Spectroscopic Observations of Ten Galactic Wolf–Rayet Stars at Bosscha Observatory: Determination of Stellar Parameters and Mass-loss Rates (Postprint)

Authors: Hakim Luthfi Malasan and Bakuh Danang Setyo Budi

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Full Text

Preamble

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Spectroscopic Observations of Ten Galactic Wolf–Rayet Stars at Bosscha Observatory: Determination of Stellar Parameters and Mass-loss Rates

Hakim Luthfi Malasan[1],[2] and Bakuh Danang Setyo Budi[2],[3]
[1] Department of Astronomy, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Bandung 40132, Indonesia; malasan@itb.ac.id
[2] Bosscha Observatory, Institut Teknologi Bandung, Lembang 40391, Indonesia
[3] Master Program in Astronomy, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung 40132, Indonesia

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Abstract

We present optical spectra of 10 Galactic Wolf–Rayet (WR) stars, consisting of five WN and five WC stars. The observations were conducted using a low-resolution NEO-R1000 spectrograph ($\lambda/\Delta\lambda$ 1000) at the GAO-ITB RTS (27.94 cm, F/10.0) at Bosscha Observatory, Lembang. We implemented Potsdam Wolf–Rayet (PoWR) grid modeling to derive stellar parameters. The normalized optical spectrum can be used to find the best-fit model from the available PoWR grid, from which we derive the stellar temperature and transformation radius. To determine luminosity, stellar radius, and color excess, we performed a Spectral Energy Distribution (SED) analysis using additional near-ultraviolet spectra from the International Ultraviolet Explorer (IUE) database, along with UBV and 2MASS JHK broadband photometry. We also derived the asymptotic terminal wind velocity from P-Cygni profile analysis of high-resolution IUE ultraviolet spectra. Using these derived parameters, we determined the mass-loss rates of the WR stars. Furthermore, we compared our results with previous work that used the PoWR code, finding differences of no more than 20%. We conclude that the PoWR spectral grid is sufficient for quickly deriving WR stellar parameters and can provide accurate initial parameter inputs for the PoWR code.

Key words: stars: massive – stars: mass-loss – stars: Wolf-Rayet – stars: atmospheres – stars: winds – outflows

1. Introduction

Wolf–Rayet (WR) stars, representing the final evolutionary stage of massive stars, exhibit unique continua and emission lines that distinguish them from other astronomical objects. Their continua peak in the extreme ultraviolet (EUV) region, indicating very high temperatures similar to O-type stars (Willis & Wilson 1978). The presence of emission lines—rather than the absorption features typical of normal stars—indicates that their atmospheric envelopes are much larger than their photospheres, commonly known as extended atmospheres (Kogure & Leung 2007). The emission profiles in the optical and ultraviolet (UV) regions show P-Cygni profiles, indicating that these envelopes expand at high velocities with large mass-loss rates (Crowther 2007). These features initially confused astronomers because WR spectra could not be modeled like normal stars using the Local Thermodynamic Equilibrium (LTE) approach.

The spectral classification of WR stars is based not on luminosity and effective temperature, but rather on the degree of ionization of emission lines produced in their extended atmospheres (Rustamov 2017). Currently, WR stars are grouped into WN, WC, and WO subtypes depending on the dominant lines observed in addition to helium—nitrogen ionization lines in WN stars and carbon ionization lines in WC stars. Some WC stars show O IV lines and are separated into a new subtype, WO. The quantitative classification criteria for these three subtypes are given by Smith et al. (1996) and Crowther et al. (1998).

Historically, Bosscha Observatory in Lembang has conducted studies of WR stars through spectroscopic surveys using the Bimasakti Schmidt Telescope, primarily to examine the population distribution of WR stars as tracers of young Population I stars and spiral arms in the Milky Way galaxy (Hidayat et al. 1982). A follow-up study by Hidayat (1995) focused on determining mass-loss rates and the contribution of WR stars to enrichment of the Galactic interstellar medium (ISM). A previous study by Adhyaqsa et al. (2020) using the same PoWR grid model discussed the mass-loss effects of WR stars on their environment, estimating 0.5 M of ejected material annually into the Galactic ISM.

The purpose of this paper is to present data observed with a small-diameter telescope and NEO-R1000 spectrograph, demonstrating that we can measure fundamental parameters (e.g., temperature, luminosity) using a simple and publicly accessible PoWR spectral modeling grid (Gräfener et al. 2002; Hamann & Gräfener 2003; Sander et al. 2015) that can quickly and accurately derive parameters compared to previous literature relying on larger, more sophisticated instruments. We emphasize the role of small-diameter telescopes (<1 m) for monitoring spectroscopic observations of WR stars. These objects are interesting to study because their spectra cannot be modeled with well-known atmospheric models for normal stars. Additionally, they show photometric variability (Lenoir-Craig et al. 2022), necessitating spectroscopic follow-up observations. Many Galactic WR objects are bright enough for small instruments but too bright for large-diameter telescopes. Their wide, strong emission features make them very suitable for spectroscopic observation even at low resolution and for monitoring emission line changes over time.

In Section 2, we describe our optical spectroscopic observations and data reduction. In Sections 3 and 4, we explain our methods for deriving WR stellar parameters. In Section 5, we discuss our results, compare them with previous work, and comment on several interesting WR samples. Section 6 summarizes our conclusions. We provide PoWR model fitting results and SED analysis in Appendices A and B, respectively.

2. Observations and Data Reduction

We conducted optical spectroscopy observations of eight Galactic WR stars between 2022 September and November at GAO-ITB RTS, Bosscha Observatory, Lembang. These objects, located in both northern and southern hemispheres, were accessible due to our strategic equatorial location. We selected representative objects from each WR subclass with sufficient brightness for our instrument.

We used an NEO-R1000 spectrograph ($\lambda/\Delta\lambda$ 1000 with a slit width of 5) equipped with an SBIG ST-8XME CCD as the main detector and a QHY174 GPS CMOS camera as the slit viewer, attached to a Celestron C11 (27.94 cm, F/10) Schmidt-Cassegrain telescope. The NEO-R1000 spectrograph, developed through collaboration between ITB and Kyoto Sangyou University (KSU) in 2015, is a compact, fast-response instrument with a wavelength range of $\lambda\lambda$ 3500–8000 Å and Fe–Ne–Ar hollow cathode lamps for comparison spectra. On-chip binning of 1 × 2 was set throughout the observations. Additionally, we retrieved two spectra (WR78 and WR79a) from the GAO-ITB RTS NEO-R1000 database, observed in June 2019, to represent WN7 and WN9 subclasses. All targets are listed in Table 1 .

The raw spectra were reduced using CCDRED to produce clean two-dimensional spectrograms, then TWODSPEC to extract one-dimensional (1D) spectra and ONEDSPEC to produce wavelength- and flux-calibrated spectra. All packages were provided in IRAF. The atmospheric transmittance and instrument response function were calibrated using spectrophotometric standard stars and the mean extinction curve of Bosscha Observatory (Malasan & Raharto 1993; Malasan et al. 2020). For wavelength calibration, Fe–Ne–Ar spectra were obtained immediately before and after each target and standard star observation. All spectrophotometric standard stars used for calibration are listed in Table 1.

For the UV region, we utilized spectra from the Mikulski Archive for Space Telescopes (MAST) from the International Ultraviolet Explorer (IUE). We retrieved clean, calibrated low-dispersion ($\Delta\lambda$ 6 Å) and high-dispersion ($\Delta\lambda$ 0.2 Å) spectra from the short-wavelength (SWP camera, λ$ $1150–2000 Å) and long-wavelength (LWP camera, λ$ $1850–3250 Å) spectrographs (Boggess et al. 1978), listed in Table 2 .

3. Stellar Atmosphere Modeling

To determine mass-loss rates, we performed spectrum modeling by reproducing the observed spectra using the PoWR code for expanding envelopes. The radiation transfer equation for non-LTE environments is solved assuming a spherically symmetric, stationary outflow that describes the velocity field (Gräfener et al. 2002). Key parameters in this modeling are the transformation radius (R), asymptotic terminal velocity (V∞), mass-loss rate (M), luminosity (L), chemical composition, clumping factor (D), stellar radius (R*), and stellar temperature (T)*.

In this atmospheric model, the inner boundary is located at radial optical depth

$\tau = 20$, corresponding to the WR “stellar” radius R. *The “stellar” temperature is then defined. The transformed radius, given by Equation (1), depends only on V∞, M, and R.* Various combinations of these parameters produce very similar emission lines as long as R and T* remain the same (Gräfener et al. 2002; Hamann & Gräfener 2003; Sander et al. 2015).

3.1. Fitting of the Normalized Optical Spectra

The PoWR model is provided through a web interface with 2D WR spectrum grids for WN (Todt et al. 2015) and WC stars (Sander et al. 2012). These grids depend only on R and T* for the WC grid, and on R , T*, and hydrogen mass fraction for the WN grids. All other parameters are held constant (see Table 3).

The process of determining a suitable grid model begins by normalizing the flux of the dereddened NEO-R1000 spectrum using extinction data from van der Hucht (2001). We then measured equivalent widths (Wλ) of strong optical emission lines using the SPLOT task in IRAF, including Hα/He II 6-4, Hβ/He II 8-4, He I $ $5876, He II $ $5412, C IV $ $5805, or O V $ $5590 for WN stars, and the “diagnostic line pair” He II $ $5412 and C IV $ $5470, C III $ $5696 and C IV $ $5808 for WC stars.

The web interface provides contour maps of constant equivalent widths for each emission line. Using these contours, the appropriate region in the (log R , log T*) coordinate space can be determined. For WN stars, several grid options exist depending on subclass (WNE or WNL) or hydrogen mass fraction (H20 or H50). In our analysis, we combined H20 and H50 models in the same region to fit our spectra. The best model was chosen by selecting several models around that region and identifying the one with the smallest ^{2} or highest R^2. The best model corresponds to specific values of R and T* (listed in Table 4). All spectral fits of the normalized spectra are provided in Appendix A.

3.2. Spectral Energy Distribution Analysis

We performed SED fitting using low-resolution NEO-R1000 and IUE spectral data (listed in Table 2) to determine L* and E(B-V). Each model has absolute flux F_{mod} in erg cm^{-2} s^{-1} Å^{-1}, assuming constant luminosity throughout the model. The model flux is then corrected for distance and reddening dilution using:

$$F_{\text{obs}} = \frac{1}{4\pi d^2} \times 10^{-0.4A_\lambda} \times F_{\text{mod}}$$

We used the G16 extinction model (Gordon et al. 2016) provided by Astropy (Astropy Collaboration et al. 2013, 2018), assuming a Galactic reddening constant R_V = 3.1 and f_A = 1, corresponding to a pure Milky Way extinction law. WR distances listed in Table 6 were taken from Gaia Data Release 3 (DR3) parallax distances (Crowther et al. 2023).

Using Equation (2), SED fitting was performed with Markov Chain Monte Carlo (MCMC) techniques using the emcee package in Python (Foreman-Mackey et al. 2013). We ran the MCMC with 50 walkers for 9000 steps, discarding the first 2000 steps as a conservative burn-in period. The priors used are summarized in Table 5 .

To compare observed flux with corrected model flux, we assumed a Gaussian log-likelihood:

$$\ln \mathcal{L} = -\frac{1}{2}\sum_{i}\left[\frac{(F_{\mathrm{obs,i}} - F_{\mathrm{mod,i}})^2}{\sigma_i^2} + \ln(2\pi\sigma_i^2)\right]$$

where the uncertainty of observed flux F_{obs} is underestimated by some fractional amount f:

$$\sigma_i = f \times F_{\mathrm{obs,i}}$$

Luminosity and reddening were determined from the median of the posterior distribution with 1σ uncertainties. Corner plots and 1D posterior distributions are shown in Appendix A. All results are listed in Table 6.

4. Asymptotic Terminal Velocity (V∞) and Mass-loss Rate (M)

WR stars exhibit distinctive P-Cygni saturated line profiles characterized by flat-bottomed absorption. These lines form at the base of the expanding envelope at speeds close to terminal velocity (V∞) (Crowther 2007). In the UV region, several resonance lines of C IV, C III, and He II form P-Cygni saturated profiles that can be used to estimate terminal velocity. Theoretically, the P-Cygni profile has a "blue" wing that is a vertical edge rising from zero to the continuum, but in reality this part has some slope (Hillier 2020). Two parameters are associated with P-Cygni profiles: V_{edge} (the wing tip position) and V_{black} (the blue end of the flat-bottomed absorption). V∞ is estimated from V_{black} (Hillier 2020) because the non-black absorption correlates with large random microturbulent motions produced by forward-propagating shocks (Prinja et al. 1990, 1991; Niedzielski & Skorzynski 2002).

We utilized high-resolution IUE spectra to calculate V_{black} for several highly ionized C, N, He, and Si lines that form P-Cygni profiles with nearly flat-bottomed absorption. V_{black} is determined by finding the wavelength with the lowest flux before rising monotonically toward the blue wing tip.

The zero reference velocity depends on the P-Cygni emission line profile shape. If the emission profile can be approximated by a Gaussian, the zero reference velocity is determined from the peak wavelength (λ{em}). *For wide, flat-topped emission profiles, it is determined from the absorption line near the emission peak (*λ{abs}). The spectrum is assumed to be in the heliocentric reference frame (González-Riestra et al. 2000) but not corrected for stellar radial velocity.

Therefore, line shifts make it difficult to determine the exact zero reference position.

We measured V_{black} uncertainty using:

$$\sigma_{V_{\text{black}}} = \frac{c \times \Delta\lambda}{\lambda_0}$$

where $\Delta\lambda$ is the high-dispersion average spectral resolution of 0.2 Å. Our analysis uncertainty is approximately 18–20 km s^{-1} per line (detailed results in Appendix B). Finally, V∞ was determined through a weighted average of V_{black} from each line, with results given in Table 6.

Before determining mass-loss rates, the stellar radius R* must be calculated using the Stefan-Boltzmann law. Defining the solar temperature as T_ = 5772 K (Prša et al. 2016), the stellar radius of WR stars is:

$$R_* = \sqrt{\frac{L_*}{4\pi\sigma T_*^4}}$$

With all necessary parameters determined, we calculated the mass-loss rate using Equation (1) with clumping factor D = 4 for WN stars and D = 10 for WC stars (Table 3). We employed the posterior distribution from SED analysis to determine R*, M, and 1σ uncertainties. We also estimated WR mass and momentum transfer efficiency (discussed in the next section) using Equations (7) and (8). All results are tabulated in Table 6.

5. Discussions

For most WN stars, our derived stellar temperatures agree well with previous calculations by Hamann et al. (2019), except for WR16. However, we found it difficult to fit WC spectra with models, resulting in most deviating from literature values (Sander et al. 2019) by up to 20%. One possible reason is that variations in helium, carbon, oxygen, and nitrogen abundances differ from PoWR grid model assumptions, yielding no adequate match to our observed spectra. This discrepancy is expected as He abundance in WC stars declines while the inner shell undergoes He nuclear burning, influencing abundance ratios as the star approaches the WO phase.

Our SED analysis shows good fits in the UV, optical, and near-infrared regions, except for WR24 (discussed below). Optical UBV and near-IR 2MASS JHK photometric points are slightly brighter than model fluxes. Since many strong emission lines fall within these broadband filters, the differences remain within reasonable limits. For objects with weaker emissions, better fits are obtained. Our luminosities agree well with previous literature; discrepancies likely arise from differences in models and UV spectra.

The reddening constants generally agree with literature values within 2σ, except for WR111, which is much smaller than literature values due to numerous emission lines around $ 2200*thatblurthetruecontinuum*, *impactinganalysisaccuracy*.*Ouranalysisusesparallaxdist* from P-Cygni profiles, which rely on Gaussian fitting and "eye" measurements, reducing accuracy. For mass-loss rates, the maximum difference is 14% for WR24 and smaller for others, despite many parameter uncertainties.

We discuss interesting objects and provide comments based on our analysis below.

WR6, widely known as EZ CMa, is a variable WR star studied extensively. It shows prominent variability in light curves, spectra, or polarization (Hamann et al. 2006) due to intrinsic properties rather than a binary companion. Recent polarization studies show that corotating regions and wind flattening may produce changing large-scale patterns in the stellar wind, leading to linear polarization variability with a rotational period of 3.7 days (de la Chevrotière et al. 2013).

WR14 has confirmed photometric variability from recent TESS data (Lenoir-Craig et al. 2022). Previous literature discussed a possible compact companion (Bromage et al. 1982; Shylaja 1990). When fitting the normalized optical spectrum, no model could fit all emission lines simultaneously. Some models had lines too strong or too weak compared to observations. We chose the best-fit model despite the C III $ $5696 Å line not fitting at all (see Figure A2), contributing to discrepancies with literature values (Sander et al. 2019).

WR16, like WR14, shows confirmed variability in TESS data (Lenoir-Craig et al. 2022), possibly causing the T* and R parameters we obtained to differ from literature (Hamann et al. 2019). WR16 is surrounded by a bubble nebula expected to show X-ray emission from shock-heated plasma as strong WR winds interact with remnant material from a red supergiant or luminous blue variable phase (Garcia-Segura & Mac Low 1995). However, Toalá & Guerrero (2013) found no hot plasma detection with XMM-Newton data, and no further studies explain the TESS variability.

WR24 is one of three WR stars in the Carina Nebula star-forming region (NGC 3372). When fitting the SED with all data (IUE spectra and 2MASS flux), we obtained much larger extinction values than Hamann et al. (2019). The $ $2200 Å bump, an important interstellar extinction feature, did not fit well with the model spectrum. Therefore, we fitted the SED using only the continuum region around $ $2200 Å, yielding reddening values consistent with literature (Hamann et al. 2019). We found clear evidence of infrared excess, strongly indicating a circumstellar disk around WR24. While no previous literature clearly mentions this, dust formation around mass-losing stars is expected. Dust is observed in luminous blue variables (LBVs) with nebulae, likely originating from large envelope eruptions or outer material swept up by strong winds (Crowther 2007). Recent research mentions possible hot plasma detection with XMM-Newton X-ray data but no companion indication (Sasaki et al. 2024).

WR90 is a WC7 star showing stochastic variability in TESS photometry

(Lenoir-Craig et al. 2022). Studies have detected unusual $ $2200 Å absorption caused by a surrounding nebula (Willis & Wilson 1977) and mapped expanded neutral hydrogen (H I) around WR90, created by WR90 and its progenitor O-type stars (Cappa de Nicolau et al. 1988). The interaction between stellar winds and material from WR90 and the pre-existing supernova remnant RCW 114 produces unique spectral features, including Na I absorption (Welsh et al. 2003). Like WR14, no model could fit all observed emission lines. Fitting with literature models produced inadequate results, while our "best" model strongly deviated from literature values. As explained in Sander et al. (2012), WC models imperfectly match some lines, particularly C III $ $4650 and lines between $ $6500–7200 Å. We therefore used the best available model despite the deviation.

WR103 shows significant variation in its TESS light curve (Lenoir-Craig et al. 2022). Spectroscopic observations by Chené & St-Louis (2011) showed line-profile variability without a clear period. This star belongs to the WC9d class, meaning WR103 produces dust persistently, possibly from colliding winds between the WR star and an OB companion (van der Hucht 2001). Massey et al. (1984) suggested a dust shell-like structure, but no recent studies confirm a companion.

We encountered the same fitting problems with **WR111** as with WR14 and WR90. WR111 is a WC5 star exhibiting parameter degeneracy mentioned in Sander et al. (2012). This occurs when winds are very dense, and different combinations of R and T* produce nearly identical spectra, making our results poorly constrained. This may explain differences between our results and literature values.

At this point, we have derived six WR star parameters: temperature, reddening constant, luminosity, terminal velocity, and mass-loss rate. We compared five of these with literature values in Table 6, using both studies with the same method and those with different approaches.

Another fundamental parameter we explored is WR mass. Theoretical WR mass can be determined from the luminosity–mass relation for WR stars. Fadeyev (2008) provides a linear fit for models with initial masses 70 M ≤ M_{ZAMS} ≤ 130 M :

$$\log(M_{\mathrm{WR}}/M_{\odot}) = 1.568\log(L_{*}/L_{\odot}) - 4.19$$

We calculated theoretical masses for our sample using Equation (7) (Table 6) and compared them with masses from Hamann et al. (2019) for WN stars and Sander et al. (2019) for WC stars, which used the Langer (1989) relation for pure helium WNE stars. Mass differences reach up to 80% due to different models and our oversimplified relation. The luminosity–mass relation depends primarily on mass-loss rate and helium fraction (Fadeyev 2008).

We also derived momentum transfer efficiency , defined as:

$$\eta = \frac{\dot{M} V_\infty c}{L_*}$$

This wind momentum to photon momentum ratio indicates how efficiently photons transfer momentum to the wind (Springmann 1994). = 1 represents the "single scattering limit" where each photon transfers momentum once. Most WR stars have > 1, so their winds cannot be explained by single scattering alone. Nugis & Lamers (2000) showed is weakly luminosity-dependent but primarily composition-dependent, with higher helium abundance yielding higher .

WR mass-loss rates are expected to correlate strongly with luminosity since winds are radiation-driven. We plotted our results in the M–L diagram (Figure 1 [Figure 1: see original paper]) and compared them with empirical laws from previous literature. Our results generally follow the correlation from Hamann et al. (2019) for WN stars with hydrogen (WNh) and hydrogen-free WN stars, and Sander et al. (2019) for WC stars. However, WR78 and WR24 have much lower mass-loss rates than expected. We could not compare WR79a with Hamann et al. (2019) as it was not in their sample, but other objects showed good agreement.

In the Hertzsprung–Russell diagram (HRD), high temperature and luminosity indicate a connection to late evolutionary stages of O stars. Conti (1975) first proposed a scenario where evolved massive O stars lose most of their hydrogen shells through stellar winds, revealing H-burning products followed by He-burning products—the "Conti Scenario." Meynet et al. (1994) showed progenitor O stars had minimum masses of 65–110 M . Current belief places the initial mass cutoff for WR progenitors around 25 M (Crowther 2007) or even as low as 18 M , challenging our understanding of nucleosynthesis in massive stars (Sander et al. 2019). The evolution scheme for progenitors >80 M (Sander et al. 2012) states they will not pass through the WC stage, instead going directly from LBV to WNL to SN IIn. This is confirmed by SN2015bh observations showing LBV progenitors (Boian & Groh 2018) and SN2014C progenitors transitioning from type Ib to IIn, indicating hydrogen-rich outer shells from LBV ejecta (Margutti et al. 2017; Brethauer et al. 2022). Lower-mass O progenitors evolve through WC and WO phases until core collapse, making WO stars excellent type Ic supernova progenitors due to their hydrogen and helium depletion (Sander et al. 2019).

Figure 2 [Figure 2: see original paper] shows our program stars on the HRD, with clear grouping between WC and WN. WN stars containing hydrogen in their outer envelopes (WNh) appear to the right of the zero-age main sequence (ZAMS) compared to hydrogen-free WN stars (e.g., WR6), indicating hydrogen-free WN stars have higher surface temperatures because deeper, hotter helium-rich layers are exposed. This strengthens the WR evolution scheme where hydrogen-free WR stars represent the stage after WNh before entering the WC phase.

WC stars result from further evolution of hydrogen-free WN stars that have lost their helium outer shells, exposing helium-burning products (Hamann et al. 2019). WC stars tend to have lower luminosities due to increasing mass erosion. The figure also shows evolution tracks for various initial masses from Ekström et al. (2012) with and without initial rotation. Single-star models with rotation reach the WR region at smaller initial masses than non-rotating models, highlighting rotation's importance in WR progenitor evolution. However, even these models have a minimum observed luminosity limit that does not explain low-luminosity WC stars, indicating these objects require much greater mass-loss rates in previous evolutionary stages (Georgy et al. 2012; Sander et al. 2019).

6. Conclusions

We obtained low-resolution optical spectra of 10 Galactic WR stars using the NEO-R1000 spectrograph at Bosscha Observatory. Additional archival low- and high-resolution UV spectra were used for stellar atmosphere modeling with the PoWR model grid. We derived fundamental parameters including stellar temperature, reddening constant, luminosity, terminal wind velocity, stellar radius, and mass-loss rate through model fitting and SED analysis.

Our results generally do not perfectly match literature values but remain within 20% maximum error for some parameters. This is quite good considering model selection limitations. This method effectively tests the NEO-R1000 spectrograph, which for many years has been an important instrument at Bosscha Observatory for studying emission-line objects, particularly novae. Future work should consider direct modeling without grid spectra to obtain more accurate parameters.

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Appendix A: Best Model Fitting Result

[Figures A1–A10 would appear here with captions describing the NEO-R1000 optical spectral fitting, SED fitting, and posterior distributions for each WR star.]

Appendix B: P-Cygni Profile Analysis Results

[Table B1 would appear here with velocity measurements of strong ultraviolet P-Cygni line profiles for each WR star.]

Note: Figure translations are in progress. See original paper for figures.

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