

Southern massive stars at high angular resolution

WR 25 is a massive hierarchical triple system

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ABSTRACT

WR 25 is a massive colliding-wind binary in the Carina nebula comprising a WN6ha primary star with an O5 companion in an eccentric 208-day orbit. Recent spectroscopic analysis estimates the total binary mass to approach $100 M_{\odot}$, and a primary-to-secondary mass ratio of $q = M_1/M_2 \approx 2$, hinting at a very massive primary star. The presence of additional spectroscopic signatures from a third, “intruder” star was also noted, making it a candidate hierarchical triple system. In this study, we present a VLTI/PIONIER interferometric observation of WR 25, spatially resolving all three components for the first time. For the inner WN6ha + O5 binary, we find a projected angular separation of 1.68 ± 0.02 milliarcseconds (mas), corresponding to a projected physical separation of 3.90 ± 0.21 au at a distance of 2.32 ± 0.12 kpc. Leveraging the fortunate timing of the VLTI observation, which was obtained when the two components were passing the line of nodes, we determined the orbital semi-major axis $a = 3.11 \pm 0.20$ au. Subsequently, the newly constrained total dynamical binary mass is $93 \pm 18 M_{\odot}$, with a primary mass $M_1 = 62 \pm 13 M_{\odot}$ and secondary mass $M_2 = 31 \pm 7 M_{\odot}$. We detect the third star or tertiary with a projected angular separation of 27.69 ± 0.02 mas from the primary, with a chance alignment probability lower than 10^{-4} . Using newly obtained brightness ratios between all components, we revisit archival spectroscopic data of WR 25 to disentangle spectra for individual components and derive their stellar parameters. The tertiary, which has a spectral type O7, is broadly coeval with the inner binary and has an evolutionary mass $M_3 = 25.6^{+2.8}_{-2.3} M_{\odot}$. Based on simulations, we estimate the tertiary period to be in the range 19–82 years. The newly confirmed triple nature of WR 25 thus makes it an important benchmark system to measure accurate dynamical masses of the inner binary and potentially the tertiary, to calibrate stellar evolution and atmosphere models, and to study its formation and stability as a hierarchical triple system.

Key words. techniques: interferometric – binaries: general – stars: massive – stars: Wolf-Rayet

1. Introduction

Massive stars ($M_{\text{ini}} > 8 M_{\odot}$) immensely influence their surroundings through life and death. The earliest O-type stars with initial masses $M_{\text{ini}} > 60 M_{\odot}$ can evolve to become extremely luminous ($\log(L/L_{\odot}) \gtrsim 5.8\text{--}6.0$) and drive strong winds even on the main sequence (Langer et al. 1994; Crowther 2007; Smith & Conti 2008). Subsequently, their spectra are dominated by strong emission lines of hydrogen, helium and nitrogen, similar to nitrogen-rich Wolf-Rayet stars but with residual hydrogen (WNh). These stars release copious amounts of ionizing radiation and nuclear processed material into their surroundings throughout their few-Myr lifetime, and possibly also during their core collapse, leaving behind a stellar-mass black hole (Langer 2012; Woosley 2019; Eldridge & Stanway 2022). They are hence rare and crucial laboratories for some of the most extreme physical phenomena and warrant special attention.

Almost all O-type stars are formed and live in multiple systems (Sana et al. 2012, 2014; Lanthermann et al. 2023),

which plays a key role in their evolution, for example, in the form of tidal effects, mass transfer, common envelope evolution and mergers (de Mink et al. 2013). In addition, massive binary (Kruckow et al. 2018; Marchant & Bodensteiner 2024) and triple (Stegmann et al. 2026) evolution are thought to be among the leading formation channels for merging stellar-mass compact objects detected with LIGO-Virgo-Kagra (e.g., The LIGO Scientific Collaboration et al. 2025). Massive stars in multiple systems also offer a special opportunity to constrain one of their most fundamental properties – their masses. In a broader context, measuring masses is an important step toward calibrating our knowledge of stellar structure and evolution.

Spectroscopic binaries that are also eclipsing allow for accurate dynamical mass measurements. Only a select number of such binaries are known that host massive WNh stars, such as: WR 20a ($M_1 = 83 \pm 5 M_{\odot}$ and $M_2 = 82 \pm 5 M_{\odot}$, Rauw et al. 2004; Bonanos et al. 2004), WR 21a ($M_1 = 93 \pm 2 M_{\odot}$ and $M_2 = 53 \pm 1 M_{\odot}$, Tramper et al. 2016; Barbá et al. 2022), NGC 3603-A1 ($M_1 = 93 \pm 11 M_{\odot}$ and $M_2 = 70 \pm 9 M_{\odot}$, Massey et al. 2025). Because of the need to have eclipses, these studies tend to

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be limited to short periods ($P \lesssim 30$ days). In some cases, binary component masses can also be constrained using wind eclipses or polarization, although both methods rely on modeling the wind of the WNh stars (St.-Louis et al. 1988; Lamontagne et al. 1996; Shenar et al. 2017, 2021). For longer periods, and thus larger orbital separations, an alternative way to measure dynamical masses is using optical long-baseline interferometry to obtain a relative astrometric orbit (Le Bouquin et al. 2017). With complementary information about the distance (e.g., from *Gaia*) and mass ratio from spectroscopic measurements, a full three-dimensional (3D) orbit and accurate model-independent masses can be obtained (e.g., Richardson et al. 2024; Holdsworth et al. 2024). WR 89 is the only massive WNh star so far with a spatially resolved companion detected with optical interferometry, pending follow-up observations for a full orbit determination (Deshmukh et al. 2024).

WR 25 or HD 93162 was first identified as a massive eccentric WNh + O binary system with a 208-day orbital period by Gamen et al. (2006). Residing in the Carina nebula, WR 25 is a member of the Trumpler 16 cluster (distance $D = 2.32 \pm 0.12$ kpc, Shull et al. 2021) and lives among some of the youngest and most massive stars known in the Galaxy. It has been a well-documented bright source in X-ray studies of the region for decades (Raassen et al. 2003; Antokhin et al. 2008; Sasaki et al. 2024). More focused studies have also extensively characterized and established WR 25 as a colliding-wind binary system (Pollock & Corcoran 2006; Pandey et al. 2014; Arora et al. 2019; Pradhan et al. 2021). A detailed spectroscopic study was recently presented by Gosset et al. (2026), which reclassified the system as a WN6ha + O5 binary and updated its orbital parameters, also estimating a total binary mass approaching $100 M_{\odot}$. The updated orbital parameters are listed in Table 1. In this table, and here onward in the paper, the provided error bars are corresponding to 1σ . Additionally, Gosset et al. (2026) also identified spectral signatures of a third component, termed as a potential “intruder” star. They estimated this intruder to have a spectral type between O6 and O8, although no direct confirmation of this star and its association to the WN6ha + O5 binary could be established.

Constraining the binary component masses of WR 25, along with establishing the nature of the third component, will be a crucial step in a comprehensive analysis of the system. In this paper, we present interferometric observations of WR 25 taken with the Very Large Telescope Interferometer (VLTI) at the European Southern Observatory (ESO) Chile. We spatially resolve the two binary components and report the first dynamical mass measurement of this system. We also detect the third component, likely gravitationally bound to the binary. Taking advantage of the brightness ratios derived from interferometry, we revisit the spectroscopic data of WR 25 and perform spectral disentangling to concomitantly separate the three components and compute their stellar parameters. The paper is structured as follows: Section 2 provides a summary of the observations and data reduction. In Section 3, we describe the analysis of interferometric data. Section 4 details our spectral disentangling approach, followed by computation of stellar parameters and orbital properties described in Section 5. Finally, we conclude in Section 6 by discussing the nature of WR 25 and future prospects for studying the system.

2. Observations and data reduction

Long-baseline interferometric observations for WR 25 were obtained in the infrared *H* band (1.52–1.76 μm) with the

Table 1. Orbital parameters for WR 25 from spectroscopy.

Parameter	Value
P [d]	207.638 ± 0.093
e	0.595 ± 0.013
ω [deg]	212.04 ± 1.59
T_0 [d]*	51184.08 ± 0.46
K_1 [km s $^{-1}$]	53.18 ± 0.82
q [M_1/M_2]	2.02 ± 0.36
f [$M_{\odot}$]	1.687 ± 0.098

Notes. Parameters include orbital period (P), eccentricity (e), argument of periastron (ω), time of periastron passage (T_0) and primary radial velocity amplitude (K_1), primary-to-secondary mass ratio (q) and binary mass function (f). *: Heliocentric Julian Date 2 400 000+.

VLTI/PIONIER instrument (Le Bouquin et al. 2011) using the four 1.8-m Auxiliary Telescopes (ATs) at ESO. The AT configuration used was A0-G1-J2-K0, offering a maximum baseline of about 130 m. WR 25 was observed on the night of January 16, 2019 (Heliocentric Julian Date or HJD 2 458 500.733). The reduced data products were retrieved from the ESO Data Archive (ESO Program ID 0102.D-0234(A), PI. Sana).

For spectral disentangling (Sect. 4), we adopt the “Data set I” spectroscopic data from Gosset et al. (2026). The data were taken using the FEROS spectrograph (Kaufer et al. 1999) at the MPG/ESO 2.2-m telescope at La Silla, Chile. They span a broad wavelength range from 3700 Å to 9200 Å, with a spectral resolving power of $\approx 48\,000$. A detailed description of the data can be found in Section 2.1 of Gosset et al. (2026).

We also include an archival ultraviolet (UV) spectrum of WR 25 obtained with the *International Ultraviolet Explorer* (IUE) at Heliocentric Julian Date 2 444 139.591 (IUE Program ID IGBJH, PI. Hesser). The UV spectrum covers the 1150–1800 Å wavelength range, and is particularly useful in determining stellar parameters of the primary.

3. Interferometric analysis

The PIONIER interferometric data consist of two observables: squared visibilities (V2) and closure phases (T3PHI). V2 encodes information about how spatially resolved the source is and the flux contrast between different components. T3PHI, on the other hand, is sensitive to point-asymmetry within the source. An unresolved source yields $V2 = 1$ and $T3PHI = 0$ for all baselines and closure triangles respectively, while a spatially resolved source shows significant deviation in comparison. For binaries or higher order multiples, the PIONIER instrument is sensitive to separations of 1–45 milliarcseconds (mas) and *H*-band flux contrasts down to $\Delta H \sim 4$ (Absil et al. 2011; Sana et al. 2014).

We use the interferometric modeling software PMOIRE¹ (Mérand 2022) version 1.2.10 for geometric modeling of WR 25 data to best explain the features seen in V2-T3PHI. On visual inspection, it is clear that V2 and T3PHI deviate significantly from the signature of an unresolved source, hinting at the target being spatially resolved (see Fig. 1). However, as a baseline model, we first try to fit the data with a single uniform disk component with its diameter allowed to vary. The best fit was poor as expected, resulting in a reduced chi-squared (χ_{red}^2) of 747.

¹ <https://github.com/amerand/PMOIRE>

We then add a level of complexity and try a binary star model. This is implemented by fixing the position of one unresolved component at the origin, and allowing the position of a second unresolved component to vary over a grid of points around the central star covering the full PIONIER field of view (Gallenne et al. 2015). Both components were modeled with uniform disks of fixed diameter 0.2 mas (thus unresolved). The fluxes of the two components were allowed to vary, with their sum fixed to 1. We used a square grid of points ranging from -45 to 45 mas in both N and E directions in steps of 1 mas. The best fit resulted in $\chi^2_{\text{red}} = 234$, which was better than the single component fit but still unsatisfactory.

To test the possible presence of a third star, we add one more component to try a triple component model. This was done similarly to the binary model, this time with the position of one component at the origin while the other two varied over their own grids. With the prior knowledge that WR 25 consists of a 208-day WN6ha + O5 binary, one of the two companions could potentially be the O5 companion, expected to be within a few mas of the primary (Gosset et al. 2026). Consequently, we set a small grid ranging from -3 to 3 mas with steps of 0.3 mas in both N and E directions to search for the O5 companion. For the third component, we set a coarser, more agnostic grid from -45 to 45 mas with steps of 1 mas in both N and E directions. The triple component best-fit is excellent as shown in Figure 1, explaining both V2 and T3PHI well, with $\chi^2_{\text{red}} = 2.84$. The final model consists of (i) the central star as the brightest component, the luminous WN6ha star; (ii) a close component at 1.68 ± 0.02 mas, the spectroscopic O5 companion; and (iii) a farther out component at 27.69 ± 0.02 mas, likely an outer companion consistent with the intruder reported by Gosset et al. (2026). Both companions are detected at a significance greater than 8σ with respect to the baseline single component model. To obtain realistic error bars for all the best-fit parameters, we used a bootstrapping routine with 1000 realizations. The results are listed in Table 2 along with component spectral types (see Sect. 4 for details). A visual representation on the plane of the sky of the three components is shown in Figure 2.

While the secondary is a known companion from spectroscopy, we present the first unambiguous detection of the third component using interferometry. Although one snapshot observation is not sufficient to determine whether the star is gravitationally bound to the inner binary, we can assess its probability of chance alignment. Following Rainot et al. (2020), we calculate the probability of this component being spuriously associated to the inner binary (P_{spur}). To do so, we query all sources from the 2MASS All-Sky Point Source Catalog (Skrutskie et al. 2003) within $120''$ and with $\Delta H < 5$ (one magnitude fainter than typical PIONIER sensitivity) with respect to WR 25 to conservatively estimate the density of nearby sources bright enough for detection with PIONIER. We then calculate the probability P_{spur} of spuriously detecting a source within the PIONIER outer working angle (~ 45 mas, Sana et al. 2014). We find $P_{\text{spur}} < 0.01\%$ for the third component, implying a very high likelihood of it being physically related to the inner binary. In Table 2 and in the following text, we systematically name this object the tertiary component despite the persisting possible doubt.

4. Spectral disentangling

With the newly confirmed presence of the third component, we turn to spectroscopic data of WR 25 taken with FEROS (Gosset et al. 2026) to isolate the spectral signatures of individual components. We employ a three-component Fourier spectral

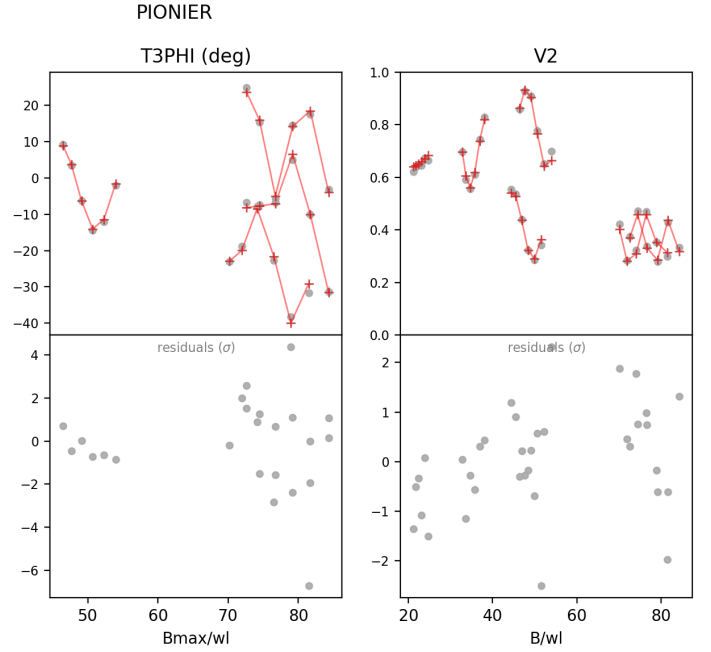


Fig. 1. Closure phases (T3PHI) and squared visibilities (V2) shown for WR 25 as functions of spatial frequencies (baseline B in m/wavelength wl in μm). The data are shown in the upper panels with grey points while the best-fit triple component model is shown with red crosses. The points connected by red lines represent different 2-telescope baselines for V2 and 3-telescope triangles for T3PHI. The lower panels show residuals corresponding to the best-fit model.

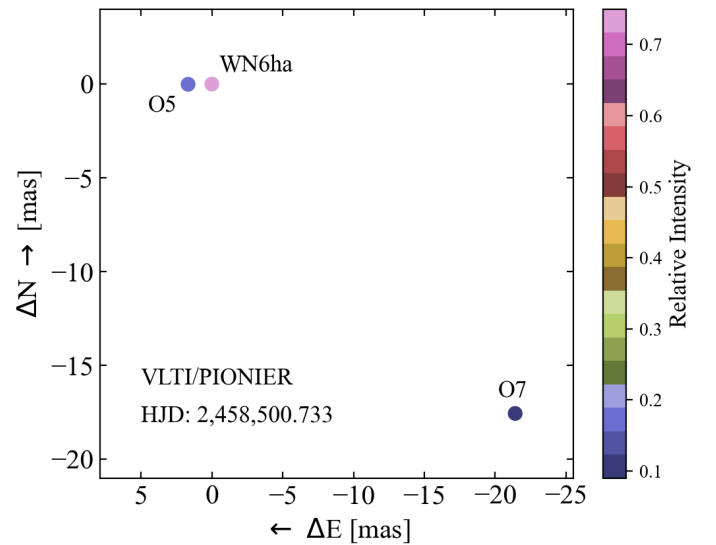


Fig. 2. Relative positions of the three components in WR 25. All error bars are smaller than the marker sizes and the colors indicate relative intensities of the components measured in the H -band by PIONIER, as listed in Table 2. Component spectral types derived from spectroscopic analysis are also shown (more details in Sect. 4).

disentangling code adapted from Ilijic et al. (2004) and Hadrava (1995). For the inner system, we adopt the orbital solution from Table 1, and assume that the third component remains stationary (see Gosset et al. 2026, for details). The flux contributions of the individual components are taken from interferometric measurements, with $f_p = 0.751$, $f_s = 0.158$, and $f_t = 0.091$ for the primary, secondary, and tertiary, respectively (Table 2). Given the O-star natures of all three components, it is safe to

Table 2. Astrometric and photometric constraints on WR 25.

Component	ΔE [mas]	ΔN [mas]	e_{maj} [mas]	e_{min} [mas]	PA [deg]	f	SpT
Primary	0*	0*	–	–	–	0.751 ± 0.003	WN6ha
Secondary	1.682	–0.014	0.020	0.007	–68.4	0.158 ± 0.002	O5
Tertiary	–21.410	–17.557	0.025	0.011	–34.1	0.091 ± 0.002	O7

Notes. Relative astrometric positions (ΔE and ΔN in mas) and relative flux contributions (f , dimensionless) of all three components in WR 25. Marked by *, the position of the primary (WR) is fixed at the origin. For the secondary and tertiary, the error ellipse is provided in the form of the semi-major axis (e_{maj}), semi-minor axis (e_{min}), and position angle (PA) of the semi-major axis measured eastward of north. Also listed are component spectral types (SpT), which are discussed in Section 4.

assume that they are in the Rayleigh-Jeans domain from the UV to the infrared. In principle, free-free excess stemming in the wind of the WR star could cause significant infrared excess in the H -band. However, this has negligible impact in the case of WR 25 due to the primary’s relatively weak wind, as we show below from a detailed spectral analysis of the individual components of the system (Sect. 5). Hence, we assume that the H -band flux ratios represent the ratios in the V -band and UV as well.

Because the spectral lines of the secondary O5 star never fully deblend from those of the WN6ha primary, particularly when blue-shifted, the reconstruction of its spectral lines can exhibit artifacts in their blue wings. In addition, the spectral lines of the tertiary component are mostly overlapping with those of the primary, with only a few exceptions, such as the He I 4471 line, where the almost static signature of the tertiary has been identified in the observed spectra (Gosset et al. 2026). The disentangled spectrum of the tertiary therefore shows only clear spectroscopic features of a limited number of lines, including He I 4471 and He II 4542. Given the broadness of the Balmer lines, and the fact that these lines never fully deblend for the three components, only a faint contribution can be extracted for the tertiary from the disentangling process. While He I 4471 and He II 4542 are clearly resolved in the disentangled spectrum, the shape of the Balmer lines could only be reconstructed using the continuum of synthetic spectra with the same spectral classification as the tertiary. Consequently, the determination of the surface gravity and wind properties for the tertiary remains highly uncertain (see Sect. 5).

As noted by Mahy et al. (2017), Fourier spectral disentangling suffers from the drawback of losing the continuum for stars that are not fully eclipsed by their companions. It is therefore crucial to correct the disentangled spectra for this effect. For the WN6ha primary, the continuum is particularly difficult to constrain, so we corrected for continuum variations by fitting a spline to a carefully-selected continuum region using synthetic models. For the secondary star, the continuum correction was also performed by fitting a spline through its continuum. For the tertiary component, as mentioned above, only the regions around the Balmer lines were defined using synthetic spectra; for the remaining portions, the continuum was fitted using a spline function, as was done for the secondary.

The WN6ha spectrum (see Fig. 3) is characterized by a prominent N IV 4058 line and a strong N V doublet at 4604–4619 Å. The He I 4471 line is not detected in the disentangled spectrum, while the Si IV 4089–4116 lines are observed in emission. The He II 4686 line is also strongly in emission.

In the spectrum of the O5 secondary (see Fig. 4), the Si IV 4089 line is absent, while Si IV 4116 is clearly detected in emission. The N III 4634–4641 doublet appears in strong emission, and He II 4686 is observed slightly in absorption. These

characteristics suggest a classification with the suffix ((f⁺)) or (f⁺) (Walborn 1972, see also the discussion in Section 7.2 of Gosset et al. 2026).

The disentangled spectrum of the tertiary component (see Fig. 5) displays clear He I and He II features, indicating a mid-O classification. The He I 4471 line has a depth comparable to that of He II 4542, suggesting a spectral type of O7–O7.5. Since He II 4686 is strongly in absorption, the tertiary can be assigned a luminosity class V. We refer to this component as an O7 star here onward.

5. Stellar parameters and evolutionary status

5.1. Atmosphere modeling

The spectra of the three components were modeled using the non-local thermodynamic equilibrium (non-LTE) radiative transfer code CMFGEN (Hillier & Miller 1998). CMFGEN solves the radiative transfer equation in the co-moving frame under the assumptions of spherical symmetry and steady state, accounting for line blanketing and complex atomic models in expanding stellar winds. The code simultaneously solves the equations of statistical equilibrium and radiative transfer, allowing for a detailed treatment of millions of spectral lines through a super-level approach to reduce computational complexity. Wind structures are prescribed via a β -type velocity law, and clumping can be incorporated through a volume-filling factor with a void inter-clump medium formalism. The temperature structure is obtained from radiative equilibrium, ensuring consistency between the radiation field and the atmospheric stratification.

5.1.1. The WN6ha primary

To model the WN6ha primary spectrum, we generated, as a first step, a grid of about 1000 models covering the parameter space: from 42 kK to 50 kK with steps of 2 kK for the effective temperature, from 0.10 to 0.30, with steps of 0.04 for the helium surface abundance, from 8.0 to 10.0 with steps of 0.5 for the nitrogen surface abundance (in $\epsilon_N = 12 + \log[N/H]$ notation), and from –5 to –4, with steps of 0.2 for the mass-loss rate in logarithmic scale ($\log \dot{M} [M_\odot \text{ yr}^{-1}]$). Other parameters were kept fixed at first: clumping volume filling factor of 0.15, β exponent of the velocity law of 1.0, terminal wind speed $v_\infty = 2500 \text{ km s}^{-1}$, and stellar luminosity of $\log(L/L_\odot) = 6.0$ in agreement with Gosset et al. (2026). We note that we do not perform a Spectral Energy Distribution fitting given the incompatibility between the extinction values provided from the blue/UV, and red/infrared (see Crowther et al. 1995; Gosset et al. 2026). Using this grid, we computed the χ^2 statistic to compare the disentangled spectrum of the primary with the different models and narrow down the parameter space around a set of representative models.

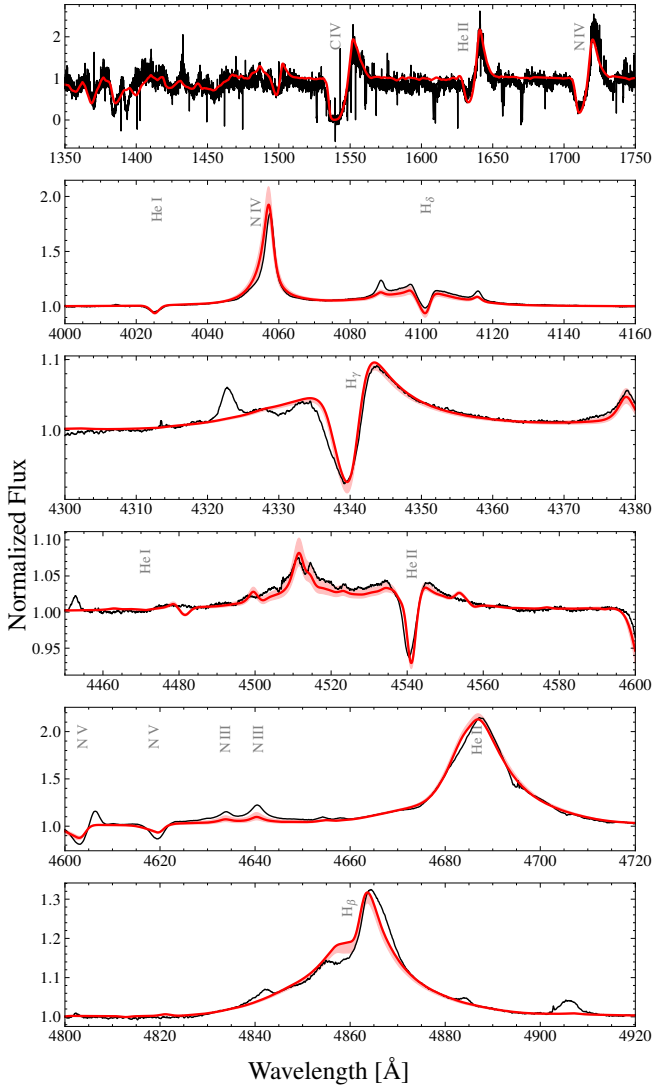


Fig. 3. Comparison between the best-fit CMFGEN model (in red, and the uncertainty region in light-red) with either the observed UV spectrum of WR 25 (in black, top panel) or with the disentangled spectrum of the primary component of WR 25 (in black, the five lower panels).

In a second step, we refined the stellar and wind parameters through an iterative fitting procedure aimed at converging toward the optimal solution. Starting from the representative models identified from the χ^2 analysis, we progressively adjusted the effective temperature, surface abundances, and wind properties to improve the agreement between the synthetic and observed spectra. To alleviate degeneracies between key parameters, we complemented the disentangled spectrum with the ultraviolet composite spectrum of WR 25 obtained with *IUE*, that includes lines like N V 1240, O V 1371, the Si IV 1393–1402 doublet, C IV 1548–1550, He II 1640, and N IV 1718. By adding the UV lines, we add more diagnostic lines to constrain the mass-loss rate, and we can now derive the terminal wind velocity for the primary by using the blue edges of the P-Cygni profiles (i.e., the C IV 1548–1550, He II 1640, and N IV 1718 lines). For this purpose, we shifted the synthetic spectra of the WN6ha primary and the O5 secondary according to their radial velocities calculated from the orbital solution presented by Gosset et al. (2026). For the tertiary, we use the same radial velocity as the primary star. We also correct for the dilution effects in the UV (see Sect. 4).

The best-fit model is shown in Fig. 3 and is compared to the composite *IUE* spectrum in the UV and to the disentangled spectrum in the optical. The temperature of the WN6ha primary was determined using the nitrogen ionization balance (N III/N IV/N V). However, the N V lines at 4604 and 4619 Å proved difficult to reproduce while simultaneously fitting the N III lines present in the disentangled spectrum (equal weight was given to both sets of ionization stages). The best-fit temperature (at $\tau = 20$) for the WN6ha star is 43 ± 1 kK, providing an effective temperature of 42.2 ± 1.0 kK (at $\tau = 2/3$). We derived a helium surface abundance of $Y_{\text{He}} = 0.14 \pm 0.02$, a nitrogen abundance of $\epsilon_{\text{N}} = 8.90 \pm 0.08$, and carbon and oxygen abundances of $\epsilon_{\text{C}} = 6.78 \pm 0.12$ and $\epsilon_{\text{O}} = 8.18 \pm 0.43$, respectively. The mass-loss rate is $\log \dot{M} [M_{\odot} \text{ yr}^{-1}] = -5.15 \pm 0.10$, and the terminal wind velocity is derived to be $v_{\infty} = 2200 \pm 100 \text{ km s}^{-1}$, from the blue edges of the UV P-Cygni profiles, such as C IV 1548–1550, He II 1640, and N IV 1718. The clumping volume-filling factor is ≈ 0.1 , and the exponent of the velocity law is $\beta \approx 1.5$. We also computed the bolometric correction using the calibration of Martins & Plez (2006) and adopted the absolute *H*-band magnitudes of the individual components. This yields a luminosity of $\log(L/L_{\odot}) = 6.21 \pm 0.06$. All best-fit parameters are listed in Table 3.

5.1.2. The O5 secondary and O7 tertiary

We first derived the projected rotational velocities of the secondary and tertiary components. For this purpose, we used a Python implementation of the IACOB-broad tool developed by Simón-Díaz & Herrero (2007, 2014), which we adapted for our analysis. For the O5 secondary, we obtained a projected rotational velocity of $v \sin i = 87 \pm 12 \text{ km s}^{-1}$ and a macroturbulent velocity of $v_{\text{mac}} = 69 \pm 34 \text{ km s}^{-1}$. For the tertiary component, we derived $v \sin i = 69 \pm 24 \text{ km s}^{-1}$ and $v_{\text{mac}} = 83 \pm 52 \text{ km s}^{-1}$.

To estimate the fundamental parameters of the secondary and tertiary components, we used a pre-computed grid of synthetic spectra calculated with CMFGEN. The grid was constructed based on the evolutionary tracks of Brott et al. (2011). We adopted a constant step of 0.1 dex in surface gravity ($\log g$), while adjusting the effective temperature, luminosity, and mass-loss rate consistently with the evolutionary models. The terminal wind velocity was estimated using the $T_{\text{eff}} - v_{\infty}$ prescription of Hawcroft et al. (2024). Surface abundances were fixed to solar values following Grevesse et al. (2010).

All models were computed with different microturbulent velocities of 2, 5, 7, 10, 12, 15, 17, and 20 km s^{-1} . The clumping volume filling factor was fixed to 0.1, while the exponent of the velocity law β was fixed to 1.0. The grid contains 5271 models, covering T_{eff} between 10 and 50 kK, surface gravities in the range $\log g = 1.4\text{--}4.3$ (cgs), and luminosities between $\log(L/L_{\odot}) = 2.60$ and 5.92.

The effective temperature was determined from the helium ionization balance, while the surface gravity was constrained from the wings of the Balmer lines, in particular H δ , H γ , and H β . The best-fitting model was selected by minimizing the χ^2 function computed over the hydrogen and helium lines. The left panels of Figures 4 and 5 present the best-fit grid models for the secondary and tertiary components, together with their associated uncertainty regions.

Given the uncertainty in the continuum correction around the Balmer-line wings in the disentangled tertiary spectrum, we adopted an additional diagnostic to estimate the stellar parameters of this component. We measured the equivalent widths of the He I 4471 and He II 4542 lines and computed their ratio. This

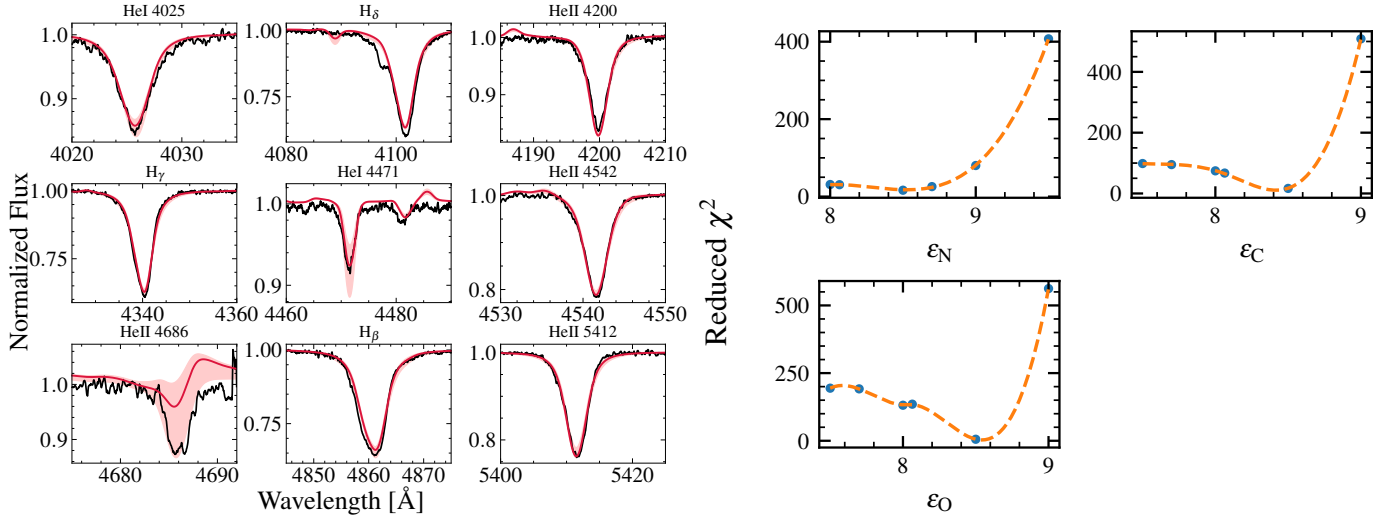


Fig. 4. Left: Comparison between the disentangled spectrum (black) of the secondary component of WR 25 with the best-fit CMFGEN model (solid red) and the uncertainty region (shaded red), shown for nine prominent H and He lines. Right: Reduced χ^2 plots for nitrogen, carbon, and oxygen surface abundances of the secondary expressed in $\epsilon_X = 12 + \log[X/H]$ formalism.

observed ratio was then compared to the ratios predicted by all synthetic spectra in our CMFGEN grid. Models for which the theoretical and observed ratios agree within uncertainties were retained as viable solutions. The right panel of Fig. 5 shows the Kiel diagram constructed from our grid models, with the region consistent with the observed line ratio highlighted in orange. This constraint is independent of the brightness-ratio correction applied to the disentangled tertiary spectrum. The acceptable parameter space for the tertiary, assuming the same distance and covality with the binary, is located in the range $34 \leq T_{\text{eff}} \leq 38 \text{ kK}$ and $3.4 \leq \log g \leq 4.2$. The luminosities of the O5 secondary and O7 tertiary were estimated from the individual absolute magnitudes corrected from the bolometric correction given by Martins & Plez (2006) using the effective temperatures of the stars and the H -band law.

Once the best-fitting models were established, we derived the surface abundances by computing additional spectra with varying carbon, nitrogen, and oxygen abundances. For that purpose, we use the N III 4097, the N III 4198, the N III quadruplet around 4515 Å, the C III 4068–70, and the O III 5592 lines. The optimal values were determined by minimizing the χ^2 function computed on these selected diagnostic lines and is shown for the secondary, for example, in the right panel of Fig. 4. The O5 secondary exhibits nitrogen enrichment, while its carbon and oxygen abundances are consistent with solar values. The O7 tertiary shows surface abundances compatible with solar values for carbon, nitrogen, and oxygen. All the individual parameters for the three components are listed in Table 3.

5.2. Dynamical mass constraints

In a spatially resolved binary, relative positions of the two components measured at different orbital phases can be combined with a known distance and spectroscopic orbital solution of one of the two components to obtain a complete 3D orbit and the total mass of the system (e.g., Frost et al. 2024). In cases where the mass ratio is known, individual component masses can also be derived. Alternatively, a double-lined spectroscopic (SB2) orbital solution including an inclination estimate can be combined with a single interferometric epoch for a direct measurement of the dynamical masses (e.g., Deshmukh et al. 2025). The

Table 3. Individual parameters of the WR 25 components and their 1σ uncertainties.

	Primary	Secondary	Tertiary
Stellar parameters			
Sp. Type	WN6ha	O5 ((f ⁺))	O7 ((f))
T_{eff} [kK]	42.2 ± 1.0	41.4 ± 1.7	36.3 ± 2.6
T_* [kK]	43.0 ± 1.0	42.2 ± 1.7	36.8 ± 2.6
$\log g$ [cgs]	–	3.9 ± 0.1	$3.9^{+0.1}_{-0.2}$
$\log(L/L_{\odot})$	6.21 ± 0.06	5.48 ± 0.07	5.08 ± 0.10
ξ_t [km s ^{−1}]	20 ± 5	15 ± 3	10 ± 2
Wind parameters			
$\log \dot{M}$ [$M_{\odot} \text{ yr}^{-1}$]	-5.15 ± 0.10	–	–
v_{∞} [km s ^{−1}]	2200 ± 100	–	–
β	1.5	1.0	1.0
f_{cl}	0.10	0.10	0.10
Surface abundances			
Y_{He}	0.14 ± 0.02	0.09 ± 0.01	0.09 ± 0.01
ϵ_N	8.90 ± 0.08	8.65 ± 0.08	7.65 ± 0.10
ϵ_C	6.78 ± 0.32	8.45 ± 0.08	8.39 ± 0.14
ϵ_O	8.18 ± 0.43	8.58 ± 0.08	8.59 ± 0.23

data available for WR 25 fall short of either condition, yet the fortunate timing of the VLTI observation still allows us to constrain the total mass of the system without invoking the poorly constrained RV solution of the secondary.

Adopting the ephemeris of the primary RV solution given in Table 1, the interferometric epoch of observation corresponds to an orbital phase of $\phi_{\text{int}} = 0.235 \pm 0.016$, where an orbital period uncertainty of 0.093 d from Gosset et al. (2026) has been included in the error propagation. This yields a true anomaly of $\nu_{\text{int}} = 144.6 \pm 3.1^\circ$ and $\nu_{\text{int}} + \omega = 356.6 \pm 3.5^\circ$. The VLTI observation therefore occurred close to the passage at one of the nodes (given by $\nu + \omega = k\pi$). The positive primary RV at $\phi_{\text{int}} \approx 0.24$ informs us that $\nu + \omega = 0$ actually corresponds to the ascending node of the primary. Interestingly, the secondary is almost directly East of the primary (Table 2), i.e. with a position angle of $\approx 90^\circ$. While not necessary for the total mass constraint, it is

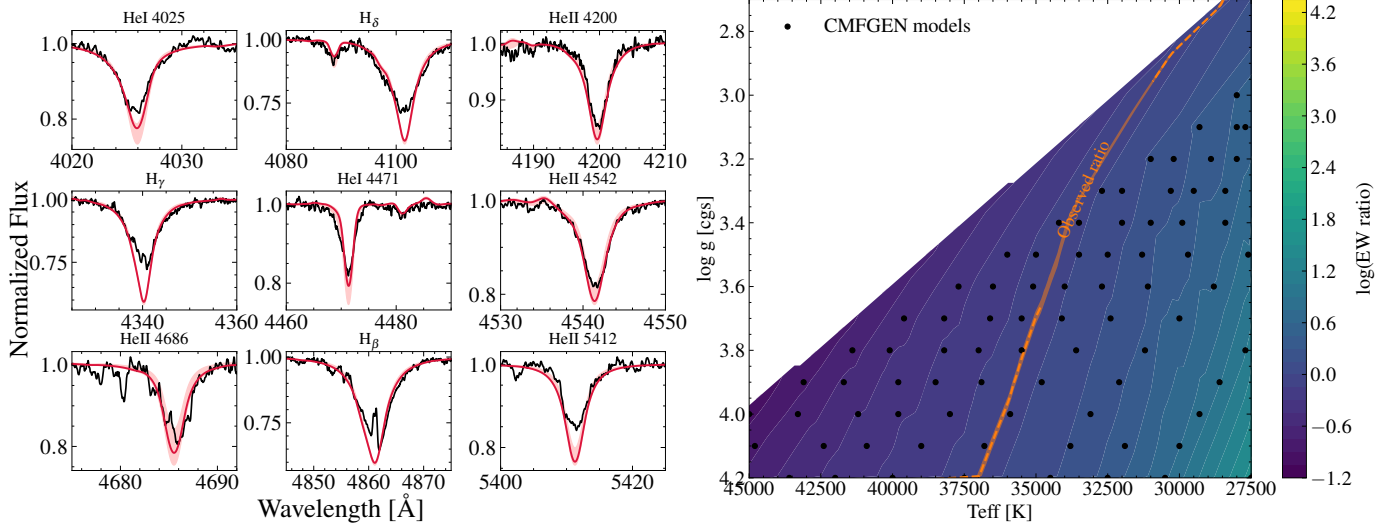


Fig. 5. Left: Same as for the left set of panels of Fig. 4 but for the tertiary component of WR 25. Right: Kiel diagram ($\log g$ vs. T_{eff}) computed from the CMFGEN grid for the tertiary component of WR 25. Each point represents a synthetic model included in the grid. The orange region indicates the models for which the predicted equivalent-width ratio of He I 4471 to He II 4542 matches the observed ratio within uncertainties.

then straightforward to estimate the value of the longitude of the ascending node Ω to be $\approx 270^\circ$.

This favorable timing allows us to directly estimate the total mass of the system using only the primary RV curve and the distance, without requiring the mass-ratio that is plagued with significant uncertainty. At a node, for a distance D to the system, the true separation r and the projected physical separation $\rho_{\text{phys}} = D \rho = D \sqrt{\Delta E^2 + \Delta N^2}$ are identical to one another. This results from the projected separation equation

$$\rho_{\text{phys}}^2 = r^2 (\cos^2(\nu + \omega) + \sin^2(\nu + \omega) \cos^2 i), \quad (1)$$

which simplifies to $\rho_{\text{phys}} \approx r$ for $\nu + \omega = k\pi$ (with $k = 0, 1, 2, \dots$). We thus obtain $\rho_{\text{phys}} = 3.90 \pm 0.21$ au. This gives us an estimate of the absolute size of the relative orbit, without the need of a precise SB2 solution or additional VLTI measurements as

$$a = \rho_{\text{phys}} \frac{1 + e \cos \nu_{\text{int}}}{1 - e^2}, \quad (2)$$

where ν_{int} is the true anomaly corresponding to the time of the interferometric observation, leading to $a = 3.11 \pm 0.20$ au. Constraints on the total mass then follow from the third Kepler law:

$$M_{\text{tot}} = \frac{4\pi}{GP^2} \left(\rho_{\text{phys}} \frac{1 + e \cos \nu_{\text{int}}}{1 - e^2} \right)^3, \quad (3)$$

yielding a total mass of $M_{\text{tot}} = 93 \pm 18 M_\odot$. Combining with the mass ratio from Table 1, we get individual component masses $M_1 = 62 \pm 13 M_\odot$ and $M_2 = 31 \pm 7 M_\odot$.

We further leverage the node observation to constrain the inclination as, at the position of the node, we have

$$\sin i \approx \frac{a_1 \sin i \cdot (1 + q)}{\rho_{\text{phys}}} \cdot \frac{1 - e^2}{1 + e \cos \nu_{\text{int}}}, \quad (4)$$

where $q = 2.02 \pm 0.36$ (Table 1). This results in $\sin i = 0.79 \pm 0.11$, and $i \approx 52 \pm 10^\circ$ or $128 \pm 10^\circ$. More interferometric observations will be necessary to break the degeneracy and enable a full 3D orbital solution.

5.3. Evolutionary masses and ages

To estimate the evolutionary masses and ages of the three components, we used the BONNSAI (BONN Stellar Astrophysics Interface) Bayesian tool (Schneider et al. 2014). BONNSAI compares the observed stellar properties with the BONN single-star evolutionary models (Brott et al. 2011).

In a first step, we performed a run using as input parameters the luminosity and effective temperature for the primary component, and the luminosity, surface gravity, effective temperature, and projected rotational velocity for the secondary and tertiary components. This yields evolutionary masses of $M_{\text{evol}} = 87.2^{+2.7}_{-11.0}$, $39.0^{+3.6}_{-2.6}$, and $25.0^{+2.6}_{-2.1} M_\odot$ for the primary, secondary, and tertiary, respectively. The corresponding evolutionary ages are $1.2^{+0.9}_{-0.2}$, $1.9^{+0.4}_{-0.5}$, and $3.4^{+0.9}_{-0.9}$ Myr, respectively.

Given the large uncertainty on the surface gravity of the tertiary component, we performed an additional run excluding this parameter. In this case, we obtain an evolutionary mass of $25.6^{+2.8}_{-2.3} M_\odot$ and an age of $3.0^{+1.2}_{-1.7}$ Myr, consistent with the aforementioned values. We adopt these updated values for the tertiary, also used in Section 5.4.

In a second step, we included the dynamical masses derived for the primary and secondary as additional constraints. BONNSAI then returns evolutionary masses of $M_{\text{evol}} = 75.2^{+8.2}_{-4.7} M_\odot$ and an age of $2.0^{+0.2}_{-0.8}$ Myr for the primary, and $M_{\text{evol}} = 38.0^{+3.1}_{-2.6} M_\odot$ with an age of $2.0^{+0.5}_{-0.5}$ Myr for the secondary.

Finally, we included, in addition to the dynamical masses, the surface nitrogen abundances of the primary and secondary components as input parameters. In this configuration, BONNSAI yields evolutionary masses of $M_{\text{evol}} = 76.6^{+3.1}_{-4.9} M_\odot$ and an age of $2.0^{+0.2}_{-0.2}$ Myr for the primary, and $M_{\text{evol}} = 37.0^{+2.4}_{-1.8} M_\odot$ with an age of $2.8^{+0.5}_{-0.5}$ Myr for the secondary.

The evolutionary masses for the primary and secondary are consistent with their dynamical masses within error bars, although the evolutionary masses do appear to be systematically higher. The dynamical masses are currently constrained with only one interferometric epoch; more epochs will allow for better mass measurements and hence better comparison with evolutionary masses. Additionally, the primary and secondary seem to be coeval, and a significant discrepancy arises only when

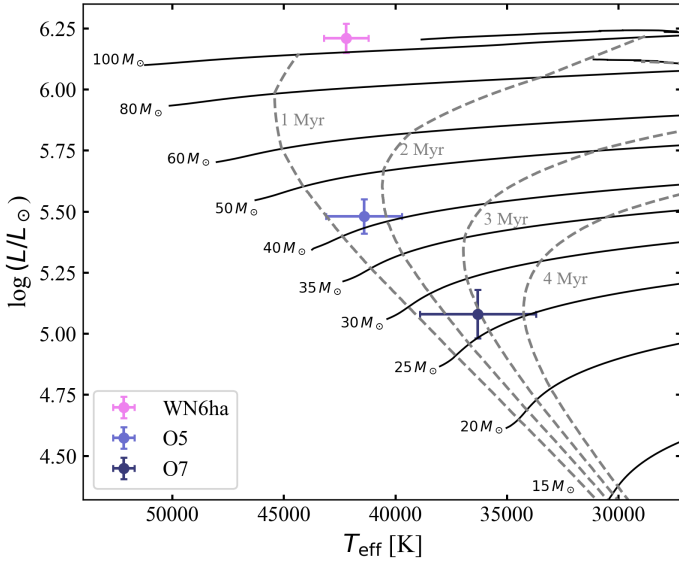


Fig. 6. All three components in WR 25 shown on a Hertzsprung-Russell diagram, with $T_{\text{eff}} - \log L$ values taken from Table 3. Also shown are evolutionary tracks computed with an initial rotational velocity of 150 km s^{-1} from Brott et al. (2011) for a few different masses (solid), and isochrones for a few different ages (dashed).

nitrogen surface abundances are included. The tertiary component remains compatible with coevality within 2σ uncertainties. Figure 6 shows all three components on a Hertzsprung-Russell diagram.

5.4. The orbit of the tertiary

With a robust measurement of the relative astrometric position of the tertiary and an estimate of its mass, it is possible to broadly constrain its orbital properties. We used the methods described in Trammer et al. (2026) and Millour et al. (2026) to estimate the posterior distribution of the orbital period/separation and velocities given the masses of $M_1 + M_2$ (dynamical) and of M_3 (evolutionary), and the observed angular separations. We adopted the total binary mass obtained in Sect. 5.2, along with the distance, ΔE , and ΔN . We marginalized over a random orientation of the system and assumed a flat eccentricity prior between 0.0–0.9. The resulting probability distribution of tertiary periods is shown in Figure 7.

The most likely tertiary period (68% highest density interval) ranges from 19–82 yr (corresponding to a semi-major axis of 38–94 au), while its sky-plane angular velocity ranges from 1.3–3.2 mas yr^{-1} , which should be easily detectable in future VLTI observations. The expected RV semi-amplitude is only of a few km s^{-1} and will be much harder to detect, if at all possible.

6. Conclusions

We present a VLTI/PIONIER interferometric observation of the massive colliding wind binary WR 25, spatially resolving the two spectroscopic components. We derive the total dynamical mass of the binary $M_{\text{tot}} = 93 \pm 18 M_{\odot}$, and subsequently the component masses $M_1 = 62 \pm 13 M_{\odot}$ and $M_2 = 31 \pm 7 M_{\odot}$. More measurements of the relative positions of the binary components will be crucial to constrain the 3D binary orbit. We also detect the third “intruder” component reported by Gosset et al. (2026)

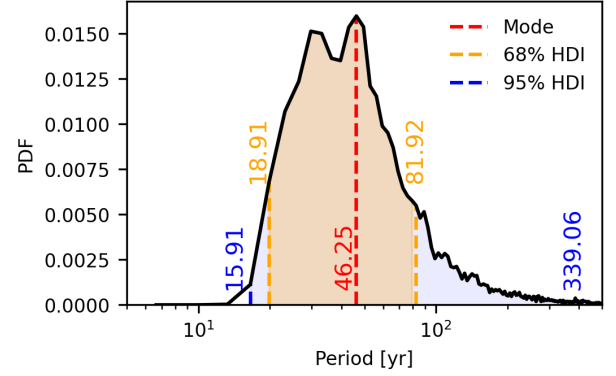


Fig. 7. Probability distribution function (PDF) of the tertiary orbital period based on estimated masses and marginalized over random orientation of the system. Also shown are the mode (red), and the 68% (orange) and 95% (blue) highest density interval (HDI) regions.

at an angular separation of $27.69 \pm 0.02 \text{ mas}$ from the primary, establishing WR 25 as a likely hierarchical triple system.

We revisit spectroscopic data of WR 25 to perform spectral disentangling and separate spectra for all three components. Following detailed atmospheric analysis performed with CMFGEN for each component, we estimate their evolutionary masses and ages using single star evolution tracks in BONNSAI. All three components in WR 25 have evolutionary ages consistent within 2σ , which are also consistent with the 1–3 Myr age estimated for Trumpler 16 (Hur et al. 2012).

Finally, we make predictions for the orbital properties of the tertiary component and estimate the outer orbital period to be in the range 19–82 yr. The corresponding sky-plane angular velocity of the tertiary is expected to be 1–3 mas yr^{-1} , meaning it is likely to show a significant shift in its position if observed now, as compared to 2019 when it was first observed with VLTI. More interferometric epochs can confirm the hierarchical triple nature of WR 25 beyond any doubt and also provide stronger constraints on the tertiary orbit.

WR 25 represents the rare case of a massive hierarchical triple where all three components are spatially resolved (more common for B-type stars, see Frost et al. 2025). Sana et al. (2025) note that several O-type massive hierarchical triple systems have been identified with interferometry, but are often inadequately constrained due to the inner binary being too close to be spatially resolved (e.g., Bordier et al. 2026). With all three components spatially resolved, WR 25 presents the opportunity to determine both the inner and outer orbits, and use their mutual orientations to study the formation and dynamical stability of the triple system (Mardling & Aarseth 2001; Tokovinin 2004). Additionally, measuring accurate and precise dynamical masses for all three components will be crucial to calibrate stellar physics for massive stars. For example, leveraging the component masses and coevality of the triple system, it will be possible to constrain internal mixing and wind mass-loss which carry significant uncertainties in current stellar evolution models. We therefore encourage continued interferometric observations of WR 25 to measure precise orbits for the inner binary, the tertiary, and the dynamical masses of all components.

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