III } \lambda \lambda 4634\text{--}4641$ triplet at phase 0.98 (black). The positions of the two apparent lines formed by the triplet are marked by red vertical lines. We also plot a spectrum obtained at phase 0.17 (green), shifted in RV so that the two apparent lines associated with the WN component are superimposed on those of the spectrum at phase 0.98. This shift is a strict minimum; the true shift could be slightly larger. Both spectra shown in Fig. 36 are taken from data set I_{glo} . The two apparent emission lines in the black spectrum are weaker than those in the green spectrum. Conversely, the black spectrum exhibits excess flux relative to the green spectrum at two positions marked by magenta dots. The explanation is straightforward. The excesses are due to an additional emission from the O star, and are clearly visible and separated from the WN component at phase 0.98. At phase 0.17, however, the same O star emission contributes directly to the WN features, which explains why the green spectrum is somewhat brighter at the positions marked by the red vertical lines. Therefore, the O star exhibits this triplet in emission and should at least be classified as “((f))” (Walborn, 1971; van der Hucht, 1996). The observed displacement suggests a very rough lower limit of about 80 km s^{-1} for the semi-amplitude K_{O} . Throughout the orbital cycle, the emissions from

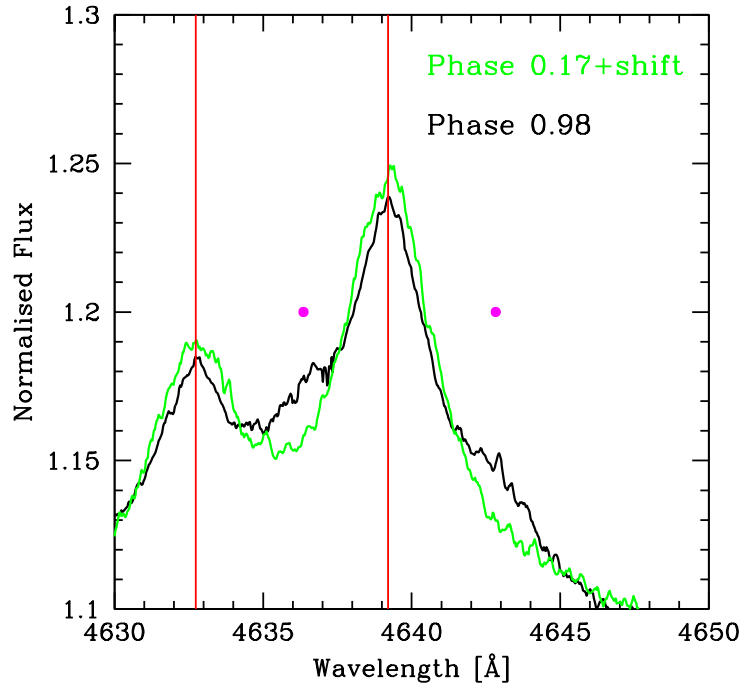


Figure 36: Spectrum of WR 25 in the region of the N III $\lambda\lambda 4634\text{--}4641$ triplet at phase 0.98 (black) with the spectrum at phase 0.17 (green) superimposed after being shifted so that the two apparent emission lines of the triplet coincide. The positions of the two transitions are marked by red vertical lines. The two magenta dots indicate the position of the O-star contribution at phase 0.98.

the two stars combine in different ways, and this hampers the correct determination of the RVs in a phase-dependent manner. This provides a natural explanation for the anomaly reported in Sect. 3.1.8. At phase 0.98, the N III triplet emission lines of the WN and O components are well separated and the measurement of the RV of the WN component is essentially unbiased and agrees well with the RV derived from the N IV $\lambda 4058$ line (see Fig. 21); at phase 0.14, and approximately until phase 0.3, the emission lines of both objects occur at nearly the same wavelengths, so the position of the blended feature is not significantly affected by the O-star contribution. Beyond phase 0.3, the O-star emission lines progressively separate from the WN features while moving towards the red. As this occurs, the O-star emission lines pull the centroid of the fitted Gaussian redwards, producing a bias towards larger RVs, which is precisely the behaviour illustrated in Fig. 21.

These results are particularly interesting because they raise the possibility that information on the orbit of the O component could be extracted through spectral-disentangling techniques (see Sect. 7).

6.4. The He I $\lambda 4471$ line

In order to improve our knowledge of the orbital motion of the O component, we searched for additional spectral lines that could provide further constraints. In particular, we looked for lines for which the detrimental effect of the WN component might be reduced. Although weak, He I $\lambda 4471$ could be of interest. Figure 37 shows this line at two extremal orbital configurations, where it is always observed in absorption. In the upper panel, contributions from both the WN and O components are clearly visible. At phase 0.98, the two absorption features are sufficiently separated to allow a simultaneous fit. The blue curve represents the Gaussian fitted to the left-hand component alone, to be associated with the WN star, whereas the magenta curve represents the fit obtained with two Gaussians and, by comparison, highlights the contribution of the O star. At phase 0.98 (more precisely 0.976), the RV of the O-star component is 171.5 km s^{-1} , in good agreement with the velocity derived at the same phase from, e.g., the He II $\lambda 4542$ line (observed at $4544.2 \text{ \AA}$, corresponding to a velocity of 172.3 km s^{-1} —see Fig. 31). However, two other spectra at phases 0.970 and 0.986 favour a velocity closer to 180 km s^{-1} . We therefore adopt a velocity of 176 km s^{-1} at phase 0.98. This choice is admittedly somewhat arbitrary. However, 5 km s^{-1} corresponds to $0.075 \text{ \AA}$, i.e., roughly one resolution element (see the end of Sect. 2.1.2), and a substantially better precision can therefore not be expected from a single isolated line. Inspection of Fig. 37 suggests that this level of accuracy is not achieved in practice. The RV associated with the WN component is -19.5 km s^{-1} (marked by the red vertical line), a result that remains to be explained. This velocity is clearly shifted with respect to the actual RV associated with the WN component. Indeed, at phase 0.98, the WN star should in principle be shifted by more than 70 km s^{-1} towards the blue relative to the systemic velocity. The He I line could potentially be formed in the expanding wind, or it may arise from an unrelated source—an intruder. The only nearby source reported for WR 25 is situated $0''.79$ away and has a magnitude difference ΔV of about 5.8 mag (Sota et al., 2014). It is unlikely that the line can be attributed to this faint object. This object is not part of the *Gaia* DR3 catalogue (*Gaia Collaboration*: Prusti

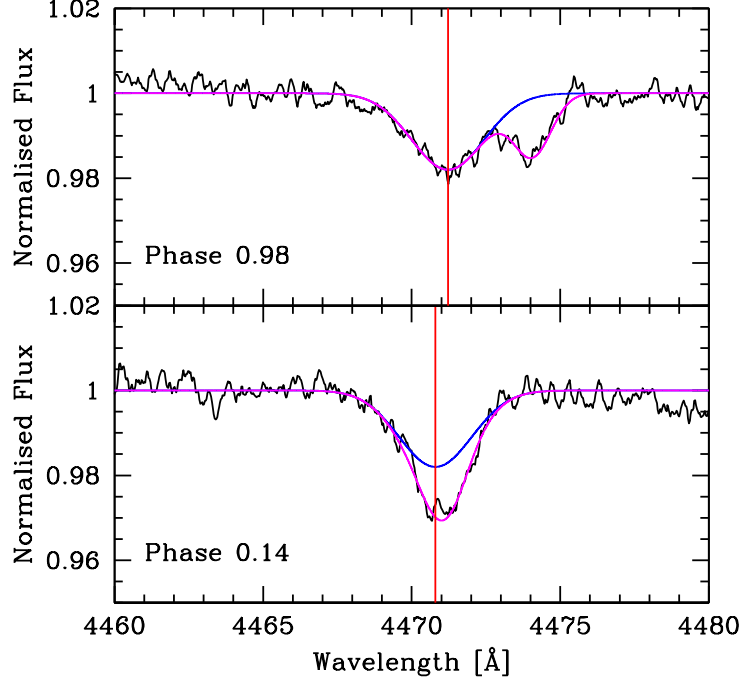


Figure 37: Spectrum of WR 25 in the region of the He I $\lambda 4471$ line at phase 0.98 (*upper panel*) and phase 0.14 (*lower panel*). The blue curves show the single-Gaussian fit, while the magenta lines correspond to the two-Gaussian fit. The red vertical lines mark the position of the component attributed to the WN component, highlighting its limited radial-velocity variation.

et al., 2016; *Gaia Collaboration*: Brown et al., 2021; *Gaia Collaboration*: Vallenari et al., 2023) and no other nearby star is listed in this catalogue in the immediate vicinity of WR 25. This point will be discussed further below.

At phase 0.14, the two lines are clearly blended. A tentative two-component fit is shown in the lower panel of Fig. 37. However, this particular fit is not secure, and other solutions are possible. No other spectrum obtained at these phases clearly reveals two separate components. Although the O-star component shifted towards the blue is reasonably consistent with the expected orbital motion of the O star, the component attributed to the WN star also appears to be shifted towards the blue, which is certainly puzzling. It is therefore possible that the assignment of the two components is not correct. In any case, this feature does not appear to follow the orbital motion of the WN star. To further illustrate the intricacy of the problem, Fig. 38 shows the measured RVs as a function of phase. Around phase 0.98, the RVs of the WN and O components can be measured separately, whereas at other phases, only the global position of the blended profile can be reported. As the spectra approach the phase interval where the two components become resolvable, the position of the blend is progressively displaced towards more positive RVs. This occurs because at these phases the O component is on the edge of deblending. The WN component itself appears to exhibit only limited motion. For the data point at phase 0.14, we report both the RV of the blend and the two RVs derived from the tentative fit shown in the lower panel of Fig. 37. These two latter measurements are indicated by two cyan

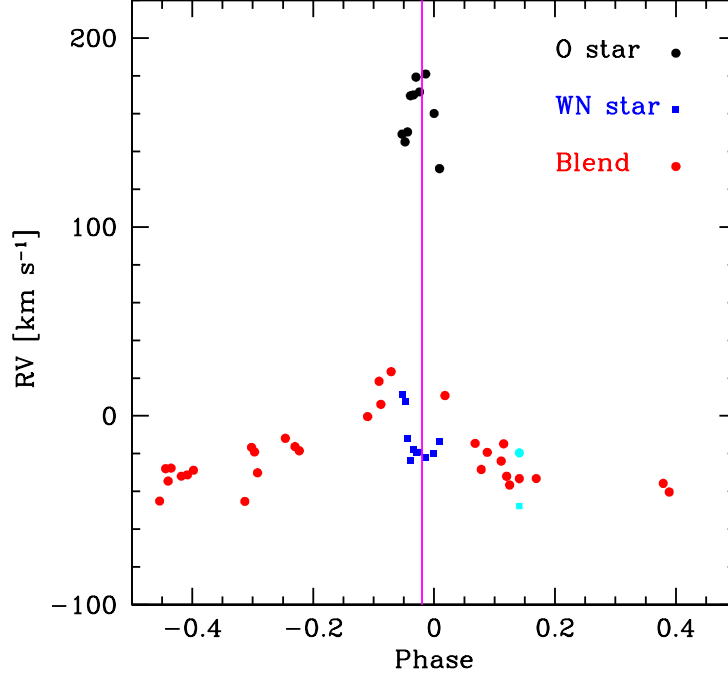


Figure 38: Radial velocities derived from the He I $\lambda 4471$ line as a function of orbital phase. The different symbols and colours correspond to the O component (black circles), the WN-star component (blue squares), and the blends (red circles). The cyan circle and cyan square indicate the RVs measured for the O- and WN-star components, respectively, depicted in the lower panel of Fig. 37 (see also text). The vertical line marks phase 0.98.

symbols in Fig. 38. Studying this He I $\lambda 4471$ line would probably benefit from analysis using a spectral-disentangling technique (see Sect. 7). Indeed, the equivalent width of the O component is not too faint compared to the supposed WN contribution, and its influence on the equivalent width of the blended profile is potentially favourable for disentangling.

At phase 0.98, the He I $\lambda 4471$ line associated with the O component is measured at a velocity of 176 km s^{-1} . At phase 0.14, the two Gaussians fitted to the blended profile are located at velocities of -27.6 km s^{-1} (the probable O component) and -47.7 km s^{-1} . The resulting velocity differences are therefore 203.6 km s^{-1} and 223.7 km s^{-1} , respectively. Phase 0.14 does not correspond exactly to the extremum, which occurs at phase 0.256. Using the shape of the WN-star orbit derived in Sect. 5.1, we estimate that the passage from phase 0.14 to phase 0.256 requires an increase of 5.5% in the measured velocity range to recover the full RV excursion of the O star, which should be a good estimator of $2K$. From the velocity differences quoted above, we obtain a preliminary estimate of the O-star’s semi-amplitude, K_O , in the range $107\text{--}108 \text{ km s}^{-1}$. Under the alternative—less likely—identification of the two components in the blended profile, the corresponding value would be 118 km s^{-1} . This latter value may be regarded as an approximate upper limit.

Since the main He I $\lambda 4471$ spectral line does not seem to follow the motion of the WN component and remains nearly stationary, we explored an alternative approach. As a working

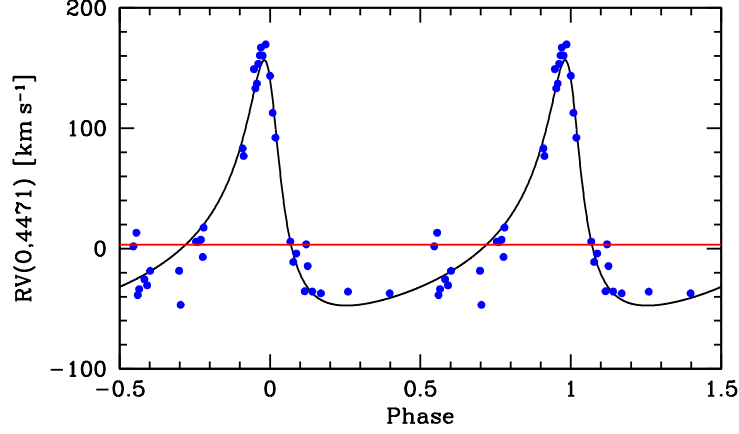


Figure 39: Preliminary RV curve of the O component as a function of orbital phase. The blue points represent the individual RV measurements obtained after removing the He I $\lambda 4471$ component assumed to be constant in RV and not associated with the O star. An orbital fit was performed (see Sect. 6.4), with parameters K_O and γ_O treated as free parameters while all other orbital elements were fixed to the values of the SB1 solution. The solid black curve shows the resulting Keplerian fit, and the red horizontal line indicates the fitted systemic velocity.

hypothesis, we assumed that this feature is constant in wavelength. We adopted a central wavelength of 4471.1 Å, corresponding approximately to the midpoint of the positions shown in Fig. 37. We also adopted the same depth (0.018 in continuum units) and width ($\sigma = 1.2$ Å) as in that figure. This component was then subtracted from all the spectra in data sets I, II and III. In principle, this procedure leaves only the absorption feature associated with the O component. We then fitted a Gaussian profile to this residual feature in each spectrum and derived the corresponding RV. Because the line is very weak, the procedure could not be applied successfully to all spectra (depending on the S/N ratio). The successfully determined RVs are listed in Appendix D. These RVs were plotted in a phase diagram and fitted for the parameters K_O and γ_O , while the other orbital parameters were fixed to the values given in Table 2. The resulting fit is shown in Fig. 39. We derived $K_O = 102.6$ (3.8) km s⁻¹ and $\gamma_O = 3.2$ (3.0) km s⁻¹. We recall that, throughout this paper, uncertainties quoted in parentheses correspond to 1σ errors. The parameters derived for the O star are not very precise. The line itself is very faint (with a typical depth of only 0.013 in continuum units), and the assumption that the subtracted primary component is strictly constant remains a working hypothesis that may introduce an unknown systematic bias. A more detailed analysis will be presented in the section devoted to spectral disentangling (Sect. 7).

6.5. The N IV triplet around 5200 Å

The N IV ion exhibits a triplet with laboratory wavelengths of 5200.41 Å, 5204.29 Å, and 5205.15 Å. The latter two transitions are closely spaced and remain unresolved in all our spectra. We therefore adopt a rest wavelength of 5204.55 Å for this blended pair. Figure 40 shows the

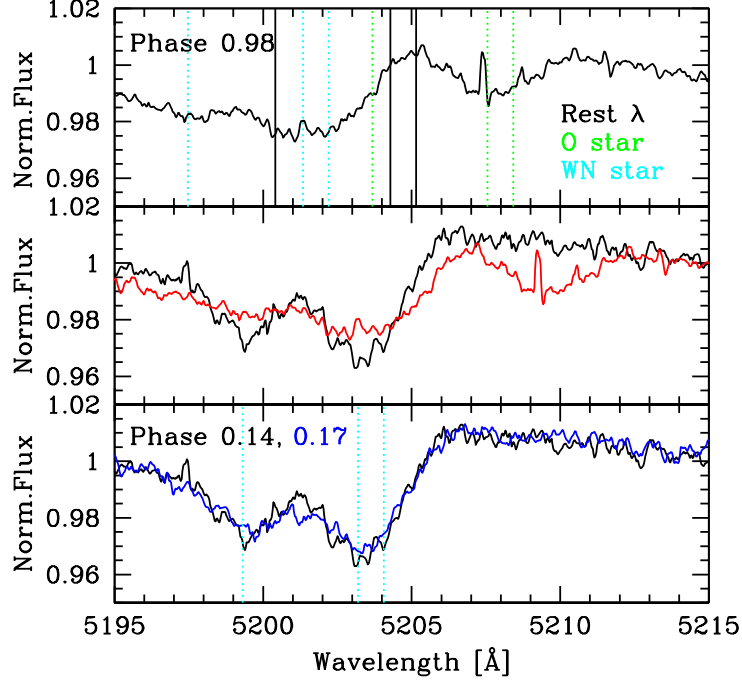


Figure 40: Spectrum of WR 25 in the region of the N IV triplet. The *upper panel* shows the spectrum at phase 0.98, while the *lower panel* presents spectra obtained at phases 0.14 (black) and 0.17 (blue). In the upper panel, the identified absorption features are labelled, and the rest wavelengths of the triplet are indicated by the solid vertical black lines. The green dotted lines mark the expected positions of the O component, whereas the cyan dotted lines indicate those of the WN component. In the lower panel, the cyan lines identify the WN component blended with the O-star contribution. The *middle panel* compares the spectrum at phase 0.14 with that at phase 0.98 shifted redwards by twice the value of K_{WN} .

spectrum of WR 25 in the region of this triplet. In the upper panel, corresponding to phase 0.98, we identify the various observed absorption features. The positions of the triplet at rest are indicated by solid vertical black lines, while their positions shifted to a radial velocity of 188.3 km s^{-1} , corresponding to the O star, are marked by green dotted lines. At this phase, the 5200.41 Å transition of the O component is blended with another feature, namely the 5204.55 Å pair associated with the WN component. The velocity of the WN component can be estimated from the 5200.41 Å transition and is approximately -169.2 km s^{-1} . The lower panel of Fig. 40 shows spectra obtained at phases 0.14 and 0.17, which are very similar. At these phases, the lines of the WN and the O components appear to be fully blended. In the middle panel, we reproduce the observed spectrum at phase 0.14 together with that obtained at phase 0.98 after shifting it redwards by 106.35 km s^{-1} (i.e. by $2 K_{\text{WN}}$). This comparison clearly demonstrates that the N IV triplet follows the orbital motion of the WN component along the orbit, unlike the He I $\lambda 4471$ line. However, the triplet remains displaced towards the blue with respect to its laboratory wavelengths. The O-star lines are again separated from those of the WN component

around phase 0.98, whereas at phases 0.14/0.17, the blended lines are noticeably deeper. This provides further evidence that the O-star lines contribute to the observed spectrum at all phases and supports the idea that a spectral-disentangling analysis could prove beneficial.

Between phases 0.98 and 0.14/0.17, the O-star lines shift by approximately $4.35 \text{ \AA}$ towards shorter wavelengths. Applying the same correction as in the previous section, we obtain a rough estimate of K_O in the range $125\text{--}130 \text{ km s}^{-1}$ from this shift.

6.6. The directly observed motion of the O component

We systematically measured the RVs of the O component using three spectral features: He II $\lambda 4542$, He I $\lambda 4471$, and the N IV triplet around $5200 \text{ \AA}$. These lines were selected following the inspection described in Sect. 6. Using multi-Gaussian fitting similarly to the method used in Sect. 3, we directly measured the RVs of the He II $\lambda 4542$ and He I $\lambda 4471$ lines by assigning one Gaussian to the O component. For the N IV triplet, we measured the position of the blend formed by the N IV $\lambda 5204.29$ and N IV $\lambda 5205.15$ transitions, adopting a laboratory wavelength of $5204.55 \text{ \AA}$ for the blend. Naturally, such measurements are possible only for spectra acquired near phase 0.98. The resulting RVs are listed in Appendix D. These velocities can be regarded as having an absolute character, in the sense that they may represent the actual dynamical motion of the O component, unlike the velocities derived from the WN-star lines. Figure 41 shows the securely measured RVs associated with the O star. The three spectral features yield mutually consistent velocities. In this phase interval, corresponding to the region of maximum radial velocity, the RVs are relatively well constrained. However, this covers only a very limited range in phase, and no constraint is available on the opposite side of the systemic velocity. Nevertheless, these RV measurements around the velocity extremum provide definitive evidence that the O star is gravitationally bound to the WN component. The overall shape of the RV curve derived from the WN star (see Sect. 5.1) can therefore reasonably be assumed to apply to the O star as well. We can thus fit an orbital solution to these measurements, taking γ_O and K_O as the only free parameters. Unfortunately, because all of the available velocities sample only one side of the orbit, the two parameters are extremely, indeed nearly perfectly, correlated. Consequently, the fit provides little hope of determining them independently and with useful precision. Figure 42 shows the results of a series of fits in which γ_O was fixed at a range of assumed values. The resulting semi-amplitude K_O , the only fitted parameter, is plotted as a function of the adopted γ_O , and the correlation is evident. Therefore, apart from the measurement obtained from the spectrum acquired at phase 0.14 (see Sect. 6.4), only a spectral-disentangling analysis is likely to provide a significantly improved determination of the orbital solution of the O component.

7. Spectral Disentangling and Individual Spectra

Up to this point, we have investigated the orbital motion through the analysis and fitting of measured RVs. We have shown that, when the WN component reaches its maximum positive velocity, the spectral lines of the O component become blended with those of the WN star. Since the O-star lines are systematically weaker, their contribution is difficult to isolate in such

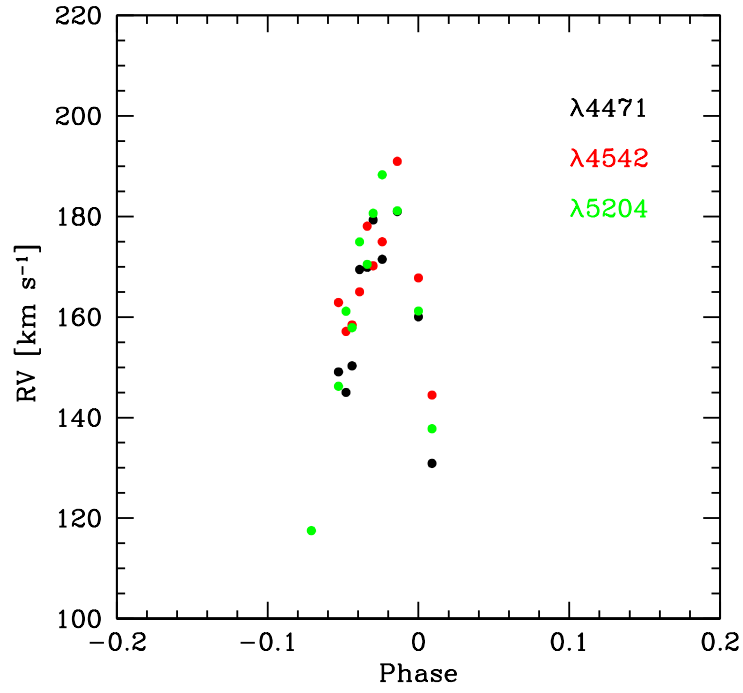


Figure 41: Radial velocities associated with the O-star component as a function of orbital phase. Black dots correspond to measurements from the He I $\lambda 4471$ line, red dots to those from the He II $\lambda 4542$ line, and green dots to the N IV $\lambda 5204.55$ blend. The data points highlight the RV motion of the O star in the vicinity of the phase interval corresponding to the maximum velocity separation between the two components.

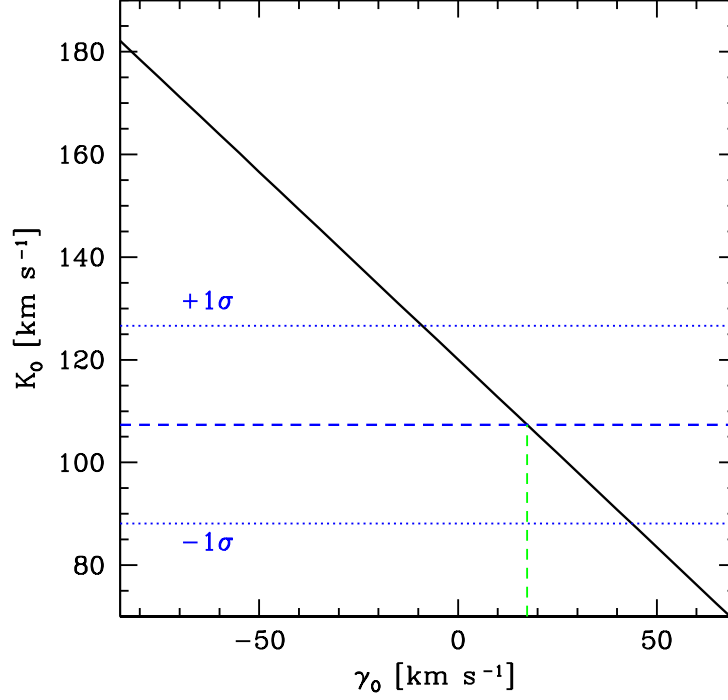


Figure 42: Fitted values of the semi-amplitude K_O as a function of the assumed systemic velocity γ_O . The formal uncertainty on the fitted parameter is comparable to the thickness of the black curve. The fit is based on the RV measurements shown in Fig. 41. The dashed horizontal blue line indicates the value of K_O derived in Sect. 7, while the dotted blue lines delineate the corresponding $\pm 1\sigma$ interval. The green line shows the determination of γ_O obtained by projecting the relation for the adopted value $K_O = 107.36 \text{ km s}^{-1}$.

circumstances. This is precisely the type of situation in which a spectral-disentangling technique can provide a significant advantage. The application of such a technique is the subject of the present section.

7.1. Disentangling and derived semi-amplitudes

Thus, in order to refine the values of K_{WN} and K_O , and to extract the individual spectral contributions of the two components, we applied a spectral-disentangling code to the spectra belonging to data set I_{glo} . The code used here is the same as that described by Mahy et al. (2022b) and is based on the Fourier approach (Hadrava, 1995; Ilijic, 2004).

As in the successful applications reported by Fabry et al. (2021) and Frost et al. (2024), we reduced the number of free parameters by fixing the orbital period P , the eccentricity e , the argument of periastron ω_{WN} , and the reference time T_0 . Only K_{WN} and K_O were allowed to vary. The apparent systemic velocities of the two components were excluded from the optimisation process. This grid search was designed to refine the determination of the RV semi-amplitudes of both components. The procedure was applied to four selected spectral features: N IV $\lambda 4058$, representative of the WN component, and He II $\lambda 4200$, He II $\lambda 4542$ and the N IV blend slightly

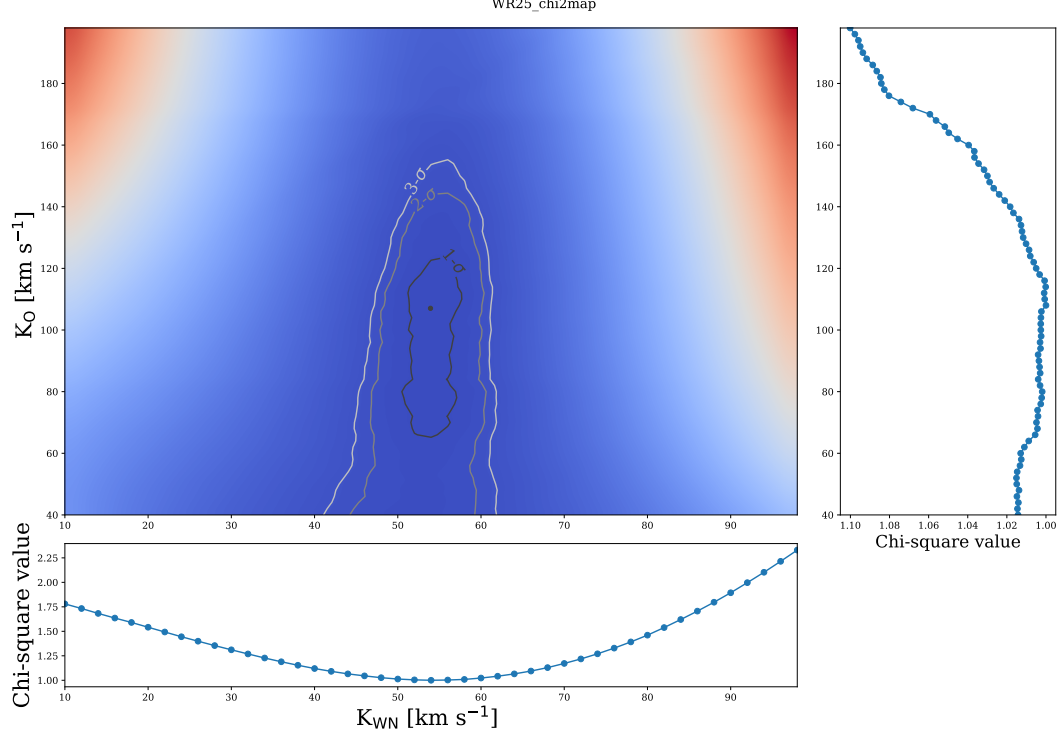


Figure 43: Two-dimensional reduced χ^2 map obtained from the Fourier disentangling as a function of the parameters K_{WN} and K_{O} . The global minimum is marked by a black dot, and contour levels corresponding to 1σ , 2σ , and 3σ are shown. The *bottom panel* shows the one-dimensional variation of χ^2 around the minimum as a function of K_{O} while the *right-hand panel* shows the corresponding one-dimensional variation as a function of K_{WN} .

above $5200 \text{ \AA}$, all of which exhibit a non-negligible contribution from the O component. The resulting χ^2 map is shown in Fig. 43. We compared the results obtained with the Fourier spectral-disentangling technique with those derived using the shift-and-add method (Shenar et al., 2022), another spectral disentangling technique. The two approaches yield consistent results. Combining them leads to $K_{\text{WN}} = 53.82 (0.99) \text{ km s}^{-1}$ and $K_{\text{O}} = 107.36 (19.24) \text{ km s}^{-1}$. Figure 43 shows that the determination of K_{WN} is well behaved, with a marginal distribution that is close to symmetric. In contrast, the determination of K_{O} is more challenging, and the minimum along this axis is noticeably asymmetric. However, the overall two-dimensional χ^2 map indicates that the two parameters are not strongly correlated. This suggests that the observed asymmetry arises primarily from the blending discussed above when the O-star component is shifted towards the blue, which constitutes a significant limitation of the analysis. The uncertainty of 19.24 km s^{-1} on K_{O} is therefore not strictly symmetric and could be more appropriately expressed as asymmetric confidence intervals, namely $\sigma^+ = 11.5 \text{ km s}^{-1}$ and $\sigma^- = 27.4 \text{ km s}^{-1}$.

The derived value of K_{WN} is in excellent agreement with that reported in Table 2, providing further support for the robustness of our results. If the value $K_{\text{O}} = 107.36 \text{ km s}^{-1}$ is projected onto Fig. 42, it corresponds to a possible systemic velocity γ_{O} of 17.4 km s^{-1} . At the position of

WR 25, the radial velocity projected along the line of sight due to Galactic rotation is expected to be approximately -11 km s^{-1} . These two values are not fully consistent and would imply an intrinsic radial motion of WR 25 of a few tens of km s^{-1} . The uncertainties on the determination of γ_0 are, however, huge, and no firm conclusion can be drawn from this apparent discrepancy.

7.2. Individual spectra

We therefore fixed the values K_{WN} and K_{O} , and re-applied the spectral disentangling procedure to extract the individual spectra of both components over the useful wavelength range covered by the observations.

Depending on the disentangling technique employed, the continua of the individual components may be lost during the process (see Mahy et al., 2017 for details). It is therefore necessary to correct the disentangled spectra for this effect. This correction differs from a standard normalisation: rather than dividing the spectra by the continuum, we force the pseudo-continuum to unity. Since the sum of the continua of the O star and the WN star must reproduce the continuum of the observed spectrum, the correction applied to the O-star continuum is directly correlated to that applied to the WN-star continuum. We apply this procedure to both objects. Figure 44 illustrates the quality of the reconstruction by comparing the sum of the two disentangled spectra shifted according to their respective radial velocities with an observed spectrum obtained at HJD 2,454,084.750. A key limitation of the disentangling analysis of WR 25 is that the O-star contribution cannot be fully separated from the WN profile when its lines are shifted towards the blue. As a result, the blue wings of the O-star lines cannot be completely reconstructed, producing artificial asymmetries in the disentangled profiles. In addition, because the brightness ratio of the two stars cannot be constrained through eclipses in the light curve of WR 25, it cannot be determined from spectroscopy alone. As a first approximation, we therefore arbitrarily adopted equal brightness contributions for the two components, i.e. a 0.50/0.50 ratio. This assumption naturally affects the absolute equivalent widths of the lines, but not their ratios. To recover the contribution of the spectral features to the global spectrum of WR 25, the equivalent widths measured in the disentangled spectra must therefore be multiplied by a factor of 1/2. Examples of the disentangled spectra are shown in Fig. 45 and in Appendix E. The secondary component displays a typical O-type star spectrum. The ratio

$$W = \log_{10}(\text{EW}(\text{He I})/\text{EW}(\text{He II})) = -0.54 (0.12)$$

derived from the equivalent widths of the $\text{He I } \lambda 4471$ and $\text{He II } \lambda 4542$ lines corresponds to a spectral type O5, with a possible uncertainty of one subclass (O4 to O5.5; Conti and Alschuler, 1971; Conti, 1973b; Mathys, 1988; Martins, 2018). It is noteworthy that the $\text{Si IV } \lambda 4116$ line appears in emission, whilst the $\text{Si IV } \lambda 4089$ transition is absent (see Fig. 45). The presence of $\text{Si IV } \lambda 4116$ emission in the spectrum of the O component explains the anomaly discussed in Sect. 3.1.9 and illustrated in Fig. 24. Figure 45 also shows that the $\text{N III } \lambda \lambda 4634\text{--}41$ lines are clearly in emission, supporting the addition of a suffix “f” in parentheses to the spectral classification.

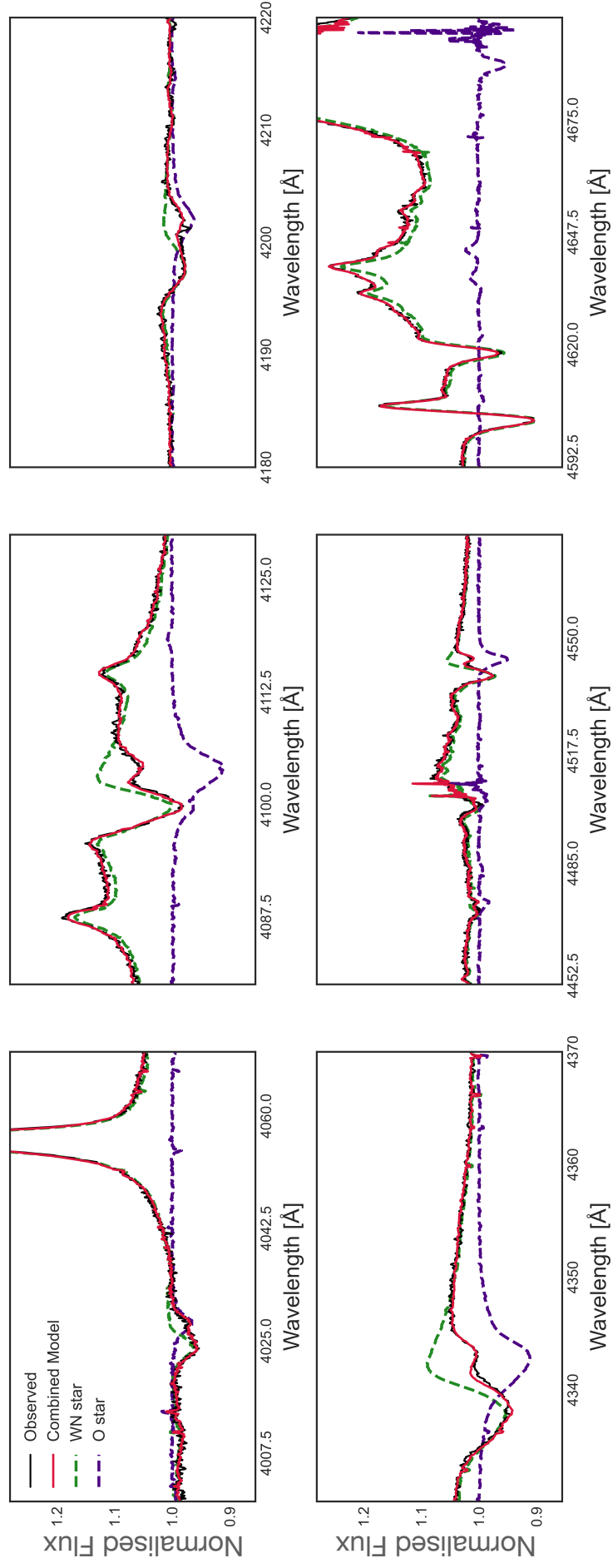


Figure 44: Combination (red) of the two disentangled spectra (green for the WN star and blue for the O star) shifted according to their respective radial velocities and summed, compared with the observed spectrum (black) obtained at HJD 2,454,084.750.

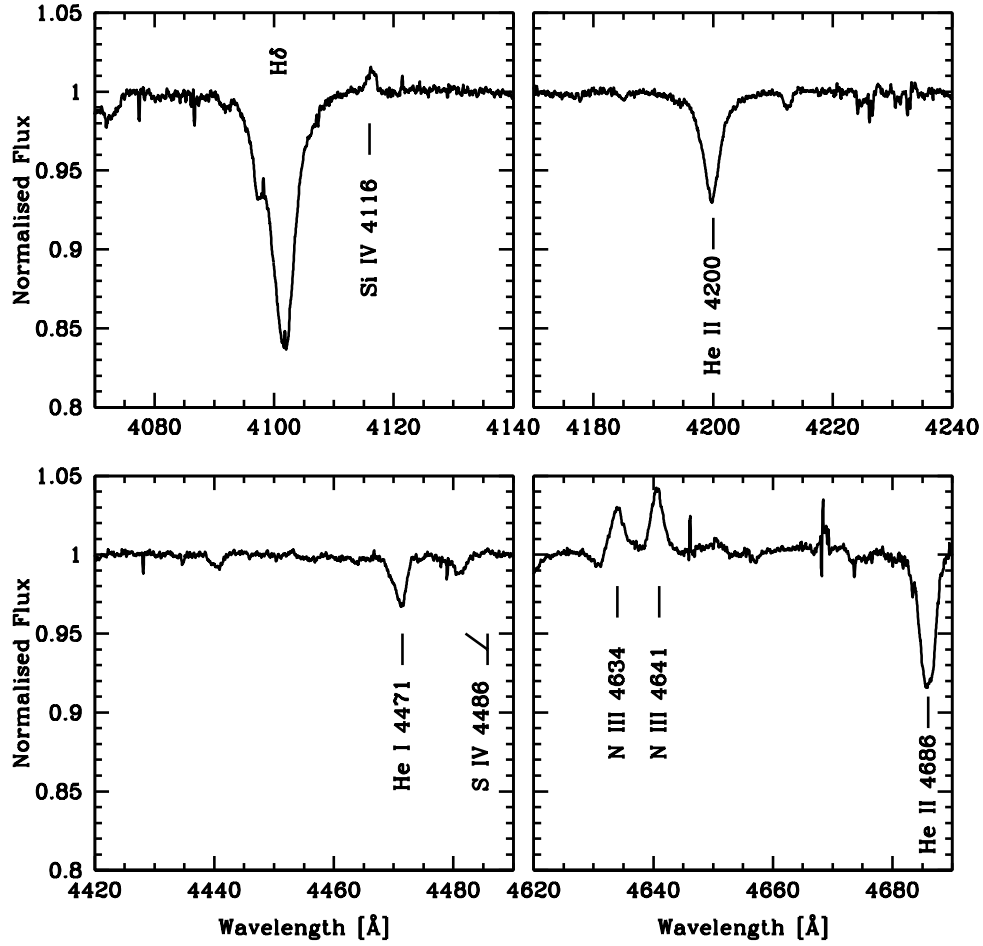


Figure 45: Disentangled spectrum of the O component in several spectral regions. These regions correspond to the $He\ II\ \lambda 4100 + H\delta$ line and the $Si\ IV\ \lambda\lambda 4089-4116$ doublet (*upper left*; the first line is not visible), the $He\ II\ \lambda 4200$ line (*upper right*), the $He\ I\ \lambda 4471$ line (*lower left*), and the triplet $N\ III\ \lambda\lambda 4634-4641$ together with the $He\ II\ \lambda 4686$ line (*lower right*).

In the vicinity of spectral type O5, the EW of He II $\lambda 4542$ is relatively constant and largely independent of whether the star belongs to the main-sequence or giant luminosity class. From the EWs published by Mathys (1988) for six stars (namely HD 168112, HD 93204, HD 152233, HD 157857, HD 167633, and HD 303308), we derive a typical EW of 705 (60) mÅ for He II $\lambda 4542$. Because of the lack of a precise brightness ratio, we do not have access to absolute EWs. However, the stable behaviour of the He II $\lambda 4542$ line makes it a suitable reference line. Around spectral type O5, the ratio of He II $\lambda 4542$ to He II $\lambda 4686$ is close to unity, even for stars classified as “((f))” (see the EWs of the six O stars listed above; Mathys, 1988). In contrast, stars carrying the “(f)” qualifier generally exhibit a He II $\lambda 4686$ line with a lower EW. From the data of Mathys (1988), we find that the “(f)” stars among the six objects are characterised by ratio below approximately 0.85. In some cases, the absorption line may even be completely filled in by emission or present a weak emission (e.g., the O5III(f) star HD 97253, Fig. 11 of Sota et al., 2014). In WR 25, the O5 component displays a clear He II $\lambda 4686$ absorption line, but its EW amounts to only about 76% of that of He II $\lambda 4542$, and its depth is also noticeably smaller. Such a ratio is more characteristic of “(f)” stars (Mathys, 1988). Indeed, the relative strengths of the two lines closely resemble those observed in the O5III(f) star HD 168112 (see Fig. 5 of Sota et al., 2011). Following the classification scheme of Walborn and Fitzpatrick (1990) and Maíz Apellániz et al. (2016), while taking into account the similarity with HD 168112, we assign the qualifier “(f)” to the companion. Admittedly, the star lies very close to the boundary separating the “(f)” and “((f))” classes. A caveat is warranted. Since the publication of Mathys (1988), several of the reference stars have been recognised as binaries. This is notably the case for HD 168112 (Putkuri et al., 2023; Blomme et al., 2024), which is now classified as O4.5IV((f)) + O5.5V(n)((f)). These two components closely bracket the O5((f)) spectral type. Consequently, the original “(f)” classification has effectively become “((f))”. In their Sect. 3.2, Putkuri et al. (2023) review the history of the revision, illustrating the borderline nature of such classifications. A more recent study by Martins (2018) suggests to place the boundary between the “((f))” and “(f)” classes at $\text{EW}(\text{He II } \lambda 4686) = 600 \text{ mÅ}$. Using the representative EW of He II $\lambda 4542$ quoted above, the threshold of Martins (2018) corresponds to a ratio of 0.85. The observed value of 0.76 therefore clearly favours our “(f)” qualifier for the O5 component of WR 25. The presence of Si IV $\lambda 4116$ in emission provides observational support for adding a “+” suffix, yielding the classification O5(f⁺). The “f⁺” notation has been in use since Walborn (1971, see also Walborn and Fitzpatrick (1990), van der Hucht (1996), and references therein). Although it was originally associated with hot O-type supergiants, being an observational evidence, it has occasionally been applied to hot objects that are non supergiants (see, e.g., Walborn, 2001; Heap et al., 2006; Mokiem et al., 2006). Sota et al. (2011) regard this “+” suffix as non-essential and recommend that it be considered obsolete. In conclusion, we assign the spectral type O5(f⁺) to the companion, although the “+” suffix may be omitted if one follows the recommendation of Sota et al. (2011).

The He I $\lambda 4471$ line in Fig. 45 exhibits a slight asymmetry, which is a consequence of the blending effect described above. A few other lines also present this artefact.

The spectrum of the WN star shows a clear emission of the N IV $\lambda 4058$ line, and a well-marked P-Cygni profile at the N V $\lambda 4604$ transition. WR 25 is reputed to be a weak-lined WN

star. It has been classified as WN6ha according to the criteria of Smith et al. (1996), but Crowther and Walborn (2011) suggested that it should rather be classified O2.5If*/WN6 on the basis of various criteria involving N lines, as well as the presence of a marked absorption component in the He II $\lambda 4859 + H\beta$ P-Cygni profile. The uncertainties surrounding the classification as either an Of/WN or a WN star were discussed in Sect. 3 of Crowther and Walborn (2011). If we use the luminosities published by Crowther et al. (2023), we find that the ratio $L(4058)/L(4630)$ (where 4630 denotes the N v–N III complex) is 0.52 for WR 25, 0.48 for WR 24 (WN6ha), and 0.63 for the classical WN6 archetype WR 67 (classified as WN6o according to Smith et al., 1996). WR 25 therefore lies approximately midway between two WN6 stars. If we consider the height (normalised to the continuum) of the peak of N IV $\lambda 4058$ (see Figs. 1 and 4), it clearly exceeds that of the 4630 complex by at least a factor of 2. We therefore conclude that WR 25 is not very different from WR 24 in this respect. In our high-resolution spectra, the height of the emission component of the N v $\lambda 4604$ line (see Fig. 8) is between about 0.2 and 0.85 times that of the N III $\lambda\lambda 4634\text{--}4641$ triplet (see Fig. 20). This is not sufficiently discriminating, and a comparison with Table 2 of Crowther and Walborn (2011) does not rule out a pure WN6 spectral type. Therefore, the determining clue for classifying WR 25 as an Of/WN star, on which we must rely following the prescription of Crowther and Walborn (2011), is the presence of a marked absorption component in the He II $\lambda 4859 + H\beta$ profile, as can be seen in Fig. 1 of Crowther and Walborn (2011). This feature is also visible in our spectrum of WR 25, e.g., at phase 0.14 (see Fig. 33). Crowther and Walborn (2011) emphasised that this $H\beta$ -based criterion is not entirely secure and requires high-resolution spectra to support such a classification.

In Sect. 6.2, we suggested that this absorption component could, in the case of WR 25, be due to the presence of the O companion. Indeed, the disentangled spectrum of the WN component shows no strong absorption in the He II $\lambda 4859 + H\beta$ line (see Fig. 46). Only a weak absorption may be present around 4855–4856 Å. The absolute value of its equivalent width is smaller than that of the neighbouring N III $\lambda 4842$ line. Expressed in terms of the $H\beta$ index, this absorption component would correspond to a minimum value of 1.08 in the global $H\beta$ profile (see Fig. 35). Therefore, at some orbital phases, the prominent absorption observed in the $H\beta$ profile in WR 25 is absent. The component intrinsic to the WN star is very weak and occurs in a region of the profile that is sensitive to wind fluctuations (see Sect. 6.2). In fact, the main contribution to the absorption usually observed in the $H\beta$ line of WR 25 is predominantly due to the absorption associated with the O star and is not intrinsic to the WN component. Consequently, we advocate classifying the WR component in WR 25 as WN6ha, similarly to WR 24.

The weak-line character of WR 25 could perhaps be due to the dilution caused by the presence of the O companion. We selected the three strong emission lines N IV $\lambda 4058$, He II $\lambda 4686$, and He II $\lambda 6560 + H\alpha$. Based on the spectra from the dataset I_{glo} , we derive typical line heights of 0.58, 0.75 and 0.78, respectively. Performing the same analysis on a spectrum of WR 24 yields values of 0.78, 1.39 and 1.60, respectively. From these three lines, we estimate the dilution factors 0.74, 0.54, and 0.49, respectively. We thus derive brightness ratios ranging roughly between 0.5/0.5 and 0.26/0.74. This domain of ratios could be correct, but it is not sufficiently precise to allow further analysis. It is also very sensitive to the possible presence of a third

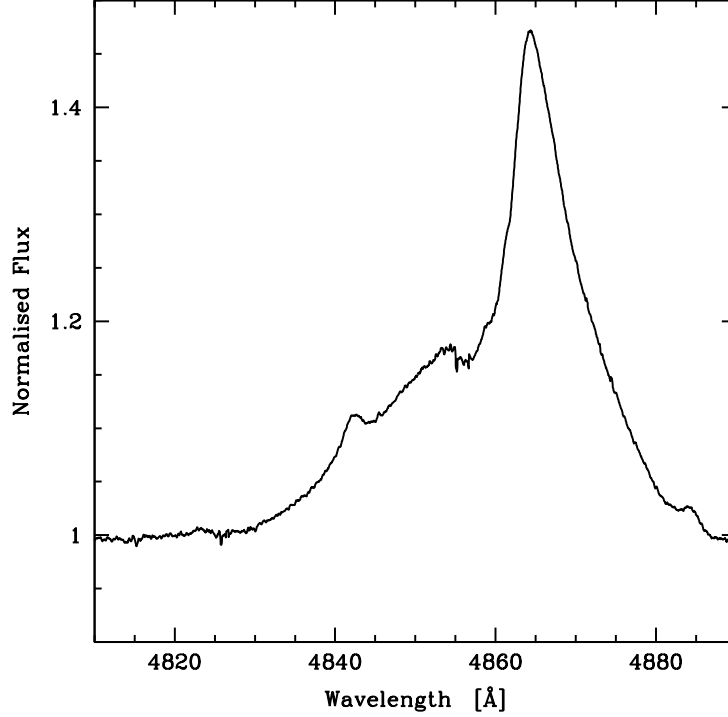


Figure 46: Disentangled spectrum of the WN component in the region of the He II $\lambda 4859 + \text{H}\beta$ line. The absence of any strong absorption component in the P-Cygni profile is conspicuous. It is interesting to note that the small emission lines N III $\lambda 4842$ and N III $\lambda\lambda 4882\text{--}4884$ are correctly attributed to the WN component by the disentangling procedure.

object. Another caveat is that WR 24 is not necessarily the best comparison object. Additional observations will be necessary to investigate this issue further. Assuming that the entire dilution is due to the O component, we derive a magnitude difference between the two objects of up to 1.1 mag.

7.3. Dilution of the O5 star lines

In the vicinity of spectral type O5, the EW of the He II $\lambda 4542$ line is rather constant. We estimated it above to be 705 (60) mÅ. If we restrict ourselves to HD 157857 and HD 303308 (which are not known to be binaries at the time of writing), we obtain a value of 725 mÅ, well within the error bar. The EW of this line in the disentangled spectrum of the O5 component is 360 mÅ, i.e. 180 mÅ as observed in the WR 25 spectrum. Given that the disentangled spectra have been corrected for the dilution factor (0.5), the measured EW is twice that measured in the observed spectra. Therefore, the EW of He II $\lambda 4542$ must be divided by a factor of 2. The dilution factor, mainly due to the presence of the WN, is thus 0.26, which leads to an estimated brightness ratio of 0.26/0.74.

The same exercise can be performed with H γ . Considering the EW of H γ of approximately spectral type O5, we can deduce from the works of Conti (1973a), Balona and Crampton (1974), and Cananzi et al. (1993) a typical EW of about 2000–2200 mÅ. The EW observed for the

O star component in the spectrum of WR 25 is 457 mÅ, leading to brightness ratios in the range 0.20/0.80 to 0.23/0.77, in good agreement with the above results derived from the He II line.

8. Additional Considerations

8.1. Brightness ratio, absolute magnitude and luminosity

We adopt an apparent magnitude $V = 8.1$ mag. for WR 25, as suggested by Smith (1968) (with the correction proposed by Massey and Conti, 1983), Feinstein (1969), Massey and Johnson (1993), Feinstein (1982), and Zacharias et al. (2013). The value of 8.8 mag. (Ducati, 2002) is probably erroneous and is not compatible with the *Gaia* value $G = 7.808$ mag. (*Gaia Collaboration*: Brown et al., 2021; *Gaia Collaboration*: Vallenari et al., 2023). The B magnitude of WR 25 is 8.55 (Zacharias et al., 2013) and a small or negative $B - V$ implies a very small value of $G - V$ (see the transformation in Fig. 15 of Carrasco et al., 2016). This underlines the incompatibility of the $V = 8.8$ mag. value. Alternatively, a $B - V$ of 0.45 (8.55–8.1) translates into $G - V = 0.13$ –0.25, yielding $V \approx 8.0$, in better agreement. WR 25 is not expected to follow exactly the characteristics of the stars used to establish the relations of Carrasco et al. (2016). Adopting a distance of 2.19 kpc for WR 25 (see the discussion in Sect. 8.3), we derive a distance modulus $DM = 11.7$ (or 11.9 considering the ALS III distance of 2.37–2.40 kpc). We therefore obtain

$$M_V + A_V = -3.6 \quad (\text{or } -3.8).$$

The evaluation of the absolute magnitude requires knowledge of the extinction. Unfortunately, this is hampered by the fact that the extinction inferred from the blue/UV range and that inferred from the red/NIR range are not mutually compatible. A large uncertainty remains, depending on whether one assumes a normal extinction law and thus the presence of a red/NIR excess, or an anomalous extinction law. A discussion of this issue is provided by Crowther et al. (1995). From the analyses of Crowther et al. (1995) and Hamann et al. (1993, 2019), we derive a range of A_V values between 1.9 and 3.4. Consequently, the absolute magnitude of WR 25, M_V , lies between -5.5 and -7.2 . This is a rigorous range of possible values, and the correct value, which remains unknown, is not necessarily close to the midpoint of the interval.

The reddening correction might be smaller if we use the H - and K -band magnitudes ($H = 5.970$ mag. and $K = 5.721$ mag.). The intrinsic $H - K$ colour is taken from Martins and Plez (2006) to be $(H - K)_0 = -0.10$. It is interesting to note that the value taken from Martins and Plez (2006) is independent of the actual spectral type of the O star. However, the use of O-star synthetic colours is a possible approximation. Synthetic colours for WN stars might be more appropriate, but no intrinsic $(H - K)_0$ for a WN star is available in the literature. We can instead refer to the analysis of WR 25 by Hamann et al. (2006), updated in Hamann et al. (2019), where the PoWR model characterised by $T_* = 50100$ K and a transformed radius $R_t = 1.5$ is associated with this star. This model is characterised by $(H - K)_0 = -0.025$. One should also be cautious with this value because the fit of Hamann et al. (2019) does not take into account the dilution effects due to the presence of the O5 companion. In addition, the temperature we attribute to the WN component in Sect. 9 is lower than that advocated by these

Table 3: Absolute magnitude M_V of WR 25 derived as a function of an unknown brightness ratio and from the three luminosity classes attributable to the O companion. Possible values are reported in bold (see text).

Brightness ratio	O5V $M_V = -5.21$	O5III $M_V = -5.85$	O5I $M_V = -6.33$
0.5/0.5	-5.96	-6.59	-7.08
0.4/0.6	-6.20	-6.83	-7.32
0.3/0.7	-6.52	-7.15	-7.64
0.2/0.8	-6.96	-7.59	-8.08
0.1/0.9	-7.71	-8.34	-8.83

authors. We then derive $E(H - K) = 0.35$ or 0.27 (adopting either the value from Martins and Plez (2006) or that from Hamann et al. (2019), respectively). From Indebetouw et al. (2005), $A_H \approx 2.8 \times E(H - K)$, where 2.8 is the mean of the values 2.6 and 3.0 provided by Nishiyama et al. (2009) and Fitzpatrick (1999), respectively. Using this relation and $DM = 11.7$, the absolute H band magnitude of the whole WR 25 system is $M_H = -6.71$ (0.10) or -6.50 (0.10), respectively.

For an assumed brightness ratio and luminosity class of the O star, we can compute the expected total M_V of WR 25. The results are presented in Table 3. Clearly, there is no room for an O5I companion in WR 25; only a main-sequence star or a giant is compatible with the observations. This conclusion reinforces the one drawn from the absence of the line N III $\lambda 4514$ (see Appendix E). The brightness ratio 0.1/0.9 must also be rejected. The lines of the O star are rather faint, making a brightness ratio of 0.5/0.5 very unlikely. Likewise, a brightness ratio of 0.2/0.8 is incompatible with an O5III companion. The acceptable values are highlighted in bold in Table 3. The constraint is not particularly strong, and it would be useful to have an independent way of estimating the brightness ratio. In particular, the possible intruder has not been taken into account in these computations.

Assuming a brightness ratio of 0.26/0.74 as derived in Sect. 7.3, a negligible effect of any intruder, and adopting the absolute V -band magnitude of WR 25, we obtain absolute magnitudes of $M_V^{\text{prim}} = -5.93 \pm 0.76$ for the WN primary and $M_V^{\text{seco}} = -4.80 \pm 0.76$ for the O5 secondary. These values are obtained by converting the range of possible absolute magnitudes discussed above. In this context, the quoted uncertainty of 0.76 does not represent a standard deviation associated with a statistical uncertainty, but rather the extent of the allowed range. Bolometric corrections were computed using the prescription of Martins and Plez (2006), based on the effective temperatures determined with the atmosphere code described in Sect. 9. We obtain $BC_V^{\text{prim}} = -3.99 \pm 0.13$ and $BC_V^{\text{seco}} = -3.74 \pm 0.14$ for the primary and secondary, respectively. Applying these corrections yields luminosities of $\log(L/L_\odot) = 5.87 \pm 0.35$ and $\log(L/L_\odot) = 5.31 \pm 0.35$ for the primary and secondary, respectively. Again, these values represent rigorous ranges of possible luminosities. Referring to Hamann et al. (2019) and their Table 1, we note

that the typical V -band bolometric correction for WN6h stars is $BC_V^{\text{prim}} = -4.2$; this is also the value attributed to WR 25. Using this alternative bolometric correction, we derive $\log(L/L_\odot) = 5.95 \pm 0.35$ for the primary, fully consistent with the previous estimate. Any more precise guess remains necessarily only prospective. Alternatively, to further constrain the discussion, one may adopt the anomalous extinction scenario advocated by Crowther et al. (1995). We therefore consider $A_V = 3.4$ and $M_V = -7.00$ as the most likely values for the extinction and the absolute magnitude of the system. In this case, we get $M_V^{\text{prim}} = -6.67$ for the primary, which yields $\log(L/L_\odot) = 6.16$ for $BC_V^{\text{prim}} = -3.99$, and $\log(L/L_\odot) = 6.24$ for $BC_V^{\text{prim}} = -4.2$. For the secondary, we derive $M_V^{\text{seco}} = -5.54$, corresponding to $\log(L/L_\odot) = 5.61$.

Using instead the absolute magnitude of WR 25 derived from the H band, and assuming the same brightness ratio, we obtain $M_H^{\text{prim}} = -6.38 \pm 0.10$ and $M_H^{\text{seco}} = -5.25 \pm 0.10$ for the WN primary and the O5 secondary, respectively. The corresponding bolometric corrections are $BC_H^{\text{prim}} = -4.80 \pm 0.14$ and $BC_H^{\text{seco}} = -4.54 \pm 0.15$. This leads to luminosities of $\log(L/L_\odot) = 6.37 \pm 0.07$ for the primary and $\log(L/L_\odot) = 5.81 \pm 0.07$ for the secondary. Alternatively, if we adopt the bolometric correction associated with WR 25 ($BC_H^{\text{prim}} = -4.95$), from de model of Hamann et al. (2019), we obtain $\log(L/L_\odot) = 6.43$ for the primary.

Although the uncertainty on the bolometric correction is not particularly severe, the luminosities derived from the V and H bands differ, depending on the adopted extinction. It is therefore essential to better constrain the extinction towards WR 25 and to obtain a more accurate determination of the brightness ratio between the two components.

An additional issue is the unknown effect of the possible intruder. We illustrate this in the framework of the adopted value $M_V = -7.00$. Since the brightness ratio 0.26/0.74 is estimated from the dilution of the lines of the O5 star, the possible intruder has no effect on the luminosity derived for this component, and we can therefore conclude that $\log(L_{\text{O5}}/L_\odot) = 5.61$. In contrast, the 74% of the brightness not attributed to the O5 star includes the combined contributions of the WN component and the intruder. To further fix ideas, let us assume that the intruder contributes half the visible brightness of the O5. The corresponding brightness ratios would then be intruder/O5/WN = 0.13/0.26/0.61. In this case, we obtain $M_V^{\text{WN}} = -6.46$ and $\log(L_{\text{WN}}/L_\odot) = 6.08$ or 6.16, depending on the adopted bolometric correction. The dependence of the results on the properties of the intruder is therefore not negligible.

8.2. Mass ratio and masses

Following the determination of K_{WN} and K_{O} in Sect. 7, we can compute the mass ratio of the system from the ratio of the semi-amplitudes:

$$q = \frac{M_{\text{WN}}}{M_{\text{O}}} = \frac{K_{\text{O}}}{K_{\text{WN}}} = 2.02 \quad (0.36).$$

This value is not particularly precise, but the uncertainty on q is dominated by the uncertainty on K_{O} . From this mass ratio and the mass function from the SB1 solution (see Table 2), we obtain

$$M_{\text{O}} \sin^3 i = f(M) \times (1 + q)^2 = 15.39 \quad (2.35) \quad M_\odot, \quad (1)$$

where i is the unknown inclination of the system. At this stage, we must make a strong assumption. If the companion is a canonical O star obeying the calibration of Martins et al. (2005), its mass can be taken as either $M_{\text{O5V}} = 37.3 M_{\odot}$ or $M_{\text{O5III}} = 41.5 M_{\odot}$. Using Eq. (1), we derive inclinations of $i = 48^{\circ}.1$ or $i = 45^{\circ}.9$, respectively. Such values are not unexpected given the apparent absence of eclipses (see Gosset et al., 2023). Assuming an O5V (or O5III) classification, we derive approximate masses for the WN component of $M_{\text{WN}} = 75.3 M_{\odot}$ (or $83.8 M_{\odot}$), respectively. These estimates remain highly uncertain. The masses provided by the calibration of Martins et al. (2005) carry uncertainties of 35–50%, suggesting that it would be misleading to quote formal error bars. In any case, we consider it unlikely that the O companion has a mass below $27 M_{\odot}$ which implies that the WN component has at least a mass of $55 M_{\odot}$. An O5-star mass of $27 M_{\odot}$ corresponds to an upper limit on the inclination of 56° . This minimum mass of $27 M_{\odot}$ for the O5 star is motivated by the masses determined for the components of HD 168112, as well as the accurately measured masses of the secondaries in HD 150136 and 9 Sgr (Putkuri et al., 2023; Mahy et al., 2018; Fabry et al., 2021). These results confirm that WR 25 is a very massive WNLh star belonging to the same family as WR 22 (Rauw et al., 1996; Schweickhardt et al., 1999), WR 29 (Gamen et al., 2009), both components of WR 20a (Rauw et al., 2005), and WR21a (Tramper et al., 2016; Barbá et al., 2022).

8.3. Semi-major axes

Based on the previously determined K , P , and e , we can compute the projected semi-major axes. We obtain

$$\begin{aligned} a_{\text{WN}} \sin i &= 0.816 (0.023) \text{ AU} \\ a_{\text{O}} \sin i &= 1.647 (0.298) \text{ AU} \\ a_{\text{tot}} \sin i &= (a_{\text{WN}} + a_{\text{O}}) \sin i = 2.463 (0.299) \text{ AU}. \end{aligned}$$

The deprojected semi-major axis of the system can be estimated, assuming the inclinations derived above, to lie between 3.31 and 3.43 AU, and certainly above 2.97 AU. At the *Gaia* (*Gaia Collaboration*: Prusti et al., 2016; *Gaia Collaboration*: Brown et al., 2021; *Gaia Collaboration*: Vallenari et al., 2023) DR3 distance of 2.19 (0.10) kpc (RUWE is 1.16; Bailer-Jones et al., 2021), the total projected semi-major axis corresponds to an angular separation on the sky of about 1.1–1.5 mas. On the basis of the same parallax but adopting a more recently derived zero-point and a prior better suited to hot stars, Pantaleoni González et al. (ALS III, 2025) derived alternative distances of $2.37^{+0.30}_{-0.24}$ kpc (median distance) or $2.40^{+0.30}_{-0.24}$ kpc (mean distance), which, if adopted, would lead to a 9% decrease of the separation on the sky, well within the uncertainties. These estimated separations are at the limit of what can be resolved using optical/IR long-baseline interferometry and could perhaps be observed, provided the close field is not too crowded.

9. CMFGEN Analysis

Now that the individual contributions for both components have been separated, we can perform an atmosphere-modelling analysis. We applied a brightness ratio of 0.26/0.74 to correct

the individual spectra for the dilution effect. This value was inspired by the work described in Sect. 7.3, but remains uncertain. We will refer to the resulting spectra as the *modified disentangled spectra*. To estimate the effective temperature (T_{eff}) and the surface gravity ($\log g$) of the O star, we used the CMFGEN atmosphere code (Hillier and Miller, 1998). CMFGEN computes non-LTE (Local Thermodynamic Equilibrium) models of massive-star atmospheres, including winds and line blanketing. The hydrodynamical structure consists of a hydrostatic photosphere and a wind. The trans-sonic velocity profile is assumed to follow a β -velocity law. The spectroscopic level populations are calculated through the rate equations. A super-level approach is used to reduce the size of the problem (and thus the computing time). To ensure good modelling of our observed spectra, we included the following elements in the calculations: H, He, C, N, O, Ne, Mg, Al, Si, S, Ar, Ca, Fe, and Ni. Solar abundances from Grevesse et al. (2010) were adopted for all elements unless otherwise stated. Once the atmospheric structure was obtained, a formal solution of the radiative transfer equation was computed.

9.1. The O star

9.1.1. Projected rotational velocities and macroturbulence

The projected rotational velocity ($v \sin i$) and the macroturbulent velocity (v_{mac}) were determined independently using the *iacob-broad* package of Simón-Díaz and Herrero (2014). Given the spectral type of the O star, He I lines are present in the spectrum but remain weak. Despite the asymmetry introduced by the spectral disentangling procedure, we selected the He I $\lambda 4471$ line, together with the He II $\lambda 4200$ line, to estimate the $v \sin i$ and v_{mac} . The He II lines are not ideally suited for determining these parameters, but given the faintness of the other He I lines and the difficulty of identifying strong metal lines in the spectra, they provide a useful alternative. The values of $v \sin i$ and v_{mac} were then kept fixed in the atmosphere analysis.

9.1.2. Effective temperature and surface gravity

The effective temperature, T_{eff} , and surface gravity, $\log g$, were estimated from a grid of synthetic CMFGEN spectra. The grid was constructed using the same stellar parameters as those adopted in the evolutionary tracks of Brott et al. (2011). We adopted a constant step in $\log g$ of $\Delta \log g = 0.1$. Appropriate values of T_{eff} and $\log(L/L_{\odot})$ were used to build the models, together with mass-loss rate prescriptions from Vink et al. (2000, 2001) for solar metallicity, scaled by a factor of three. We used the empirical terminal wind-speed prescription provided by Hawcroft et al. (2024). The exponent β of the velocity law was set to 1.0 (Repolust et al., 2004), and the clumping filling factor was adopted as $f_{\text{cl}} = 0.1$.

The final grid covers non-uniformly the ranges $10,000 \text{ K} < T_{\text{eff}} < 50,000 \text{ K}$ and $2.6 < \log(L/L_{\odot}) < 6.0$. For each model, a depth-dependent microturbulent velocity was used to compute the emergent spectrum. The microturbulence varies from 2, 5, 7, 10, 12, 15, 17, or 20 km s^{-1} at the photosphere to 10% of the terminal wind velocity at the top of the atmosphere. The final grid at Galactic metallicity comprises 4138 synthetic spectra.

The effective temperature was constrained through the ionisation balance between He I and He II lines. We used the He I/II $\lambda 4026$, He I $\lambda 4143$, He I $\lambda 4388$, He I $\lambda 4471$, He II $\lambda 4200$, He II $\lambda 4542$, and He II $\lambda 5412$ lines. The surface gravity was determined from the wings of the H δ and H γ lines, as these are less sensitive to wind effects than H β and H α . The quality of the fit was quantified by means of a χ^2 analysis applied to the spectral lines mentioned above. The χ^2 value was computed for each model in the grid and linearly interpolated between grid points with steps of $\Delta T_{\text{eff}} = 100$ K and $\Delta \log g = 0.01$ (cgs). The 1σ uncertainties on the two parameters were estimated from $\Delta\chi^2 = 2.30$ (for two degrees of freedom; Press et al., 2007).

For the O5 star, we find an effective temperature of $T_{\text{eff}} = 41400$ (2000) K (defined at the Rosseland optical depth $\tau_{\text{Ross}} = 2/3$), a surface gravity of $\log g = 3.85$ (0.05) cgs, a $\log(L/L_{\odot}) = 5.72$ (0.08), and a microturbulent velocity of 15 (5) km s $^{-1}$. The projected rotational velocity is $v \sin i = 85$ (17) km s $^{-1}$ and the macroturbulent velocity is $v_{\text{mac}} = 95$ (33) km s $^{-1}$. Figure 47 shows the comparison between the best-fit CMFGEN model (red), the models within the 1σ confidence interval (light red), and the modified disentangled spectrum of the O5 star (black).

The abundances of the metals were kept fixed at their solar values, as detailed abundance analysis is beyond the scope of this paper. A discrepancy is also present for the He II $\lambda 4686$ line which is known to be sensitive to wind properties.

9.2. The WN star

CMFGEN was also used to model the modified disentangled spectrum of the WN star. However, we carried out a preliminary by-eye fit, as the large number of physical parameters makes a fully automated approach difficult. A more robust atmosphere analysis of the individual components will be performed in Deshmukh et al. (in prep). The fitting process is further complicated by discrepancies between the synthetic and observed continua.

9.2.1. Atmosphere modelling

The effective temperature was estimated from the ionisation balance of the nitrogen lines (N III/N IV/N V). For most WR models, the value of $\log g$ has no significant impact on the synthetic spectrum, which is formed predominantly in the wind. We also varied the mass-loss rate, while keeping the surface abundances of nitrogen and carbon fixed at their solar values.

We find that the WN6ha star has an effective temperature $T_{*}(\text{WN6ha})$ of approximately 45 000 (2000) K, a mass-loss rate of about $\log(\dot{M}/(M_{\odot} \text{ yr}^{-1})) = -5.1$ (0.5), and a terminal wind speed $v_{\infty} = 2500$ (100) km s $^{-1}$. Finally, we fixed the luminosity to a typical value of $\log(L/L_{\odot}) = 6.0$, as some uncertainties remain regarding this parameter (see Sect. 8.1 for further discussion). We also fixed the clumping factor to 0.1 and the exponent of the β -velocity law to 1.0. In this sense, the fit should be regarded as preliminary. It is shown in Fig. 48. Alternatively, we may estimate the consequences of adopting a higher luminosity of $\log(L/L_{\odot}) = 6.3$. We find that an increase of 0.3 dex in luminosity has almost no effect on the synthetic spectrum, provided that the mass-loss rate is increased by 0.2–0.3 dex. No change of the temperature is required. The luminosity and mass-loss rate therefore have a correlated

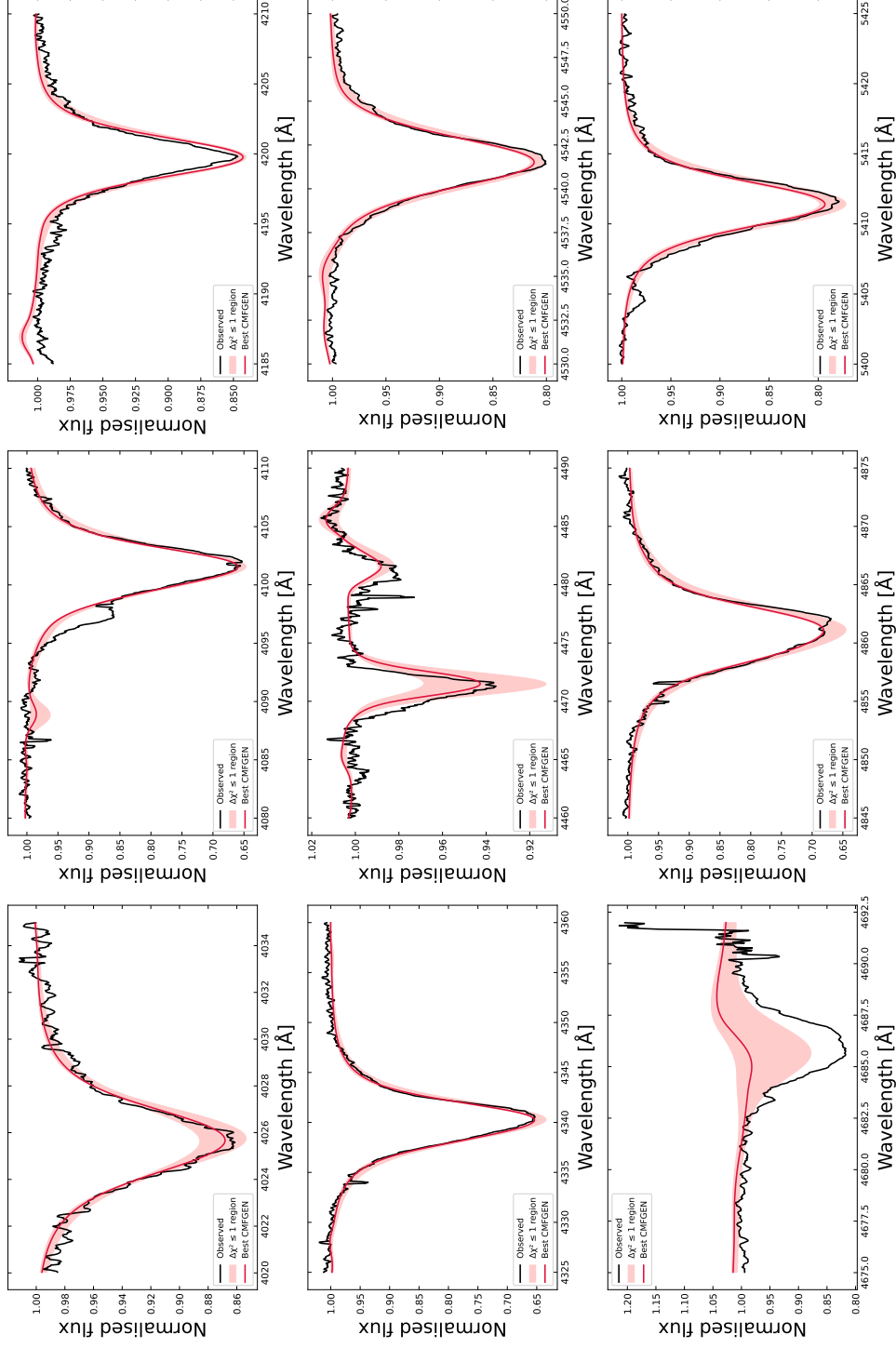


Figure 47: Comparison between the modified disentangled spectrum of the O5 star (black) and the best-fit CMFGEN model (red) in several spectral regions. The C, N, and O surface abundances were kept fixed at their solar values. The light red region indicates the range spanned by the synthetic spectra corresponding to models lying within the 1σ confidence interval of the best-fit solution.

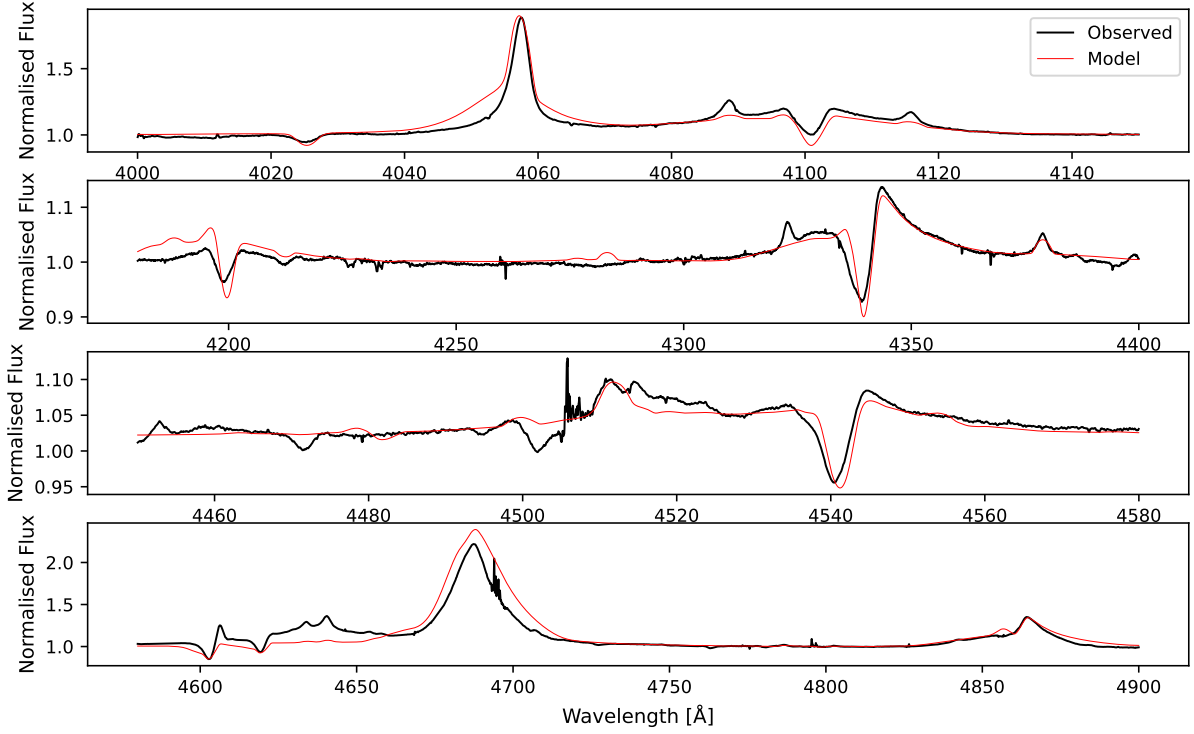


Figure 48: Comparison between the modified disentangled spectrum of the WN star (black) and the best-fit CMFGEN model (red) in selected spectral regions.

impact, at least in the relevant region of parameter space. This further underlines the need for accurate brightness ratios.

The disentangled spectrum of the WN6ha star shows the presence of the He I $\lambda 4471$ line (see Figs. 48 and E.2). Given the temperature estimated from the CMFGEN fit, no He I $\lambda 4471$ line should be present. This strengthens the conclusion that the spectrum of WR 25 is composed not of two but of three objects, including an additional OB component cooler than the O5 secondary star. According to our analysis, this object must either be gravitationally bound to the system or lie along its line of sight.

9.2.2. *The potential intruder*

We attempt to characterise the nature of the potential third object. To this end, we measured the equivalent width (EW) of the He I $\lambda 4471$ line in the observed spectrum taken at orbital phase 0.98 (see Sect. 6.4). The He I $\lambda 4471$ lines of the O5 star and of the intruder are expected to be diluted by the WN star in the same way; therefore, the ratio of their EWs is preserved. Assuming that the blue-shifted absorption profile originates from a third object and that the red-shifted one arises from the O5 star, we measure EWs of 0.054 Å and 0.023 Å respectively, yielding an absolute ratio (O5 over intruder) of 0.41.

This ratio is then multiplied by the dilution ratio between the O5 and the third object. This dilution is not known, and depends on the nature of the third object. We tentatively estimated it

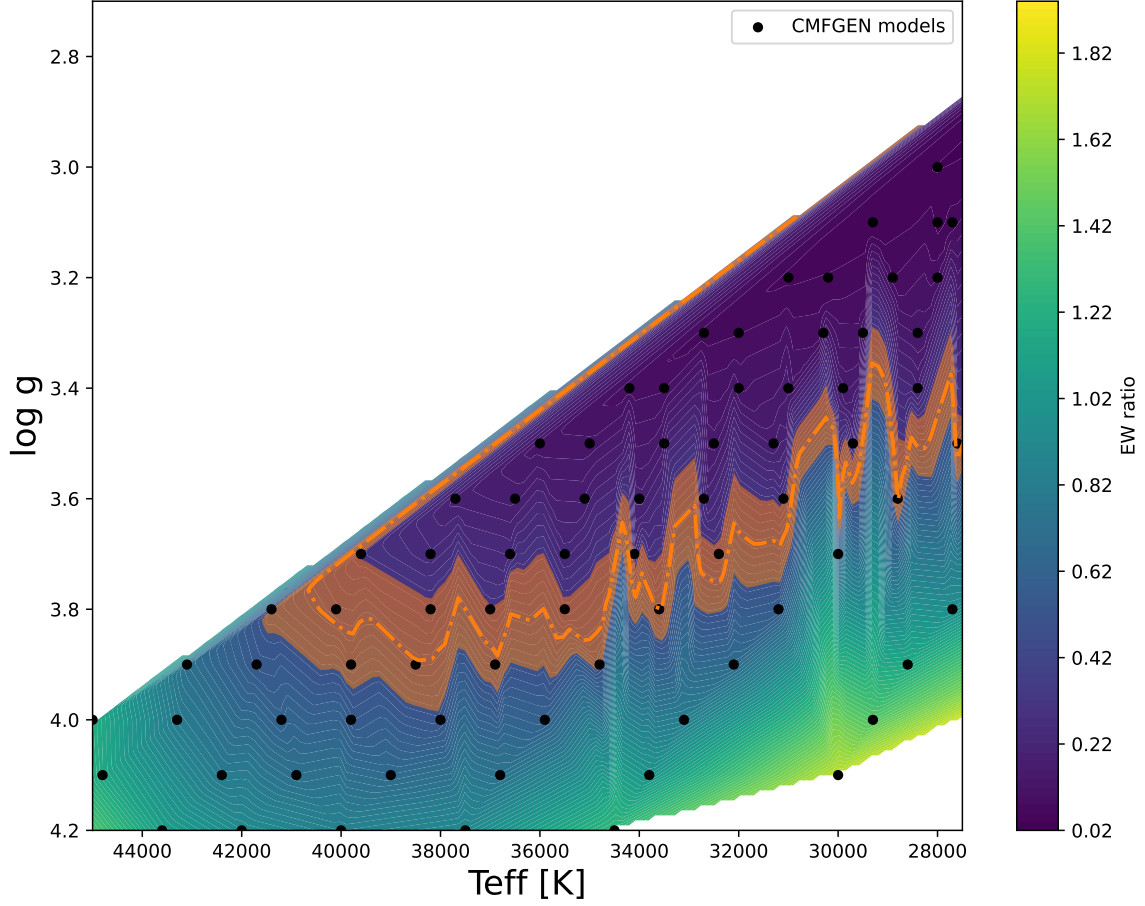


Figure 49: Constraint on the effective temperature of the third object based on the He I $\lambda 4471$ equivalent-width ratio. The orange region shows CMFGEN models whose predicted EW ratios between the O5 component and the intruder reproduce the observed ratio of 0.41 within uncertainties.

by simulating the fluxes in the V band of two black bodies with temperatures corresponding to those of the O5 star and the third object. For each model in our grid (tentatively representing the third star), the dilution ratio was estimated and applied to the EW ratio of the two He I $\lambda 4471$ lines. We then compared this result with the absolute EW ratios computed between the best-fit CMFGEN model for the O5 star and all synthetic spectra in the CMFGEN grid. These ratios must agree within the uncertainties. A conservative uncertainty of 0.1 is adopted to account for potential differences between the estimated dilution ratio and the true dilution ratio of the two stars. All models for which the absolute ratios are consistent with 0.41 are selected. In Fig. 49, the orange region corresponds to the set of models satisfying this criterion (the orange diagonal line is an artefact, and must not be considered physical).

Assuming that the intruder is coeval with the primary and secondary components (i.e., that it is a main-sequence star or a giant), its effective temperature is estimated to lie between 34 000 and 41 000 K, corresponding to a spectral type between O8 and O6. We implicitly assumed that the intruder is located at the same distance as the binary system, which remains to be

demonstrated. Here again, an independent determination of the brightness ratios is a crucial next step.

9.3. Comments

The CMFGEN analysis was performed on the modified disentangled spectra, assuming a brightness ratio 0.26/0.74. This value is certainly not fully secure, and in this sense, the results should be regarded as preliminary. However, we consider the results of the analysis of the O5 spectrum to be reasonably robust. The derived temperature is in good agreement with the inferred spectral type, which is determined independently of the adopted brightness ratio.

The analysis case of the WN component is more problematic, as the disentangled spectrum appears to exhibit He I lines that are not compatible with the temperature expected for a WN6ha star. This suggests the presence of a third object, for which we have neither much information nor any secure knowledge of its impact on the brightness ratio. We just demonstrated that this object is cooler than the two components of the main binary system. Owing to the lack of information on the contributions of each of the three objects to the total brightness, a more detailed analysis, such as a three-component disentangling, is beyond the scope of the present paper.

10. Conclusion

We acquired new high-resolution optical spectroscopic data of the binary star WR 25. These new observations, sometimes combined with older ones, were carefully analysed and improved the phase coverage of the 208 d period exhibited by the RV variations of the WN star, first discovered by Gamen et al. (2006). The data allowed us to derive new SB1 ephemerides that are significantly more accurate than the preliminary orbital solution proposed by Gamen et al. (2006). The resulting orbital parameters are given in the fourth column of Table 2. We derive a semi-amplitude of $K_{\text{WN}} = 53.18 (0.82) \text{ km s}^{-1}$. These results are based on a few selected lines that are expected to provide an adequate representation of the orbital motion of the WN component.

A fainter contribution to the WR 25 spectrum is present and can be attributed to an O star, as first pointed out by Gamen et al. (2008). In the present work, we identified this additional component in several spectroscopic lines and provided definitive proof that it originates from an O star gravitationally bound to the WN component. Unfortunately, the O-star contribution is not easily detectable at all orbital phases and is often blended with the absorption lines of the WN component. To measure and constrain the RV semi-amplitude of the O star, we applied spectral disentangling techniques that provided $K_{\text{O}} = 107.36 (19.24) \text{ km s}^{-1}$ and thus a mass ratio of 2.02 (0.36). These values remain relatively uncertain. Taking the mass ratio at face value and assuming that the O star is a canonical star following the calibration of Martins et al. (2005), we derived a mass for the WN component in the range $75\text{--}84 M_{\odot}$, and certainly above $55 M_{\odot}$. This confirms that WR 25 is, as suspected, a very massive star similar to the class of WNLh objects. After completion of the present work, a broadly comparable SB2 solution was

Table 4: Physical parameters of the WN6ha and O5 stars and their 1σ errors.

Parameter	WN6ha	O5
T_* [K]	45000 (2000)	—
T_{eff} [K]	—	41400 (2000)
$\log g$ [cgs]	—	3.85 (0.05)
$v \sin i$ [km s $^{-1}$]	—	85 (17)
v_{mac} [km s $^{-1}$]	—	95 (33)

also obtained by applying a disentangling technique to the available FEROS spectra. This result will be presented in a forthcoming paper (in preparation) describing the SB2 orbital solutions from the OWN Survey (see, e.g., Barbá et al., 2017, for details of the project).

From the disentangled spectrum of the WN component, we confirm the WN6ha classification identification. We demonstrated that the absorption component of the H β P-Cygni profile observed in WR 25 during most of the time is not intrinsic to the WN star, but instead originates from the O-star companion. We therefore argue against the O2.5If*/WN6ha classification proposed by Crowther and Walborn (2011) for WR 25. This conclusion relies primarily on our use of high-resolution, high-S/N spectra,

WR 25 is often regarded as a weak-line WN star with the highest known hydrogen content among the Galactic WNLh stars and exhibiting absorption in the upper Balmer lines. We confirmed the presence of numerous absorption lines, many of which are blended with those of the O-star companion. We also argued that the relative faintness of the emission lines in the normalised spectra is primarily due to dilution by the O companion. Our high-S/N data allowed us to detect, and subsequently confirm through spectral disentangling, the presence of several weak N III lines that are also observed in WR 24 and WR 78 (see Sect. 3.1). The spectrum of the WN component appears to exhibit a He I λ 4471 line, although this feature could in fact originate from an intruder (Sects. 6.4 and 9.2.2). Using a CMFGEN analysis of the WN spectrum, we derived physical parameters for the WN6ha object (see Table 4 for the temperature). The difficulty in reproducing the He I lines in the disentangled spectrum of the WN component suggests that an additional, probably late O type, star contributes to the composite spectrum of WR 25.

The gravitationally bound companion was found to be of spectral type O5(f $^+$). Its luminosity class is either main-sequence (V) or giant (III), but certainly not a supergiant. A detailed CMFGEN analysis yielded the physical parameters listed in Table 4.

The absolute magnitude of WR 25, and consequently its luminosity, remain difficult to determine. In the *Gaia* era, this uncertainty is dominated by the poorly constrained interstellar extinction. This stems from the well-established inconsistency between the extinction inferred from the blue/UV domain and derived from the red/NIR domain (see, e.g., Sect. 4.2 of Crowther et al., 1995).

An improved understanding of WR 25 will certainly require a substantial observational effort. We identified two main avenues for future progress. First, we found only one secure spectral line of the O star that appears suitable for deriving a precise orbital motion, namely O III λ 5592. This line is present in the O-star spectrum and lies in a spectral region where the WN component exhibits almost no features. However, this line is faint and has a depth of only about 1% of the continuum. Its exploitation will therefore require spectra with even higher S/N ratios than those currently available, while maintaining the same spectral resolution. The search for additional lines of this kind, possibly even in other wavelength domains, could also prove beneficial. Acquiring extremely high-S/N data over the 208 d orbital period of the system represents a genuine observational challenge. Second, a precise determination of the brightness ratio is still lacking. Such a measurement is essential to improve the luminosity estimates of both components, and to better quantify line-dilution effects. This will also allow us to assess the intrinsic luminosities of the WN emission lines, beyond spectrophotometric analyses. The projected separation of both objects on the sky is probably slightly larger than 1 mas, making long-baseline interferometry the only technique currently capable of directly addressing this issue. Although this lies at the limit of present-day capabilities, such observations could yield the orbital inclination of the system (provided that the close environment is not excessively crowded) and thus the absolute masses of the components. A first exploratory observation will be reported by Deshmukh et al. (in preparation).

Acknowledgments

The authors are thankful to the two anonymous referees who contributed to the improvement of the paper. This work is based on data collected at the European Southern Observatory (La Silla, Chile) and at the Las Campanas Observatory (Chile), including one observation at the Magellan II (Clay) 6.5-m Telescope. The raw data were processed using the MIDAS and IRAF reduction packages. This study used IRAF versions 2.13, 2.14, 2.15 and 2.16, which were developed at the National Optical Astronomy Observatories (NOAO, now integrated into the National Optical-Infrared Astronomy Research Laboratory, NOIRLab). These facilities, as well as NSF NOIRLab, are operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under a cooperative agreement with the U.S. National Science Foundation (NSF). The first author would like to acknowledge discussions with Pascal Quinet about atomic transitions and related databases. He is also greatly indebted to Alain Detal and Francine Mélen for various forms of support related to computing. The Belgian Fund for Scientific Research—F.R.S.-FNRS has provided financial support that was essential for this project.

Further Information

Author contributions

The spectroscopic observational campaign was organised by EG on the European Southern Observatory side and by RG, NM and RB on the Las Campanas Observatory side. HS performed

the basic FEROS reduction, as well as the global continuum normalisation. RG performed the basic reduction of the Las Campanas data. LM contributed to the spectral disentangling and performed the detailed CMFGEN analysis. EG, RG and LM are responsible for the detailed analysis. EG wrote the original draft of the paper and directed the review and editing of the final version, with input from RG, LM, NM and HS.

Conflicts of interest

The authors declare that there is no conflict of interest.

Authors' ORCID identifiers

0000-0002-5536-5993 (Eric GOSSET)

0000-0002-5227-9627 (Roberto GAMEN)

0000-0003-0688-7987 (Laurent MAHY)

0000-0003-2535-3091 (Nidia MORRELL)

0000-0001-6656-4130 (Hugues SANA)

0000-0003-1086-1579 (Rodolfo H. BARBÁ)

References

- Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R. X., Adya, V. B., and 1001 *more* (LIGO Scientific Collaboration and Virgo Collaboration) (2016) Observation of gravitational waves from a binary black hole merger. *PhRvL*, **116**(6), 061102. <https://doi.org/10.1103/PhysRevLett.116.061102>.
- Anders, E. and Grevesse, N. (1989) Abundances of the elements: Meteoritic and solar. *GeCoA*, **53**(1), 197–214. [https://doi.org/10.1016/0016-7037\(89\)90286-X](https://doi.org/10.1016/0016-7037(89)90286-X).
- Arora, B., Pandey, J. C., and De Becker, M. (2019) Long-term soft and hard X-ray investigation of the colliding wind WN+O binary WR 25. *MNRAS*, **487**(2), 2624–2638. <https://doi.org/10.1093/mnras/stz1447>.
- Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., and Andrae, R. (2021) Estimating distances from parallaxes. V. Geometric and photogeometric distances to 1.47 billion stars in *Gaia* Early Data Release 3. *AJ*, **161**(3), 147. <https://doi.org/10.3847/1538-3881/abd806>.
- Balona, L. and Crampton, D. (1974) The Hy-absolute magnitude calibration. *MNRAS*, **166**, 203–217. <https://doi.org/10.1093/mnras/166.1.203>.
- Banyard, G., Sana, H., Mahy, L., Bodensteiner, J., Villaseñor, J. I., and Evans, C. J. (2022) The observed multiplicity properties of B-type stars in the Galactic young open cluster NGC 6231. *A&A*, **658**, A69. <https://doi.org/10.1051/0004-6361/202141037>.

- Barbá, R. H., Gamen, R., Arias, J. I., and Morrell, N. I. (2017) OWN survey: a spectroscopic monitoring of Southern Galactic O and WN-type stars. In *The Lives and Death-Throes of Massive Stars*, edited by Eldridge, J. J., Bray, J. C., McClelland, L. A. S., and Xiao, L., *IAU Symposium*, volume 329, pages 89–96. <https://doi.org/10.1017/S1743921317003258>.
- Barbá, R. H., Gamen, R. C., Martín-Ravelo, P., Arias, J. I., and Morrell, N. I. (2022) The winking eye of a very massive star: WR 21a revealed as an eclipsing binary by *TESS*. *MNRAS*, **516**(1), 1149–1157. <https://doi.org/10.1093/mnras/stac2173>.
- Blomme, R., Rauw, G., Volpi, D., Nazé, Y., and Abdul-Masih, M. (2024) The colliding-wind binary HD 168112. *A&A*, **687**, A106. <https://doi.org/10.1051/0004-6361/202450227>.
- Brott, I., de Mink, S. E., Cantiello, M., Langer, N., de Koter, A., Evans, C. J., Hunter, I., Trundle, C., and Vink, J. S. (2011) Rotating massive main-sequence stars. I. Grids of evolutionary models and isochrones. *A&A*, **530**, A115. <https://doi.org/10.1051/0004-6361/201016113>.
- Cananzi, K., Augarde, R., and Lequeux, J. (1993) An atlas of Balmer lines (H δ and H γ). *A&AS*, **101**, 599–619. <https://ui.adsabs.harvard.edu/abs/1993A&AS..101..599C>.
- Carrasco, J. M., Evans, D. W., Montegriffo, P., Jordi, C., van Leeuwen, F., Riello, M., Voss, H., De Angeli, F., Busso, G., Fabricius, C., and 17 more (2016) *Gaia* Data Release 1. Principles of the photometric calibration of the *G* band. *A&A*, **595**, A7. <https://doi.org/10.1051/0004-6361/201629235>.
- Cherepashchuk, A. M. (1976) Detectability of Wolf–Rayet binaries from X-rays. *SvAL*, **2**(4), 138–139. <https://ui.adsabs.harvard.edu/abs/1976SvAL....2..138C>.
- Conti, P. S. (1973a) Spectroscopic studies of O-type stars. II. Comparison with non-LTE models. *ApJ*, **179**, 161–179. <https://doi.org/10.1086/151856>.
- Conti, P. S. (1973b) Spectroscopic studies of O-type stars. III. The effective-temperature scale. *ApJ*, **179**, 181–188. <https://doi.org/10.1086/151857>.
- Conti, P. S. and Alschuler, W. R. (1971) Spectroscopic studies of O-Type stars. I. Classification and absolute magnitudes. *ApJ*, **170**, 325–344. <https://doi.org/10.1086/151218>.
- Conti, P. S., Leep, E. M., and Lorre, J. J. (1977) Spectroscopic studies of O-type stars. VIII. Radial velocities and the *K*-term. *ApJ*, **214**(3), 759–772. <https://doi.org/10.1086/155305>.
- Crowther, P. A., Rate, G., and Bestenlehner, J. M. (2023) Line luminosities of Galactic and Magellanic Cloud Wolf–Rayet stars. *MNRAS*, **521**(1), 585–612. <https://doi.org/10.1093/mnras/stad418>.
- Crowther, P. A., Smith, L. J., Hillier, D. J., and Schmutz, W. (1995) Fundamental parameters of Wolf–Rayet stars. III. The evolutionary status of WNL stars. *A&A*, **293**, 427–445. <https://ui.adsabs.harvard.edu/abs/1995A&A...293..427C>.

- Crowther, P. A. and Walborn, N. R. (2011) Spectral classification of O2–3.5 If*/WN5–7 stars. *MNRAS*, **416**(2), 1311–1323. <https://doi.org/10.1111/j.1365-2966.2011.19129.x>.
- Ducati, J. R. (2002) Catalogue of stellar photometry in Johnson’s 11-color system (2002). VizieR Online Data Catalog, Cat. II/237. <https://cdsarc.cds.unistra.fr/viz-bin/cat/II/237>.
- Dunstall, P. R., Dufton, P. L., Sana, H., Evans, C. J., Howarth, I. D., Simón-Díaz, S., de Mink, S. E., Langer, N., Maíz Apellániz, J., and Taylor, W. D. (2015) The VLT-FLAMES Tarantula Survey. XXII. Multiplicity properties of the B-type stars. *A&A*, **580**, A93. <https://doi.org/10.1051/0004-6361/201526192>.
- Fabry, M., Hawcroft, C., Frost, A. J., Mahy, L., Marchant, P., Le Bouquin, J.-B., and Sana, H. (2021) Resolving the dynamical mass tension of the massive binary 9 Sagittarii. *A&A*, **651**, A119. <https://doi.org/10.1051/0004-6361/202140452>.
- Feinstein, A. (1969) The OB stars in Carina-Centaurus. *MNRAS*, **143**(3), 273–287. <https://doi.org/10.1093/mnras/143.3.273>.
- Feinstein, A. (1982) Faint stars in the open cluster Trumpler 16. *AJ*, **87**(7), 1012–1021. <https://doi.org/10.1086/113183>.
- Fitzpatrick, E. L. (1999) Correcting for the effects of interstellar extinction. *PASP*, **111**(755), 63–75. <https://doi.org/10.1086/316293>.
- Frost, A. J., Sana, H., Mahy, L., Wade, G., Barron, J., Le Bouquin, J.-B., Mérand, A., Schneider, F. R. N., Shenar, T., Barbá, R. H., Bowman, D. M., Fabry, M., Farhang, A., Marchant, P., Morrell, N. I., and Smoker, J. V. (2024) A magnetic massive star has experienced a stellar merger. *Sci*, **384**, 214–217. <https://doi.org/10.1126/science.adg7700>.
- Gaia Collaboration*: Brown, A. G. A., Vallenari, A., Prusti, T., de Bruijne, J. H. J., Babusiaux, C., Biermann, M., Creevey, O. L., Evans, D. W., Eyer, L., Hutton, A., and 415 more (2021) *Gaia* Early Data Release 3. Summary of the contents and survey properties. *A&A*, **649**, A1. <https://doi.org/10.1051/0004-6361/202039657>.
- Gaia Collaboration*: Prusti, T., de Bruijne, J. H. J., Brown, A. G. A., Vallenari, A., Babusiaux, C., Bailer-Jones, C. A. L., Bastian, U., Biermann, M., Evans, D. W., Eyer, L., and 615 more (2016) The *Gaia* mission. *A&A*, **595**, A1. <https://doi.org/10.1051/0004-6361/201629272>.
- Gaia Collaboration*: Vallenari, A., Brown, A. G. A., Prusti, T., de Bruijne, J. H. J., Arenou, F., Babusiaux, C., Biermann, M., Creevey, O. L., Ducourant, C., Evans, D. W., and 445 more (2023) *Gaia* Data Release 3. Summary of the content and survey properties. *A&A*, **674**, A1. <https://doi.org/10.1051/0004-6361/202243940>.
- Gamen, R., Gosset, E., Morrell, N., Niemela, V., Sana, H., Nazé, Y., Rauw, G., Barbá, R., and Solivella, G. (2006) The first orbital solution for the massive colliding-wind binary HD 93162 ($\equiv$ WR 25). *A&A*, **460**(3), 777–782. <https://doi.org/10.1051/0004-6361:20065618>.

- Gamen, R., Gosset, E., Morrell, N. I., Niemela, V. S., Sana, H., Nazé, Y., Rauw, G., Barbá, R. H., and Solivella, G. R. (2008) The first orbital solution for the massive colliding-wind binary HD 93162 ($\equiv$ WR 25). In *Massive Stars: Fundamental Parameters and Circumstellar Interactions*, edited by Benaglia, P., Bosch, G., and Cappa, C., *RMxAC*, volume 33, pages 91–93. <https://astronomia.unam.mx/journals/rmxac/article/view/2008rmxac..33...91g>.
- Gamen, R. C., Fernández-Lajús, E., Niemela, V. S., and Barbá, R. H. (2009) The massive Wolf–Rayet binary LSS 1964 (= WR 29). II. The v light curve. *A&A*, **506**(3), 1269–1275. <https://doi.org/10.1051/0004-6361/200810112>.
- Gosset, E., Damerdjí, Y., Morel, T., Delchambre, L., Halbwachs, J. L., Sadowski, G., Pourbaix, D., Sozzetti, A., Panuzzo, P., and Arenou, F. (2025) *Gaia* Data Release 3: Spectroscopic binary-star orbital solutions: The SB1 processing chain. *A&A*, **693**, A124. <https://doi.org/10.1051/0004-6361/202450600>.
- Gosset, E., Gamen, R., Mahy, L., Morrell, N., Sana, H., and Barba, R. (2023) New progresses on the spectroscopic orbital solution for the colliding-wind binary WR 25. Oral communication at the colloquium ‘The Wolf–Rayet phenomenon in the Universe’ held in Morelia (Mexico), June 19–23, 2023 (available at <https://hdl.handle.net/2268/334901>).
- Gosset, E. and Nazé, Y. (2016) The X-ray light curve of the massive colliding wind Wolf–Rayet + O binary WR 21a. *A&A*, **590**, A113. <https://doi.org/10.1051/0004-6361/201527051>.
- Gosset, E., Rauw, G., Manfroid, J., Vreux, J.-M., and Sterken, C. (1994) Photometric monitoring of Wolf–Rayet stars: Strömgren *uvby* and narrow-band photometry. In *The Impact of Long-Term Monitoring on Variable Star Research: Astrophysics, Instrumentation, Data Handling, Archiving*, edited by Sterken, C. and de Groot, M., *NATO Advanced Study Institute (ASI) Series C*, volume 436, pages 101–116. Kluwer Academic Publishers, Dordrecht (NL). https://doi.org/10.1007/978-94-011-1164-5_9.
- Gosset, E., Royer, P., Rauw, G., Manfroid, J., and Vreux, J. M. (2001) A first detailed study of the colliding wind WR+O binary WR 30a. *MNRAS*, **327**(2), 435–451. <https://doi.org/10.1046/j.1365-8711.2001.04755.x>.
- Grevesse, N., Asplund, M., Sauval, A. J., and Scott, P. (2010) The chemical composition of the Sun. *Ap&SS*, **328**(1-2), 179–183. <https://doi.org/10.1007/s10509-010-0288-z>.
- Hadrava, P. (1995) Orbital elements of multiple spectroscopic stars. *A&AS*, **114**, 393–396. <https://ui.adsabs.harvard.edu/abs/1995A&AS..114..393H>.
- Hamann, W.-R., Gräfener, G., and Liermann, A. (2006) The Galactic WN stars. Spectral analyses with line-blanketed model atmospheres versus stellar evolution models with and without rotation. *A&A*, **457**(3), 1015–1031. <https://doi.org/10.1051/0004-6361:20065052>.
- Hamann, W. R., Gräfener, G., Liermann, A., Hainich, R., Sander, A. A. C., Shenar, T., Ramachandran, V., Todt, H., and Oskinova, L. M. (2019) The Galactic WN stars re-

- visited: Impact of *Gaia* distances on fundamental stellar parameters. *A&A*, **625**, A57. <https://doi.org/10.1051/0004-6361/201834850>.
- Hamann, W. R., Koesterke, L., and Wessolowski, U. (1993) Spectral analyses of the galactic Wolf–Rayet stars: a comprehensive study of the WN class. *A&A*, **274**, 397–414. <https://ui.adsabs.harvard.edu/abs/1993A&A...274..397H>.
- Hawcroft, C., Sana, H., Mahy, L., Sundqvist, J. O., de Koter, A., Crowther, P. A., Bestenlehner, J. M., Brands, S. A., David-Uraz, A., Decin, L., and 19 *others* (2024) X-shooting ULLYSES: Massive stars at low metallicity. III. Terminal wind speeds of ULLYSES massive stars. *A&A*, **688**, A105. <https://doi.org/10.1051/0004-6361/202245588>.
- Heap, S. R., Lanz, T., and Hubeny, I. (2006) Fundamental properties of O-Type stars. *ApJ*, **638**(1), 409–432. <https://doi.org/10.1086/498635>.
- Heck, A., Manfroid, J., and Mersch, G. (1985) On period determination methods. *A&AS*, **59**, 63–72. <https://ui.adsabs.harvard.edu/abs/1985A&AS...59...63H>.
- Hillier, D. J. and Miller, D. L. (1998) The treatment of non-LTE line blanketing in spherically expanding outflows. *ApJ*, **496**(1), 407–427. <https://doi.org/10.1086/305350>.
- Ilijic, S. (2004) Thoughts about disentangling in wavelength and in Fourier-space. In *Spectroscopically and Spatially Resolving the Components of the Close Binary Stars*, edited by Hilditch, R. W., Hensberge, H., and Pavlovski, K., *Astronomical Society of the Pacific Conference Series*, volume 318, pages 107–110. https://www.aspbooks.org/a/volumes/article_details/?paper_id=140.
- Indebetouw, R., Mathis, J. S., Babler, B. L., Meade, M. R., Watson, C., Whitney, B. A., Wolff, M. J., Wolfire, M. G., Cohen, M., Bania, T. M., Benjamin, R. A., Clemens, D. P., Dickey, J. M., Jackson, J. M., Kobulnicky, H. A., Marston, A. P., Mercer, E. P., Stauffer, J. R., Stolovy, S. R., and Churchwell, E. (2005) The wavelength dependence of interstellar extinction from 1.25 to 8.0 μm using GLIMPSE data. *ApJ*, **619**(2), 931–938. <https://doi.org/10.1086/426679>.
- Kaufer, A., Stahl, O., Tubbesing, S., Nørregaard, P., Avila, G., Francois, P., Pasquini, L., and Pizzella, A. (1999) Commissioning FEROS, the new high-resolution spectrograph at La Silla. *Msngr*, **95**, 8–12. <https://www.eso.org/sci/publications/messenger/archive/no.95-mar99/messenger-no95-8-12.pdf>.
- Li, S., Frank, A., and Blackman, E. G. (2014) Triggered star formation and its consequences. *MNRAS*, **444**(3), 2884–2892. <https://doi.org/10.1093/mnras/stu1571>.
- Lucy, L. B. and Sweeney, M. A. (1971) Spectroscopic binaries with circular orbits. *AJ*, **76**(6), 544–556. <https://doi.org/10.1086/111159>.
- Luo, D., McCray, R., and Mac Low, M.-M. (1990) X-rays from colliding stellar winds. *ApJ*, **362**(1), 267–273. <https://doi.org/10.1086/169263>.

- Mahy, L., Damerdj, Y., Gosset, E., Nitschelm, C., Eenens, P., Sana, H., and Klotz, A. (2017) A modern study of HD 166734: a massive supergiant system. *A&A*, **607**, A96. <https://doi.org/10.1051/0004-6361/201730674>.
- Mahy, L., Gosset, E., Manfroid, J., Nitschelm, C., Hervé, A., Semaan, T., Sana, H., Le Bouquin, J. B., and Toonen, S. (2018) The triple system HD 150136: From periastron passage to actual masses. *A&A*, **616**, A75. <https://doi.org/10.1051/0004-6361/201832810>.
- Mahy, L., Hutsemékers, D., Royer, P., and Waelkens, C. (2016) Tracing back the evolution of the candidate LBV HD 168625. *A&A*, **594**, A94. <https://doi.org/10.1051/0004-6361/201628584>.
- Mahy, L., Lanthermann, C., Hutsemékers, D., Kluska, J., Lobel, A., Manick, R., Miszalski, B., Reggiani, M., Sana, H., and Gosset, E. (2022a) Multiplicity of Galactic luminous blue variable stars. *A&A*, **657**, A4. <https://doi.org/10.1051/0004-6361/202040062>.
- Mahy, L., Sana, H., Shenar, T., Sen, K., Langer, N., Marchant, P., Abdul-Masih, M., Banyard, G., Bodensteiner, J., Bowman, D. M., Dsilva, K., Fabry, M., Hawcroft, C., Janssens, S., Van Reeth, T., and Eldridge, C. (2022b) Identifying quiescent compact objects in massive Galactic single-lined spectroscopic binaries. *A&A*, **664**, A159. <https://doi.org/10.1051/0004-6361/202243147>.
- Maíz Apellániz, J., Sota, A., Arias, J. I., Barbá, R. H., Walborn, N. R., Simón-Díaz, S., Negueruela, I., Marco, A., Leão, J. R. S., Herrero, A., Gamen, R. C., and Alfaro, E. J. (2016) The Galactic O-Star Spectroscopic Survey (GOSSS). III. 142 additional O-type systems. *ApJS*, **224**(1), 4. <https://doi.org/10.3847/0067-0049/224/1/4>.
- Martins, F. (2018) Quantitative spectral classification of Galactic O stars. *A&A*, **616**, A135. <https://doi.org/10.1051/0004-6361/201833050>.
- Martins, F. and Plez, B. (2006) *UBVJHK* synthetic photometry of Galactic O stars. *A&A*, **457**(2), 637–644. <https://doi.org/10.1051/0004-6361:20065753>.
- Martins, F., Schaerer, D., and Hillier, D. J. (2005) A new calibration of stellar parameters of Galactic O stars. *A&A*, **436**(3), 1049–1065. <https://doi.org/10.1051/0004-6361:20042386>.
- Massey, Ph. and Conti, P. S. (1983) Wolf–Rayet stars in the LMC: how faint are the faintest? *ApJ*, **264**, 126–133. <https://doi.org/10.1086/160579>.
- Massey, Ph. and Johnson, J. (1993) Massive stars near eta Carinae: The stellar content of Tr 14 and Tr 16. *AJ*, **105**(3), 980–1001, 1225–1233. <https://doi.org/10.1086/116487>.
- Mathys, G. (1988) The upper main sequence of OB associations. I. Spectral types and lines of C and N of southern single-lined O stars. *A&AS*, **76**(3), 427–444. <https://ui.adsabs.harvard.edu/abs/1988A&AS...76..427M>.
- Mokiem, M. R., de Koter, A., Evans, C. J., Puls, J., Smartt, S. J., Crowther, P. A., Herrero, A., Langer, N., Lennon, D. J., Najarro, F., Villamariz, M. R., and Yoon, S.-C. (2006) The

- VLT-FLAMES survey of massive stars: mass loss and rotation of early-type stars in the SMC. *A&A*, **456**(3), 1131–1151. <https://doi.org/10.1051/0004-6361:20064995>.
- Niemela, V. S., Gamen, R. C., Barbá, R. H., Fernández Lajús, E., Benaglia, P., Solivella, G. R., Reig, P., and Coe, M. J. (2008) The very massive X-ray bright binary system Wack2134 (= WR 21a). *MNRAS*, **389**(3), 1447–1452. <https://doi.org/10.1111/j.1365-2966.2008.13684.x>.
- Nishiyama, S., Tamura, M., Hatano, H., Kato, D., Tanabé, T., Sugitani, K., and Nagata, T. (2009) Interstellar extinction law toward the Galactic center III: J , H , K_S bands in the 2MASS and the MKO systems, and 3.6, 4.5, 5.8, 8.0 μm in the *Spitzer*/IRAC system. *ApJ*, **696**(2), 1407–1417. <https://doi.org/10.1088/0004-637X/696/2/1407>.
- Pandey, J. C., Pandey, S. B., and Karmakar, S. (2014) Phase-resolved *XMM-Newton* and *Swift* observations of WR 25. *ApJ*, **788**(1), 84. <https://doi.org/10.1088/0004-637X/788/1/84>.
- Pantaleoni González, M., Maíz Apellániz, J., Barbá, R. H., Reed, B. C., Berlanas, S. R., Parras Rico, A., and Bodaghee, A. (2025) The Alma catalogue of OB stars – III. a cross-match with *Gaia* DR3 and an extension based on new spectral classifications. *MNRAS*, **543**(1), 63–82. <https://doi.org/10.1093/mnras/staf1409>.
- Parkin, E. R. and Gosset, E. (2011) Investigating the X-ray emission from the massive WR+O binary WR 22 using 3D hydrodynamical models. *A&A*, **530**, A119. <https://doi.org/10.1051/0004-6361/201016125>.
- Pollock, A. M. T. and Corcoran, M. F. (2006) Evidence for colliding winds in WR 25 from *XMM-Newton* observations of X-ray variability. *A&A*, **445**(3), 1093–1097. <https://doi.org/10.1051/0004-6361:20053496>.
- Pradhan, P., Huenemoerder, D. P., Ignace, R., Pollock, A. M. T., and Nichols, J. S. (2021) The colliding winds of WR 25 in high-resolution X-rays. *ApJ*, **915**(2), 114. <https://doi.org/10.3847/1538-4357/ac02c4>.
- Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P. (2007) *Numerical Recipes: The Art of Scientific Computing*. Cambridge University Press, 3rd edition.
- Prilutskii, O. F. and Usov, V. V. (1976) X rays from Wolf–Rayet binaries. *SvA*, **20**(1), 2–4. <https://ui.adsabs.harvard.edu/abs/1976SvA....20....2P>.
- Pritchard, J. (2005) *FEROS-II User Manual*. <http://www.eso.org/sci/facilities/lasilla/instruments/feros/doc/manual/P77/FEROSII-UserManual-77.0.pdf>.
- Puls, J., Vink, J. S., and Najarro, F. (2008) Mass loss from hot massive stars. *A&ARv*, **16**(3-4), 209–325. <https://doi.org/10.1007/s00159-008-0015-8>.
- Putkuri, C., Gamen, R., Morrell, N. I., Maíz Apellániz, J., Arias, J. I., Simón-Díaz, S., Ferrero, G. A., Rodríguez, C. N., Sota, A., Benvenuto, O. G., and Barbá, R. H. (2023) The spectroscopic

- orbit of HD 168112 A,B in NGC 6604: another massive binary target for interferometry. *MNRAS*, **525**(4), 6084–6096. <https://doi.org/10.1093/mnras/stad2657>.
- Rauw, G., Crowther, P. A., De Becker, M., Gosset, E., Nazé, Y., Sana, H., van der Hucht, K. A., Vreux, J. M., and Williams, P. M. (2005) The spectrum of the very massive binary system WR 20a (WN6ha + WN6ha): Fundamental parameters and wind interactions. *A&A*, **432**(3), 985–998. <https://doi.org/10.1051/0004-6361:20042136>.
- Rauw, G., Vreux, J.-M., Gosset, E., Hutsemékers, D., and Magain, P. (1995) WR22 as a core hydrogen-burning Wolf–Rayet star. In *Stellar Evolution: What Should Be Done?*, edited by Noels, A., Fraipont-Caro, D., Gabriel, M., Grevesse, N., and Demarque, P., *Liege International Astrophysical Colloquia*, volume 32, pages 463–467. <https://hdl.handle.net/2268/15913>.
- Rauw, G., Vreux, J. M., Gosset, E., Hutsemékers, D., Magain, P., and Rochowicz, K. (1996) WR 22: the most massive Wolf–Rayet star ever weighed. *A&A*, **306**, 771–782. <https://ui.adsabs.harvard.edu/abs/1996A&A...306..771R>.
- Renson, P. (1978) Méthode de recherche des périodes des étoiles variables [Method for finding the periods of variable stars]. *A&A*, **63**, 125–129. <https://ui.adsabs.harvard.edu/abs/1978A&A....63..125R>. In French, with a summary in English.
- Repolust, T., Puls, J., and Herrero, A. (2004) Stellar and wind parameters of Galactic O-stars. The influence of line-blocking/blanketing. *A&A*, **415**, 349–376. <https://doi.org/10.1051/0004-6361:20034594>.
- Sana, H. (2009) The nature of the line profile variability in the spectrum of the massive binary HD 152219. *A&A*, **501**(1), 291–295. <https://doi.org/10.1051/0004-6361/200810271>.
- Sana, H., de Koter, A., de Mink, S. E., Dunstall, P. R., Evans, C. J., Hénault-Brunet, V., Maíz Apellániz, J., Ramírez-Agudelo, O. H., Taylor, W. D., Walborn, N. R., Clark, J. S., Crowther, P. A., Herrero, A., Gieles, M., Langer, N., Lennon, D. J., and Vink, J. S. (2013) The VLT-FLAMES Tarantula Survey. VIII. Multiplicity properties of the O-type star population. *A&A*, **550**, A107. <https://doi.org/10.1051/0004-6361/201219621>.
- Sana, H., de Mink, S. E., de Koter, A., Langer, N., Evans, C. J., Gieles, M., Gosset, E., Izzard, R. G., Le Bouquin, J. B., and Schneider, F. R. N. (2012) Binary interaction dominates the evolution of massive stars. *Sci*, **337**, 444–446. <https://doi.org/10.1126/science.1223344>.
- Sana, H., Gosset, E., and Rauw, G. (2006) The OB binary HD 152219: a detached, double-lined, eclipsing system. *MNRAS*, **371**(1), 67–80. <https://doi.org/10.1111/j.1365-2966.2006.10654.x>.
- Sana, H., Le Bouquin, J. B., Lacour, S., Berger, J. P., Duvert, G., Gauchet, L., Norris, B., Olofsson, J., Pickel, D., Zins, G., Absil, O., de Koter, A., Kratter, K., Schnurr, O., and Zinnecker, H. (2014) Southern massive stars at high angular resolution: Observational campaign and companion detection. *ApJS*, **215**(1), 15. <https://doi.org/10.1088/0067-0049/215/1/15>.

- Sana, H., Shenar, T., Bodensteiner, J., Britavskiy, N., Langer, N., Lennon, D. J., Mahy, L., Mandel, I., de Mink, S. E., Patrick, L. R., and 66 more (2025) A high fraction of close massive binary stars at low metallicity. *NatAs*, **9**, 1337–1346. <https://doi.org/10.1038/s41550-025-02610-x>.
- Schweickhardt, J., Schmutz, W., Stahl, O., Szeifert, Th., and Wolf, B. (1999) Revised mass determination of the super massive Wolf–Rayet star WR 22. *A&A*, **347**, 127–136. <https://ui.adsabs.harvard.edu/abs/1999A&A...347..127S>.
- Seward, F. D. and Chlebowski, T. (1982) X-ray emission from the Carina Nebula and the associated early stars. *ApJ*, **256**, 530–542. <https://doi.org/10.1086/159929>.
- Seward, F. D., Forman, W. R., Giacconi, R., Griffiths, R. E., Harnden, J., F. R., Jones, C., and Pye, J. P. (1979) X-rays from Eta Carinae and the surrounding nebula. *ApJL*, **234**(1), L55–L58. <https://doi.org/10.1086/183108>.
- Shenar, T., Sana, H., Mahy, L., Maíz Apellániz, J., Crowther, P. A., Gromadzki, M., Herrero, A., Langer, N., Marchant, P., Schneider, F. R. N., Sen, K., Soszyński, I., and Toonen, S. (2022) The Tarantula Massive Binary Monitoring. VI. Characterisation of hidden companions in 51 single-lined O-type binaries: A flat mass-ratio distribution and black-hole binary candidates. *A&A*, **665**, A148. <https://doi.org/10.1051/0004-6361/202244245>.
- Simón-Díaz, S. and Herrero, A. (2014) The IACOB project: I. Rotational velocities in northern Galactic O- and early B-type stars revisited. The impact of other sources of line-broadening. *A&A*, **562**, A135. <https://doi.org/10.1051/0004-6361/201322758>.
- Smith, L. F. (1968) A revised spectral classification system and a new catalogue for galactic Wolf–Rayet stars. *MNRAS*, **138**(1), 109–121. <https://doi.org/10.1093/mnras/138.1.109>.
- Smith, L. F., Shara, M. M., and Moffat, A. F. J. (1996) A three-dimensional classification for WN stars. *MNRAS*, **281**(1), 163–191. <https://doi.org/10.1093/mnras/281.1.163>.
- Sota, A., Maíz Apellániz, J., Morrell, N. I., Barbá, R. H., Walborn, N. R., Gamen, R. C., Arias, J. I., and Alfaro, E. J. (2014) The Galactic O-Star Spectroscopic Survey (GOSSS). II. Bright southern stars. *ApJS*, **211**(1), 10. <https://doi.org/10.1088/0067-0049/211/1/10>.
- Sota, A., Maíz Apellániz, J., Walborn, N. R., Alfaro, E. J., Barbá, R. H., Morrell, N. I., Gamen, R. C., and Arias, J. I. (2011) The Galactic O-Star spectroscopic survey. I. Classification system and bright northern stars in the blue-violet at $R \sim 2500$. *ApJS*, **193**(2), 24. <https://doi.org/10.1088/0067-0049/193/2/24>.
- Stevens, I. R., Blondin, J. M., and Pollock, A. M. T. (1992) Colliding winds from early-type stars in binary systems. *ApJ*, **386**(1), 265–287. <https://doi.org/10.1086/171013>.
- Tramper, F., Sana, H., Fitzsimons, N. E., de Koter, A., Kaper, L., Mahy, L., and Moffat, A. (2016) The mass of the very massive binary WR21a. *MNRAS*, **455**(2), 1275–1281. <https://doi.org/10.1093/mnras/stv2373>.

- Tsang, B. T. H. and Milosavljević, M. (2018) Radiation pressure in super star cluster formation. *MNRAS*, **478**(3), 4142–4161. <https://doi.org/10.1093/mnras/sty1217>.
- van der Hucht, K. A. (1996) Past and present classification of hot massive stars. In *Wolf–Rayet Stars in the Framework of Stellar Evolution*, edited by Vreux, J.-M., Detal, A., Fraipont-Caro, D., Gosset, E., and Rauw, G., *Liege International Astrophysical Colloquia*, volume 33, pages 1–22. <https://ui.adsabs.harvard.edu/abs/1996LIACo..33....1V>.
- van der Hucht, K. A. (2001) The VIIth catalogue of galactic Wolf–Rayet stars. *NewAR*, **45**(3), 135–232. [https://doi.org/10.1016/S1387-6473\(00\)00112-3](https://doi.org/10.1016/S1387-6473(00)00112-3).
- van Hoof, P. A. M. (2018) Recent development of the Atomic Line List. *Galax*, **6**(2), 63. <https://doi.org/10.3390/galaxies6020063>.
- Villaseñor, J. I., Sana, H., Mahy, L., Shenar, T., Bodensteiner, J., Britavskiy, N., Lennon, D. J., Moe, M., Patrick, L. R., Pawlak, M., and 23 more (2025) Binarity at LOw Metallicity (BLOeM): Enhanced multiplicity of early B-type dwarfs and giants at $Z = 0.2Z_{\odot}$. *A&A*, **698**, A41. <https://doi.org/10.1051/0004-6361/202453166>.
- Vink, J. S., de Koter, A., and Lamers, H. J. G. L. M. (2000) New theoretical mass-loss rates of O and B stars. *A&A*, **362**, 295–309. <https://doi.org/10.48550/arXiv.astro-ph/0008183>.
- Vink, J. S., de Koter, A., and Lamers, H. J. G. L. M. (2001) Mass-loss predictions for O and B stars as a function of metallicity. *A&A*, **369**, 574–588. <https://doi.org/10.1051/0004-6361:20010127>.
- Walborn, N. (2001) Selective emission lines in O-type spectra. In *Eta Carinae and Other Mysterious Stars: The Hidden Opportunities of Emission Spectroscopy*, edited by Gull, T. R., Johansson, S., and Davidson, K., *Astronomical Society of the Pacific Conference Series*, volume 242, pages 217–228. https://www.aspbooks.org/a/volumes/article_details/?paper_id=22980.
- Walborn, N. R. (1971) Some spectroscopic characteristics of the OB stars: an investigation of the space distribution of certain OB stars and the reference frame of the classification. *ApJS*, **23**, 257–282. <https://doi.org/10.1086/190239>.
- Walborn, N. R. and Fitzpatrick, E. L. (1990) Contemporary optical spectral classification of the OB stars: A digital atlas. *PASP*, **102**, 379. <https://doi.org/10.1086/132646>.
- Werner, K. and Rauch, T. (2001) Identification of the 4486, 4504 Å emission lines in O-type spectra. In *Eta Carinae and Other Mysterious Stars: The Hidden Opportunities of Emission Spectroscopy*, edited by Gull, T. R., Johansson, S., and Davidson, K., *Astronomical Society of the Pacific Conference Series*, volume 242, pages 229–232. https://www.aspbooks.org/a/volumes/article_details/?paper_id=22981.
- Zacharias, N., Finch, C. T., Girard, T. M., Henden, A., Bartlett, J. L., Monet, D. G., and Zacharias, M. I. (2013) The fourth US Naval Observatory CCD Astrograph Catalog (UCAC4). *AJ*, **145**(2), 44. <https://doi.org/10.1088/0004-6256/145/2/44>.

A. Journal of the Observations

This appendix presents the journal of the observations directly associated with the present work. The four tables correspond to the four data sets (I, II, III, and IV). For each observation, we provide the date, the Universal Time (UT) at the start of the exposure (except for Table A.3), the Heliocentric Julian Day at mid-exposure, the exposure time and the orbital phase computed using the adopted period P and phase-zero time T_0 from the fourth column of Table 2.

Table A.1: Journal of the observations (data set I) including exposure time.

Date yyyy-mm-dd	UT hh:mm:ss	HJD(2400000+) (mid-exposure)	Exp. [s]	Phase	Global (Y/N)
2006-03-02	02:33:41	53796.6176	1500	0.582	Y
2006-03-04	02:30:54	53798.6158	1500	0.592	Y
2006-03-06	03:49:50	53800.6706	1500	0.602	Y
2006-04-08	00:23:53	53833.5275	1380	0.760	Y
2006-04-10	02:23:22	53835.6105	1380	0.770	Y
2006-04-12	01:33:33	53837.5759	1380	0.779	Y
2006-05-04	23:40:24	53860.4978	1500	0.890	Y
2006-05-08	23:18:56	53864.4829	1500	0.909	Y
2006-05-13	02:49:37	53868.6284	1380	0.929	Y
2006-06-10	23:00:52	53897.4685	1380	0.068	Y
2006-06-12	23:34:10	53899.4916	1380	0.078	Y
2006-06-15	01:52:07	53901.5873	1380	0.088	Y
2006-06-26	01:11:24	53912.5575	1200	0.141	N
2006-07-01	23:45:53	53918.4988	1380	0.169	Y
2006-12-03	07:18:50	54072.8108	1380	0.912	N
2006-12-15	05:50:43	54084.7501	1380	0.970	Y
2006-12-23	07:40:45	54092.8269	1380	0.009	Y
2006-12-25	07:19:46	54094.8124	1380	0.018	Y
2007-05-27	02:15:50	54247.6017	900	0.754	Y
2009-03-20	00:13:15	54910.5224	1800	0.947	N
2009-03-21	00:16:08	54911.5244	1800	0.952	N
2009-03-22	00:04:23	54912.5162	1800	0.956	N
2009-03-22	23:43:46	54913.5019	1800	0.961	Y
2009-03-23	23:57:43	54914.5116	1800	0.966	N
2009-03-26	00:39:15	54916.5405	1800	0.976	Y
2009-03-28	01:46:49	54918.5875	1800	0.986	Y
2009-03-31	01:56:07	54921.5940	1800	0.000	Y

Notes: A ‘Y’ in the last column indicates that the global version of the spectrum exists.

Table A.2: Journal of the observations (data set II).

Date yyyy-mm-dd	UT hh:mm:ss	HJD(2400000+) (mid-exposure)	Exp. [s]	Phase
2007-02-13	07:00:30	54144.8064	2220	0.259

Table A.3: Journal of the observations (data set III).

Date yyyy-mm-dd	UT hh:mm:ss	HJD(2400000+) (mid-exposure)	Exp. [s]	Phase
2001-05-08	03:15:25	52037.6384	600	0.111
2001-05-09	01:59:50	52038.5859	600	0.115
2001-05-10	02:46:04	52039.6180	600	0.120
2001-05-11	02:52:19	52040.6223	900	0.125
2002-03-02	03:35:12	52335.6516	600	0.546
2002-03-04	04:23:33	52337.6853	800	0.556
2002-03-05	03:12:22	52338.6359	800	0.560
2002-03-06	03:16:48	52339.6391	900	0.565
2002-04-19	00:05:50	52383.5071	1800	0.777
2003-05-23	00:09:11	52782.5087	1800	0.698
2003-05-23	23:53:07	52783.4975	1800	0.703
2003-05-24	23:46:28	52784.4929	1800	0.708
2004-05-06	00:10:43	53131.5101	1500	0.379
2004-05-08	02:27:23	53133.6051	1500	0.389
2004-05-09	23:35:06	53135.4854	1200	0.398

Notes: The UT values in this table correspond to the mid-exposure.

Table A.4: Journal of the observations (data set IV).

Date yyyy-mm-dd	UT hh:mm:ss	HJD(2400000+) (mid-exposure)	Exp. [s]	Phase
2006-05-18	01:07:34	53873.5529	600	0.953
2006-05-19	01:12:50	53874.5645	900	0.958
2006-05-20	00:49:23	53875.5402	600	0.962
2006-05-21	01:27:05	53876.5675	800	0.967
2006-05-21	01:45:45	53876.5781	400	0.967
2006-05-22	00:37:32	53877.5319	600	0.972
2006-05-22	02:36:22	53877.6157	800	0.972
2006-05-23	00:21:19	53878.5206	600	0.977
2006-05-23	00:49:24	53878.5401	600	0.977
2006-05-23	01:20:51	53878.5619	600	0.977
2007-01-02	08:06:17	54102.8424	900	0.057
2007-01-02	08:23:54	54102.8529	600	0.057

B. Radial Velocities for the N IV $\lambda 4058$ Line

This appendix presents the material related to the radial velocities measured from the N IV $\lambda 4058$ line. We also present an extended version of Fig. 7 that includes, in addition, the data from data sets II and III. The overall agreement between the various measurements supports the idea that the two fitted Gaussians provide a suitable representation of the total line profile, whose shape remains remarkably stable throughout the orbital cycle despite the relative orbital motion.

Table B.1: Radial velocities [km s^{-1}] for the N IV $\lambda 4058$ line (data set I).

HJD(2400000+)	Phase	RV _{loc}		RV _{glo}		RV _{glo}	
		One Gaussian	Gaussian 1	Gaussian 2	One Gaussian	Gaussian 1	Gaussian 2
53796.6176	0.582	-29.33	-21.75	-111.44	-29.80	-18.40	-80.71
53798.6158	0.592	-33.69	-26.96	-101.17	-33.78	-23.53	-83.30
53800.6706	0.602	-32.91	-23.07	-109.83	-33.05	-19.43	-91.13
53833.5275	0.760	-47.27	-38.97	-104.33	-45.97	-36.12	-101.60
53835.6105	0.770	-50.38	-44.17	-116.09	-49.49	-42.19	-100.48
53837.5759	0.779	-46.38	-39.74	-117.50	-47.88	-35.10	-98.87
53860.4978	0.890	-77.54	-72.72	-120.90	-77.23	-70.46	-136.19
53864.4829	0.909	-90.53	-83.40	-164.16	-90.75	-81.14	-146.17
53868.6284	0.929	-100.68	-93.80	-167.97	-99.56	-91.47	-156.54
53897.4685	0.068	-46.50	-38.50	-108.39	-45.34	-36.99	-95.64
53899.4916	0.078	-35.61	-27.79	-110.75	-34.19	-25.72	-92.42
53901.5873	0.088	-33.53	-25.78	-103.56	-33.46	-24.36	-84.03
53912.5575	0.141	-20.52	-12.66	-82.59	—	—	—

Table B.1: continued

HJD(2400000+)	Phase	RV _{loc}		RV _{loc}		RV _{glo}		RV _{glo}	
		One Gaussian		Gaussian 1		Gaussian 2		One Gaussian	
		One Gaussian	Gaussian 1	Gaussian 1	Gaussian 2	One Gaussian	Gaussian 1	Gaussian 2	
53918.4988	0.169	-19.39	-11.63	-91.60	-19.28	-9.29	-73.02		
54072.8108	0.912	-90.43	-81.34	-143.32	—	—	—		
54084.7501	0.970	-124.57	-115.97	-200.20	-124.17	-112.61	-181.67		
54092.8269	0.009	-107.67	-101.04	-169.92	-107.13	-99.50	-155.90		
54094.8124	0.018	-95.71	-87.24	-165.51	-95.53	-84.46	-154.80		
54247.6017	0.754	-41.91	-36.31	-89.57	-41.74	-34.26	-84.13		
54910.5224	0.947	-114.22	-103.28	-170.89	—	—	—		
54911.5244	0.952	-116.74	-109.09	-170.81	—	—	—		
54912.5162	0.956	-117.56	-109.61	-167.58	—	—	—		
54913.5019	0.961	-115.38	-106.63	-193.90	-114.36	-104.52	-170.02		
54914.5116	0.966	-116.74	-109.86	-179.47	—	—	—		
54916.5405	0.976	-120.95	-112.36	-187.98	-120.65	-109.67	-175.76		
54918.5875	0.986	-119.01	-109.85	-188.23	-118.57	-107.82	-171.83		
54921.5940	0.000	-117.63	-110.99	-171.53	-116.75	-108.66	-160.43		

Table B.2: Radial velocities [km s^{-1}] for the N IV $\lambda 4058$ line (data sets II and III).

HJD(2400000+)	Phase	RV _{loc}	RV _{loc}	
		One Gauss.	1	2
54144.8064	0.259	−15.99	− 6.35	− 67.87
52037.6384	0.111	−13.22	−13.22	− 65.56
52038.5859	0.115	−18.59	−18.59	− 90.30
52039.6180	0.120	−19.04	−19.04	− 91.49
52040.6223	0.125	−14.53	−14.53	−101.78
52335.6516	0.546	−14.30	−14.30	− 80.98
52337.6853	0.556	−26.72	−26.72	− 84.06
52338.6359	0.560	−17.59	−17.59	− 96.70
52339.6391	0.565	−20.46	−20.48	− 87.74
52383.5071	0.777	−46.21	−46.21	−110.04
52782.5087	0.698	−31.06	−31.06	− 92.66
52783.4975	0.703	−28.52	−28.52	− 96.48
52784.4929	0.708	−27.49	−27.49	− 95.03
53131.5101	0.379	− 9.70	− 9.70	− 83.27
53133.6051	0.389	− 8.75	− 8.75	− 72.87
53135.4854	0.398	− 9.00	− 9.01	− 73.78

Table B.3: Radial velocities [km s^{-1}] for the N IV $\lambda 4058$ line (data set IV).

HJD(2400000+)	Phase	RV _{loc}	RV _{loc}	
		One Gauss.	1	2
53873.5529	0.953	−115.18	−109.95	−302.43
53874.5645	0.958	−119.71	− 98.47	−243.40
53875.5402	0.962	−119.38	−106.57	−265.07
53876.5675	0.967	−124.06	−105.20	−221.95
53876.5781	0.967	−124.38	−108.23	−238.55
53877.5319	0.972	−125.01	−107.00	−242.54
53877.6157	0.972	−124.23	−111.53	−260.73
53878.5206	0.977	−124.38	−108.93	−154.05:
53878.5401	0.977	−122.28	−113.84	−279.68
53878.5619	0.977	−122.68	−113.49	−290.96
54102.8424	0.057	− 49.83	− 29.07	−125.13
54102.8529	0.057	− 50.45	− 28.31	−122.53

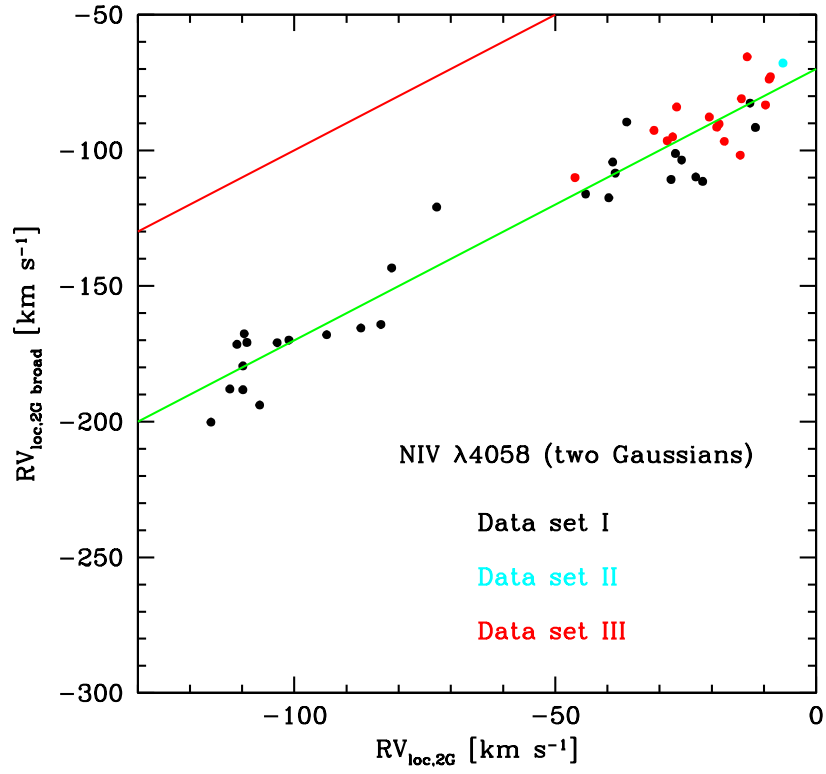


Figure B.1: Comparison between the RVs of Gaussian 1 with those of Gaussian 2, which fits the broader component. This figure extends Fig. 7 by including, in addition to data set I, the measurements from data sets II and III.

C. Radial Velocities of the WN Component for the Selected Spectral Lines

This appendix presents the “gold sample” of measured radial velocities for the selected subset of spectral lines that are intended to best represent the relative orbital motion of the WN star.

Table C.1: Radial velocities RV_{loc} [km s^{-1}] of the WN component in the selected spectral lines.

HJD(2400000+)	Phase	N IV $\lambda 4058$	N V $\lambda 4604$	N IV $\lambda 6220$	N IV $\lambda 7110$	N V $\lambda 4945$	N IV $\lambda 5737$	Si IV $\lambda 4089$	Mean
53796.6176	0.582	-21.75	162.93	-5.36	-18.12	26.79	-15.49	-19.14	11.83
53798.6158	0.592	-26.96	158.56	-12.34	-22.98	24.18	-20.13	-20.38	7.56
53800.6706	0.602	-23.07	156.90	-0.24	-20.75	35.07	-17.64	-17.74	12.21
53833.5275	0.760	-38.97	150.80	-11.17	-35.25	21.15	-30.97	-32.48	-0.56
53835.6105	0.770	-44.17	145.13	-25.71	-41.11	9.39	-33.42	-32.77	-7.10
53837.5759	0.779	-39.74	149.59	-12.41	-36.54	12.02	-31.31	-28.30	-1.96
53860.4978	0.890	-72.72	115.07	-56.85	-65.85	-32.90	-63.47	-58.51	-37.47
53864.4829	0.909	-83.40	99.18	-72.08	-75.24	-34.85	-71.60	-74.64	-48.53
53868.6284	0.929	-93.80	94.09	-77.54	-84.73	-37.63	-79.85	-89.08	-56.51
53897.4685	0.068	-38.50	146.78	-22.75	-37.22	14.75	-33.18	-30.28	-3.92
53899.4916	0.078	-27.79	161.80	0.97	-24.43	30.24	-21.07	-19.21	10.49
53901.5873	0.088	-25.78	159.00	-7.38	-23.97	31.46	-19.83	-14.66	10.25
53912.5575	0.141	-12.66	173.15	4.46	-11.41	44.98	-5.21	-6.75	22.79
53918.4988	0.169	-11.63	177.91	15.74	-7.28	46.64	-1.42	-5.43	26.78
54072.8108	0.912	-81.34	103.92	-70.78	-77.89	-30.84	-73.45	-75.59	-47.58

Table C.1: *continued*

HJD(2400000+)	Phase	N IV $\lambda 4058$	N V $\lambda 4604$	N IV $\lambda 6220$	N IV $\lambda 7110$	N V $\lambda 4945$	N IV $\lambda 5737$	Si IV $\lambda 4089$	Mean
54084.7501	0.970	-115.97	66.66	-101.86	-111.83	-60.97	-101.72	-113.13	-80.84
54092.8269	0.009	-101.04	84.67	-87.78	-97.69	-37.06	-84.94	-93.92	-63.55
54094.8124	0.018	-87.24	101.46	-75.61	-78.90	-40.42	-76.06	-79.99	-51.97
54247.6017	0.754	-36.31	148.98	-6.52	-32.84	25.51	-27.52	-26.69	2.51
54910.5224	0.947	-103.28	83.77	-90.21	-96.14	-46.86	-93.11	-104.48	-68.20
54911.5244	0.952	-109.09	77.50	-94.01	-101.21	-43.42	-95.91	-106.61	-71.40
54912.5162	0.956	-109.61	72.95	-93.53	-102.67	-46.99	-98.76	-101.40	-72.44
54913.5019	0.961	-106.63	74.11	-94.30	-107.31	-63.43	-98.14	-99.35	-74.59
54914.5116	0.966	-109.86	77.72	-93.27	-108.42	-48.13	-94.61	-104.99	-72.66
54916.5405	0.976	-112.36	72.98	-96.75	-109.02	-67.04	-97.68	-101.91	-76.98
54918.5875	0.986	-109.85	81.75	-92.16	-104.83	-61.91	-94.66	-108.73	-73.92
54921.5940	0.000	-110.99	76.13	-92.74	-109.52	-59.66	-96.38	-104.70	-74.99
54144.8064	0.259	-6.35	176.90	20.56	-5.01	45.18	10.47	-2.15	30.36

Table C.1: *continued*

HJD(2400000+)	Phase	N IV $\lambda 4058$	N V $\lambda 4604$	N IV $\lambda 6220$	N IV $\lambda 7110$	N V $\lambda 4945$	N IV $\lambda 5737$	Si IV $\lambda 4089$	Mean
52037.6384	0.111	-13.22	141.54	-6.10	-16.89	37.16	-17.76	-18.59	11.30
52038.5859	0.115	-18.59	168.65	4.51	-19.72	41.66	-13.61	-10.86	17.85
52039.6180	0.120	-19.04	162.66	-10.38	-23.91	45.88	-16.76	-18.14	13.32
52040.6223	0.125	-14.53	166.51	-3.98	-16.27	41.61	-13.48	-4.68	18.30
52335.6516	0.546	-14.30	152.13	-7.46	-16.57	21.81	-18.99	-20.61	9.85
52337.6853	0.556	-26.72	153.48	-10.36	-13.62	33.80	-20.10	-17.85	10.22
52338.6359	0.560	-17.59	165.33	1.75	-11.74	34.21	-14.69	-16.49	16.25
52339.6391	0.565	-20.48	144.16	-8.73	-13.49	21.67	-15.21	-11.85	9.86
52383.5071	0.777	-46.21	137.29	-29.44	-44.09	5.68	-40.73	-38.43	-11.86
52782.5087	0.698	-31.06	147.90	-16.37	-30.99	20.0:	-24.51	-18.77	2.73
52783.4975	0.703	-28.52	137.29	-14.16	-28.09	19.63	-19.79	-18.77	2.93
52784.4929	0.708	-27.49	140.13	-2.10	-30.09	17.58	-21.25	-21.25	4.07
53131.5101	0.379	-9.70	150.32	-0.44	-9.85	32.04	-3.79	-2.81	18.39
53133.6051	0.389	-8.75	171.59	0.52	2.26	42.55	-1.52	-0.58	25.57
53135.4854	0.398	-9.01	179.11	1.25	-9.78	43.64	-2.96	-0.19	25.00

Notes: except for the N IV $\lambda 4058$ line, the RVs have an arbitrary zero-point (see Sect. 3.1 *et seq.*). The 'Mean' column is a combination of the other columns that is shifted to obtain a γ_{WN} of zero.

D. Radial Velocities of the O Component

This appendix contains the material related to the RVs used to directly trace the motion of the O-star companion. Table D.1 lists the radial velocities measured from the few spectral lines for which the O-star contribution can be clearly separated from that of the WN component owing to significant deblending. These RVs correspond to a small, limited region of values for the phases around 0.98. Table D.2 presents the RVs derived from the He I $\lambda 4471$ line after subtraction of a line assumed to be constant in radial velocity, depth, and width. This line was initially attributed to the WN component but could in fact originate from the intruder (the third spectrum).

Table D.1: Directly measured radial velocities for the O star.

HJD (2400000+)	RV He I $\lambda 4471$ [km s ⁻¹]	RV He II $\lambda 4542$ [km s ⁻¹]	RV N IV $\lambda \lambda 5204-5205$ [km s ⁻¹]
53868.6284	—	—	117.52
54084.7501	179.31	170.18	180.63
54092.8269	130.89	144.48	137.78
54910.5224	149.09	162.89	146.23
54911.5244	145.00	157.14	161.15
54912.5162	150.29	158.44	157.88
54913.5019	169.45	165.02	174.95
54914.5116	169.87	178.07	170.48
54916.5405	171.48	174.96	188.29
54918.5875	180.97	190.96	181.13
54921.5940	160.05	167.77	161.19

Table D.2: Radial velocities for the He I $\lambda 4471$ line measured from spectra cleaned of the main line, initially attributed to the WN component and assumed to be constant in radial velocity, depth, and width.

HJD(2400000+)	Radial velocity [km s ⁻¹]	HJD(2400000+)	Radial velocity [km s ⁻¹]
52038.5859	-35.53	53899.4916	-11.17
52039.6180	3.52	53901.5873	-4.12
52040.6223	-14.58	53912.5575	-35.68
52335.6516	1.85	53918.4988	-37.22
52337.6853	13.10	54072.8108	76.90
52338.6359	-38.73	54084.7501	167.04
52339.6391	-33.72	54092.8269	112.77
52383.5071	-6.99	54094.8124	92.16
52782.5087	-18.47	54144.8064	-35.86
52783.4975	-46.82	54247.6017	5.71
53135.4854	-37.23	54910.5224	149.08
53796.6176	-25.59	54911.5244	133.10
53798.6158	-30.55	54912.5162	137.11
53800.6706	-18.57	54913.5019	153.59
53833.5275	5.35	54914.5116	160.49
53835.6105	7.30	54916.5405	160.31
53837.5759	17.43	54918.5875	169.60
53864.4829	83.18	54921.5940	143.55
53897.4685	5.76		

E. Disentangled Spectra

In this appendix, we present the disentangled spectrum of the secondary O5 component and that of the primary WN component, although the latter may be affected by the presence of a third, fainter object. Figure E.1 shows an excerpt of the O5-star spectrum together with the identification of the main spectral lines. The disentangled spectrum exhibits features with amplitudes well below the 1% level in continuum units. We recall that the disentangling procedure was performed assuming a brightness ratio of 0.5/0.5, a choice that is convenient for interpretation but is certainly not the correct value.

Beyond the usual lines expected to be present in an O5 star and those discussed in Sect. 7.2, it is noteworthy that the spectrum displays faint but reliable detections of the N v $\lambda\lambda 4604\text{--}4619$ doublet in absorption as well as the O III $\lambda 5592$ absorption line. The S IV $\lambda 4486$ and S IV $\lambda 4504$ lines are also present (Werner and Rauch, 2001). They appear to exhibit P-Cygni profiles, although the emission component of S IV $\lambda 4504$ is affected by a disentangling artefact and the possible absorption component is blended with a DIB. The P-Cygni profile of S IV $\lambda 4486$ is consistent with the synthetic spectrum, as can be seen in Fig. 47 (Sect. 9.1). The line C III $\lambda 5696$ is also present as a weak emission feature, while the C IV $\lambda\lambda 5801\text{--}5812$ lines are visible in absorption. The N III $\lambda 4514$ line is clearly absent, supporting the idea that the O5 does not belong to the supergiant luminosity class (Mathys, 1988). It is worth noting that artefacts of the disentangling procedure affecting constant spectral features are visible in the vicinity of the nebular lines [O III] $\lambda 5007$ and [O III] $\lambda 4959$, which are visible in the individual spectra.

Figure E.2 presents the disentangled spectrum of the WN component. In addition to the usual emission lines of a WN6ha object (see Sect. 3), a few weak lines appear to move with the WN component, in particular the N III $\lambda 4321$, N III $\lambda 4842$, and N III $\lambda 4882\text{--}4884$ lines. The position at rest of the line labelled N III $\lambda 4321$ in the disentangled WN spectrum is actually at $4322.8 \text{ \AA}$, which may cast some doubt on the identification. The C III $\lambda 5696$ line appears also to be present as a weak emission feature. This line therefore seems to be present in both objects, although the relatively small RV variations of the WN star mean that it could instead originate from the possible third object. The He I $\lambda 4471$ and He I $\lambda 5876$ absorption lines are also present and they are difficult to explain (see Sect. 9). These features could likewise be associated with the possible third object.

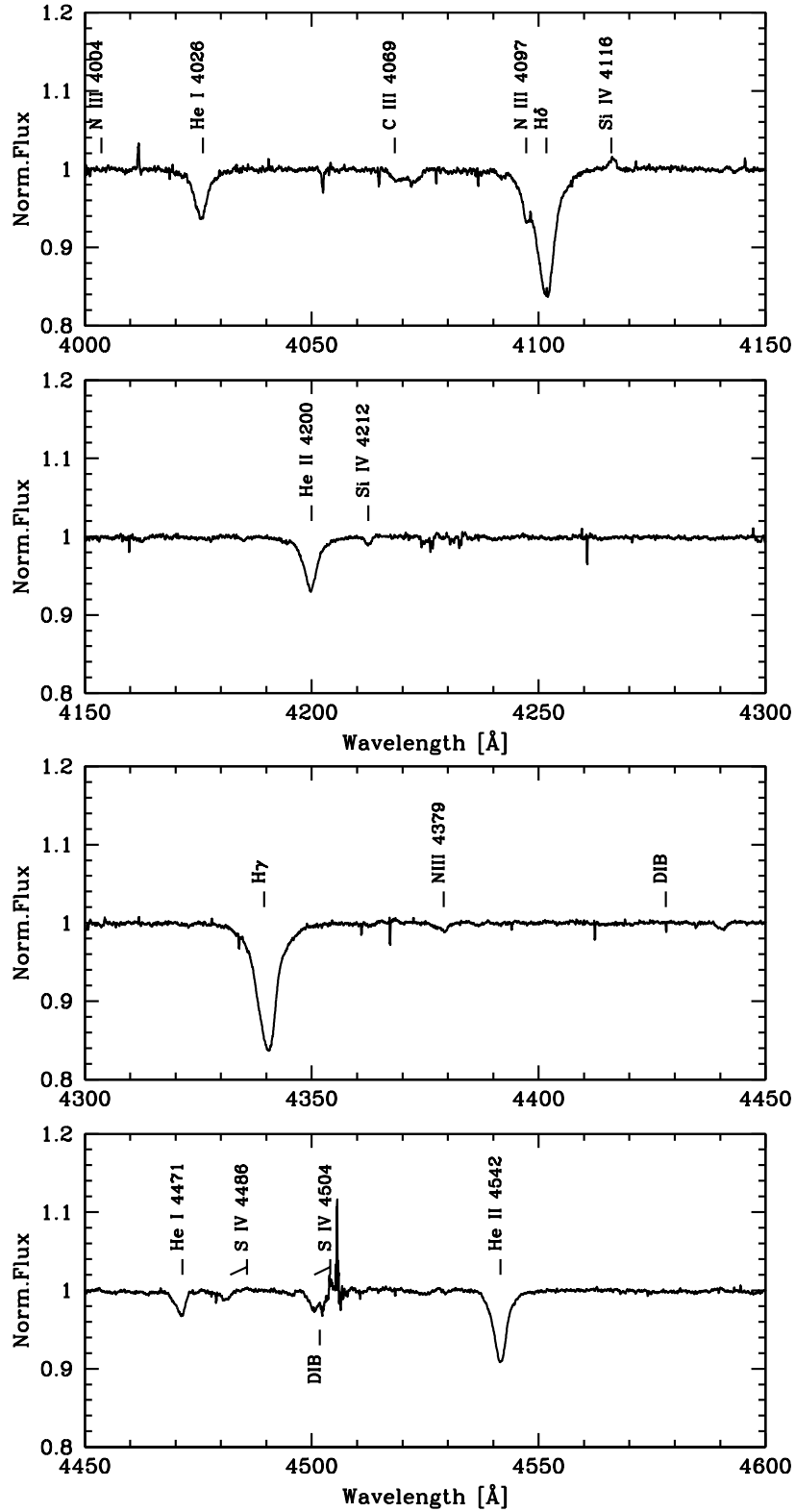


Figure E.1: Disentangled spectrum of the O5 star, with identifications of the main lines.

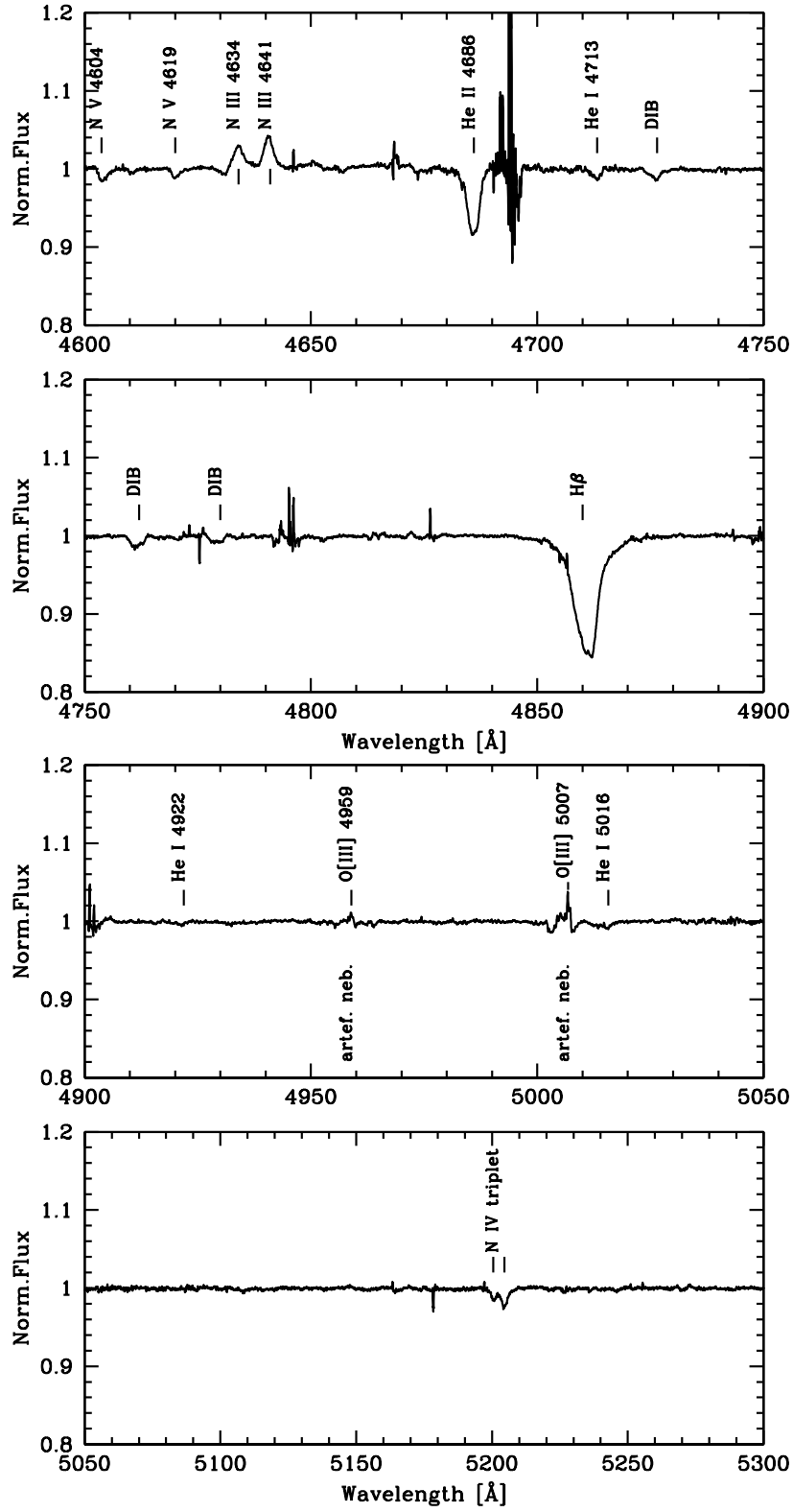


Figure E.1: *continued.*

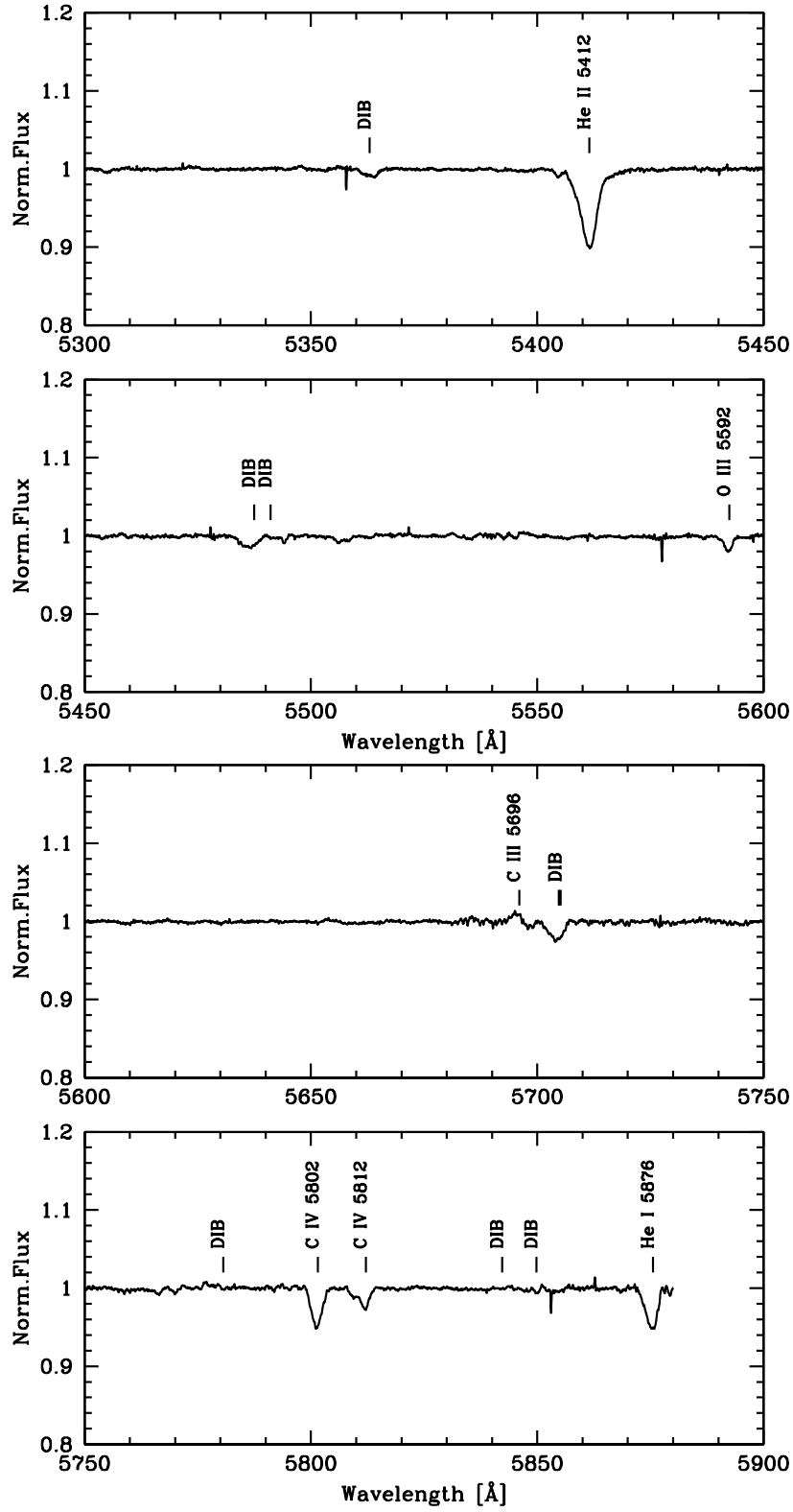


Figure E.1: *continued.*

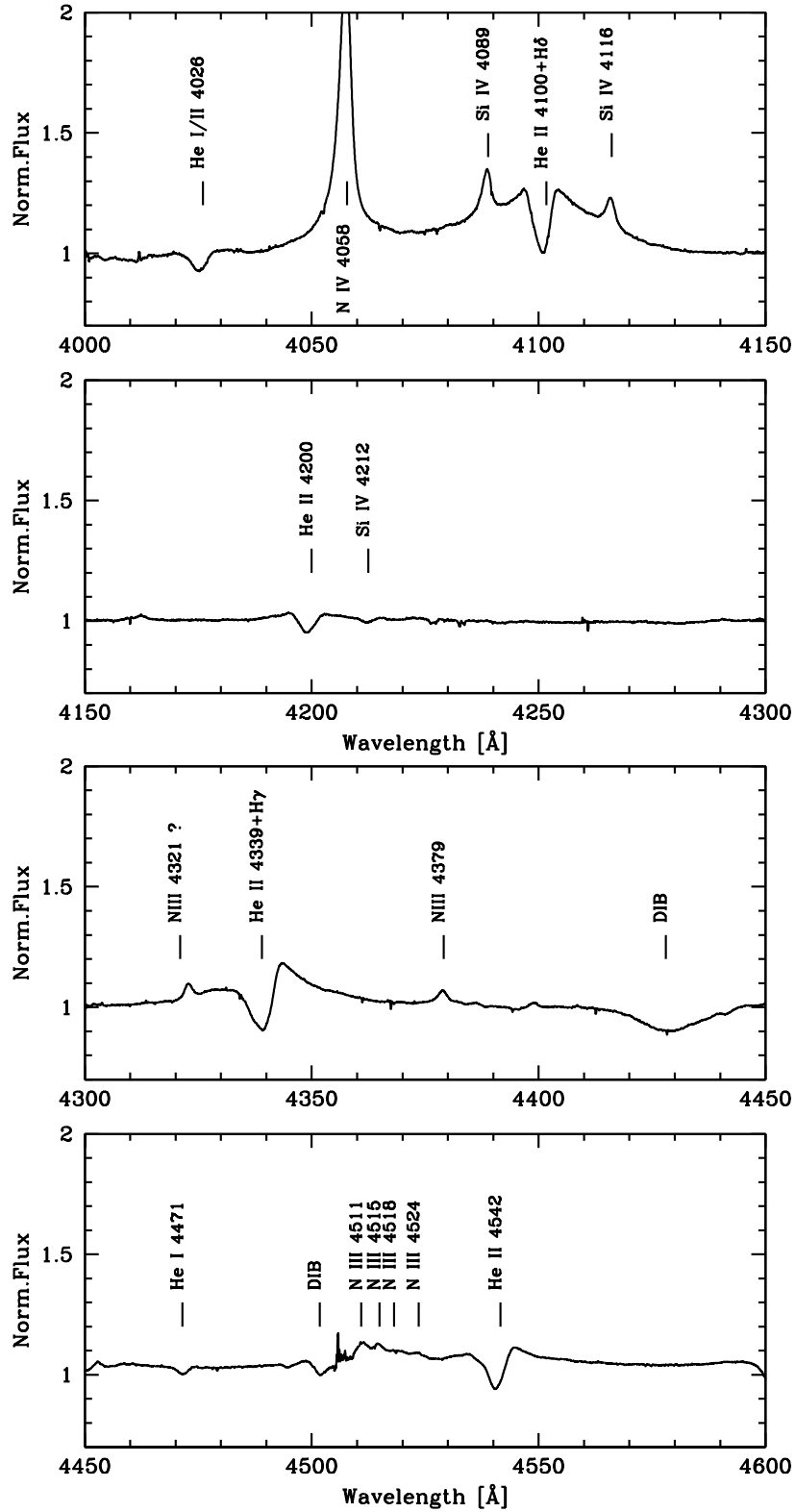


Figure E.2: Disentangled spectrum of the WN6ha star, with identifications of the main lines.

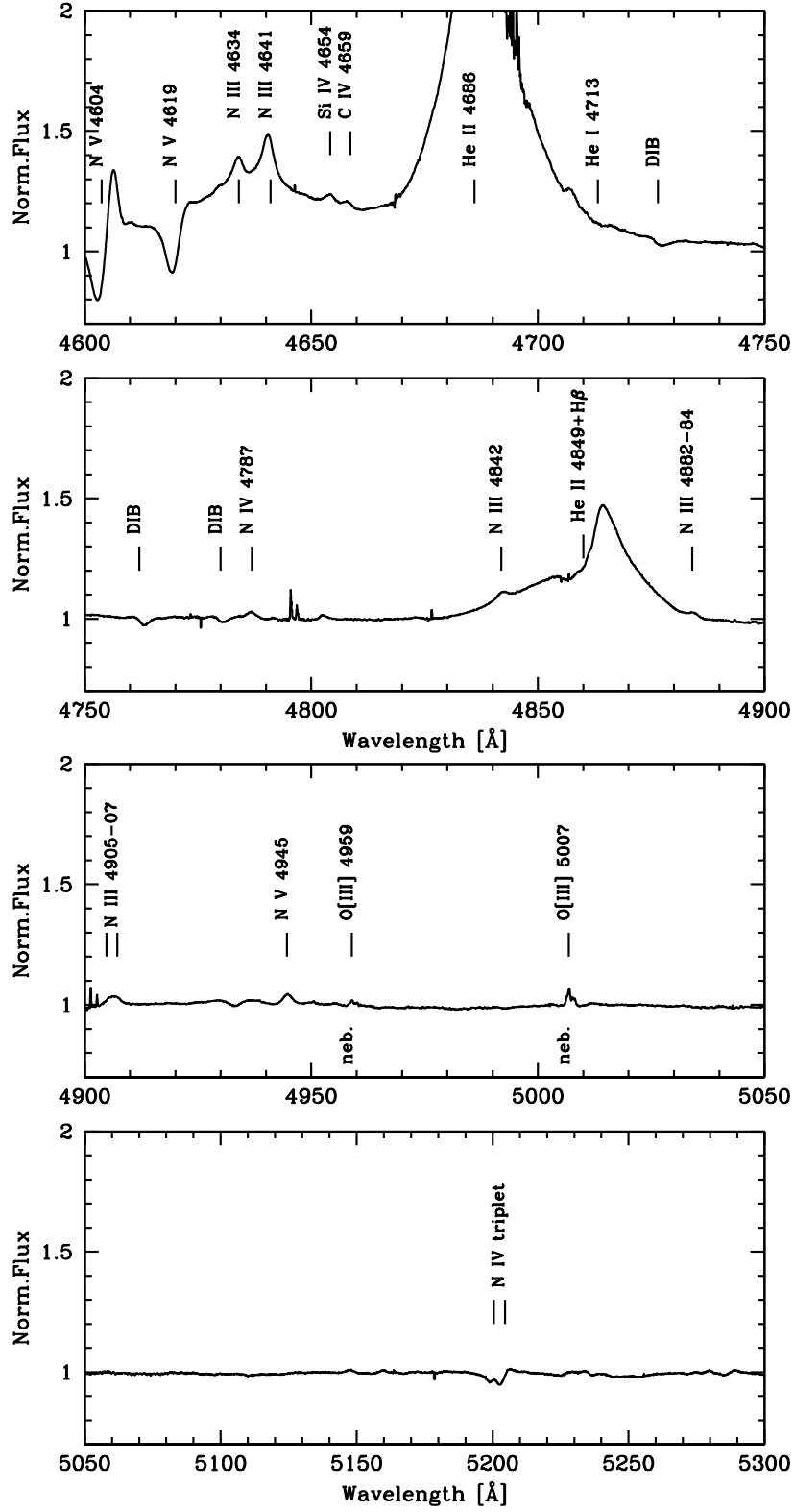


Figure E.2: *continued.*

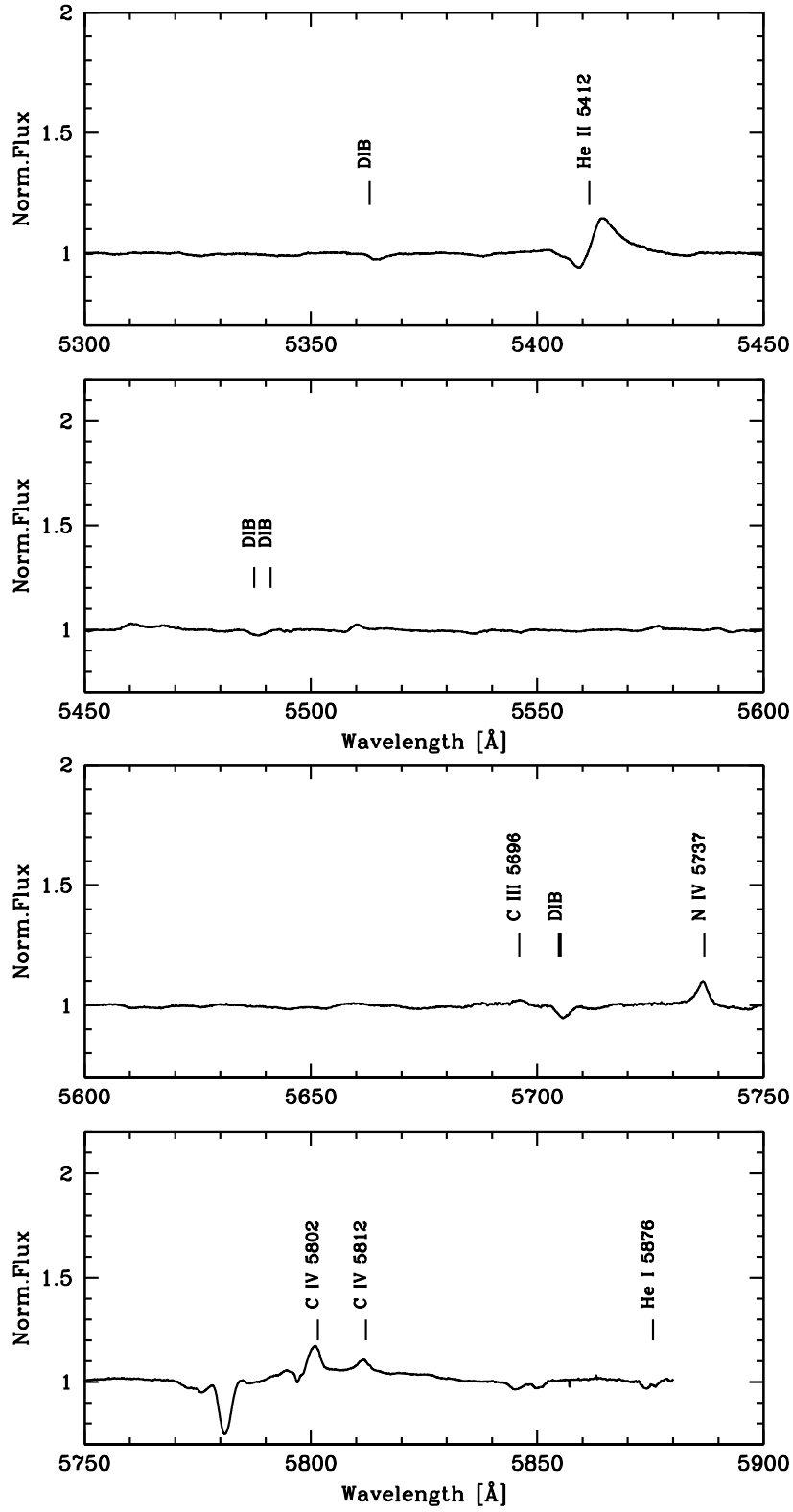


Figure E.2: *continued.*