Spectroscopic Observation of Wolf-Rayet Stars: Study of Expansion Velocity and Mass Loss as Contributors of Interstellar Matter Enrichment

Azlizan Adhyaqsa\textsuperscript{1}, Hakim I Malasan\textsuperscript{2,3}, Aprilia\textsuperscript{2}, Lucky Puspitarini\textsuperscript{2}

\textsuperscript{1}Undergraduate Program in Astronomy, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jl. Ganesha 10 Bandung 40132, Indonesia
\textsuperscript{2}Astronomy Research Division, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jl. Ganesha 10 Bandung 40132, Indonesia
\textsuperscript{3}ITERA Astronomical Observatory, Jl. Terusan Ryacudu Lampung 35365, Indonesia

Abstract. Wolf-Rayet (WR) stars exhibit broad emission lines in their spectra. Based on the featured lines, they are classified into three types: nitrogen-rich WN, carbon-rich WC, and oxygen-rich WO. Broad emission lines indicate high expansion velocity and also previous studies showed that WR stars possessed higher mass-loss rates compared with another type of stars. Thus, it is suggested that the expansion velocity and the mass loss of WR stars play a role in the enrichment of interstellar matter. Our observations were conducted between July 2018 and June 2019 using NEO-R1000 (R~1000) spectrograph with spectral range 4500-7000Å at the Bosscha Observatory and consisted of WN and WC type stars. Data reduction and expansion velocities determination were carried out using IRAF with \textit{longslit-transform} routine and Gaussian fitting respectively. To obtain mass-loss rates, we compared our observed spectra with models provided by Potsdam Wolf-Rayet Models (PoWR). In several cases, the contribution of WR stars can be directly observed as Wolf-Rayet nebulae, whose structures are influenced by the high expansion velocity of the nearby WR stars. Assuming that the total of WR stars in the Milky Way is \(\sim 2600\), we estimated that the population release \(\sim 0.507 \, M_\odot\) of material annually into Galactic environment.

1.Introduction

Broad emission lines of WR stars are caused by the high velocity expansion of their atmosphere. Since the stellar winds also have dense properties, it can be explained that WR stars also possess high mass-loss rates [1]. Based on the observed emission lines, WR stars are classified into WN, WC, and WO types. WN stars are dominated by ionized nitrogen, WC stars feature emission of ionized carbon and oxygen, and if O\textsubscript{VI} emission lines can be observed, they belong to the WO type [2]. For each type of WR stars, there are also subtypes based on the strength of the related emission lines.

With their interesting expansion velocity and mass-loss properties, WR stars are expected to influence the enrichment of interstellar matter. Although there are roughly 600 WR stars in the Galactic WR catalog, recent studies showed that there are possibly more WR stars near the Galactic center but the interstellar extinction prevent us to observe them. The statistical study estimated that the population of Galactic WR stars can reach up to \(\sim 2600\) stars [3]. Thus, the influence of WR stars for the interstellar matter can be better estimated than before.
We will employ all observed emission lines within the optical spectra of WR stars. Since they are sufficiently broad, observations using a low-resolution spectrograph are adequate to perform an early study for this matter. From our observations, we aim to determine the expansion velocities and mass-loss rates. Then, we would use our samples of WR stars to analyze the implication of those properties to their environment and estimate the mass contribution of WR stars population to the Galactic medium.

2. Observations and Data Reduction
Our spectroscopic observations were conducted in the optical regime between July 2018 and June 2019 at the Bosscha Observatory, Lembang, Indonesia. We employed NEO-R1000 spectrograph (R~1000) attached on Celestron C-11 28-cm Schmidt-Cassegrain telescope (f/10) with SBIG ST-8XME CCD. The NEO-R1000 is a fast and efficient compact spectrograph for emission line objects [4]. We observed 11 WR stars consist of 7 WN stars and 4 WC stars (see table 1), which are located in both southern and northern parts of the sky. Then, we conducted spectral reduction, wavelength, and flux calibration using longslit.transform routine within Image Reduction and Analysis Facility (IRAF) in the usual manner [5]. We used multiplet table by Moore [6] to identify the emission line wavelengths on the WR spectra.

| Star in WR Catalogue | Subtype and Binary Status |
|----------------------|---------------------------|
| WR78                 | WN5o+O9I                  |
| WR79a                | WN9ha                     |
| WR133                | WN5o+O9I                  |
| WR134                | WN6b                      |
| WR136                | WN6b(h)                   |
| WR138                | WN5o+B                    |
| WR139                | WN5o+O6III-V              |
| WR79                 | WC7+O5-8                  |
| WR90                 | WC7                       |
| WR135                | WC8                       |
| WR137                | WC7pd+O9                  |

Although some of our observed stars belong to a binary system, we treated all of our stars as single stars in our analysis. This assumption can be made because we only employed the broad emission lines in the spectra, which belong to the WR counterpart of the binary system.

3. Expansion Velocity and Mass Loss Rate
In our spectra, the P-Cygni profiles of the emission lines are not observable because of our spectral resolution. Assuming that the expansion occurs isotropically, the expansion velocity can be estimated by measuring the width of the broad lines [7]. Hence, the velocity can be determined by measuring full width half maximum (FWHM) of the Gaussian fitted emission lines with equation (1).
\[ v = \frac{FWHM}{\lambda_0} c \]  

(1)

As in the equation, \( \lambda_0 \) is the reference line wavelength, which can be acquired from the multiplet table, and \( c \) is the speed of light. Then, after the measurement of several line velocities, we averaged them to obtain the expansion velocity. For WN stars, we employed 9 spectral lines: N v \( \lambda 4620 \), N iii \( \lambda 4640 \), He ii \( \lambda 4686 \), He ii \( \lambda 4861 \), N v \( \lambda 4933 \), C iv \( \lambda 5812 \), He i \( \lambda 5876 \), and He ii \( \lambda 6560 \). For WC stars, we employed 11 spectral lines: He ii \( \lambda 4686 \), C iv \( \lambda 4789 \), He ii \( \lambda 4861 \), He ii \( \lambda 5412 \), C iv \( \lambda 5470 \), O v \( \lambda 5590 \), C iii \( \lambda 5696 \), C iv \( \lambda 5812 \), He i \( \lambda 5876 \), and He ii \( \lambda 6560 \).

Afterward, we modeled our spectra using WR model atmospheres provided by Potsdam Wolf-Rayet Models (PoWR) [8]. We measured the equivalent width of the PoWR spectral reference lines to determine the most suitable model for our observed spectra. Our modeling examples can be seen in figure 1 and figure 2.

**Figure 1.** The spectrum of WR134 compared with WNE 11-18 model from PoWR. Strong helium and few nitrogen lines are typical for every WN stars but may have different line strengths for each case.

**Figure 2.** The spectrum of WR135 compared with WC 09-14 model from PoWR. Instead of nitrogen lines, WC star spectrum ordinarlly shows strong carbon lines with oxygen line started to appear.
From the figures, the atmospheric models provided by PoWR model grids can represent the observed spectra in overall. In our case, minor discrepancies are acceptable since the spectra are in low-resolution and they will not significantly change the results. However, for high-resolution studies, individual case-by-case adjustments for the utilized model atmospheres are necessary to have better fitting precision between the model and the data. After that, in order to determine the mass-loss rates of our observed WR stars, we employed the equation (2).

\[
R_t = R_\star \left[ \frac{v_\infty}{2500 \text{ km s}^{-1}} \sqrt{\frac{M}{10^{-5} M_\odot \text{ yr}^{-1}}} \right]^{2/3}
\]

Each model of PoWR would provide the value of several properties such as transformed radius \(R_t\), stellar radius \(R_\star\), terminal velocity \(v_\infty\), mass-loss rates \(\dot{M}\), clumping factor of the WR atmosphere \(D\), and luminosity of \(L = 5.3 L_\odot\). Detailed explanation and derivation of the equation (2) are described by Schmutz et al. [9]. To determine the observed mass-loss rates of the WR stars, model parameters of stellar radius and terminal velocity were replaced with observational values. The corrected stellar radii were derived from the observed luminosity, which was obtained by Nugis and Lamers [10]. For the terminal velocity, we employed the measured values from our own observations. Our measurements of expansion velocities and mass-loss rates are provided in table 2, which are sorted according to their subtypes.

**Table 2. Expansion velocity and mass-loss rates of the observed WR Stars**

| Star in WR Catalogue | WR Subtype | Expansion Velocity (km/s) | Mass Loss Rates \((\times 10^{-5} M_\odot \text{ year})\) |
|----------------------|------------|---------------------------|--------------------------------------------------|
| WR78                | WN5o       | 1469.44 ± 368.98          | 3.38 ± 0.48                                      |
| WR133               | WN5o       | 1792.82 ± 204.69          | 0.19 ± 0.02                                      |
| WR138               | WN5o       | 1751.90 ± 336.27          | 1.27 ± 0.15                                      |
| WR139               | WN5o       | 1956.97 ± 715.33          | 0.60 ± 0.33                                      |
| WR134               | WN6b       | 2640.61 ± 208.78          | 8.28 ± 0.55                                      |
| WR136               | WN6b(h)    | 2074.64 ± 254.09          | 17.03 ± 0.94                                     |
| WR79a               | WN9ha      | 1254.43 ± 547.61          | 1.15 ± 0.50                                      |
| WR79                | WC7        | 2515.30 ± 500.25          | 2.08 ± 0.29                                      |
| WR90                | WC7        | 2355.51 ± 477.21          | 1.95 ± 0.40                                      |
| WR137               | WC7        | 1986.14 ± 296.98          | 2.09 ± 0.17                                      |
| WR135               | WC8        | 1730.04 ± 208.82          | 1.49 ± 0.17                                      |

Error propagation method was employed to derive the uncertainties of our measurements. For WN stars, the expansion velocity of our WN9 sample has the least value. The value confirmed that WNL stars exhibit smaller expansion velocity than the WNE stars [2]. Within the WNE subtypes, it can be seen that overall, WN6 group has faster expansion velocity compared to the WN5. For the obtained WC stars, the expansion velocity of the WC8 star is slower than the WC7 stars.

The mass loss rates of the observed WN stars have a steep range from 0.19 \(M_\odot\)/year to 17.03 \(M_\odot\)/year. For the WC stars, our measured mass loss rates show similar values. Interestingly, two of our
stars, which have the highest mass loss rates, namely WR134 and WR136, are known to be surrounded by nebulous structures. Furthermore, we are going to utilize the median value of our mass loss rates samples to estimate mass contribution of Galactic WR population.

4. Discussion

4.1. Local Environment of WR134 and WR136
Nebula surrounding WR134, WR135, and WR137 is showed in figure 3 and categorized as diffuse nebula. Therefore, it is rarely being studied and it is complicated to determine its composition accurately. Although further observations still have to be done, a study by Kwitter [11] indicated that it is nitrogen- and helium-enriched. Hence, the WR star responsible for the enrichment is WR134, which belong to the WN type. Infrared study of the nebula conducted by Pineault and Terebey [12] showed that WR134 is interacting with its surrounding medium and responsible for the formation of the bow shock, neither WR135 nor WR137. If we consider the expansion velocities, then WR134 has the fastest with 2640.61 km/s, compared to WR135 and WR137 with 1730.04 km/s and 1986.14 km/s respectively.

![Figure 3. Nebulosity surrounding WR134, WR135, and WR137 in false colour. Bow shock structure is clearly visible and presumed to be caused by high velocity winds of WR134. Image: Don Goldman from apod.nasa.gov](image)

In the other hand, NGC6888 surrounding WR136, which is showed in figure 4, is a well-studied nebula. Compositional analysis showed that NGC6888 is highly enriched in nitrogen compared to the Orion nebula [13]. Hence, it is indicated that the nebula was influence by the nearby WN star, WR136. Observation of NGC6888 with the Hubble Space Telescope also showed that the winds of the star
played a major role in the structure formation. High expansion velocity of WR136 swept the material produced by previous evolutionary stages of the massive star. The process made the outer layer became a lot denser and thus made it observable [14].

![Figure 4](image-url)  

**Figure 4.** False colour image of the nebula surrounding WR136, namely NGC6888. High velocity winds and mass loss of WR 136 influence the structure formation and composition of the nebula respectively.  
Image: Michael Miller and Jimmy Walker from apod.nasa.gov

Currently, the mass of the nebula around WR134 and NGC6888 are ~2500 M\(_\odot\) and ~1200 M\(_\odot\) respectively [15]. Since both WR134 and WR136 exhibit high mass loss rates, it is indicated that they also contributed mass to the nebulae. If it is assumed that the lifetime of WR stars is at least in the order of 10^5 years [16], then their contribution can be estimated. With our measured mass loss rates, we calculated that within their lifetime, each WR134 and WR136 would release at least ~8.28 M\(_\odot\) and ~17.03 M\(_\odot\) to their corresponding nebulae.

4.2. WR Stars Mass Contribution for the Milky Way
In order to derive the mass contribution of the WR stars in the Galaxy, we employed the median value of our measured mass loss rates, which is 1.95 \(\times\)10^\(\text{\text{-5}}\) M\(_\odot\)/year. Infrared survey done by Kanarek estimated that there can be up to ~2600 WR stars in the Milky Way [3]. Therefore, we can estimate that the Galactic environment receive ~0.507 M\(_\odot\) annually from the WR population.

In comparison, we compare the case with the occurrence of supernova in our Galaxy. Tammann et al. [17] estimated that a star explodes into a supernova every 40 ± 10 year. Within the same period of time, the WR star population would release 20.28 ± 5.07 M\(_\odot\). Fascinatingly, only 10% of the supernovae caused by stars with mass more than 20 M\(_\odot\) [18]. Therefore, the contribution of Galactic WR population for the enrichment of interstellar matter is similar to the amount of mass released by a massive core-collapsed supernova.
5. Summary
The Galactic WR stars population is shown to have a great role in interstellar matter enrichment. In some cases, the enrichment process can be directly observed as nebulae surrounding a WR star, for instance WR134 and WR136. In both cases, the WR stars not only influence the structure of the nebulae with their high-speed winds, but also contribute to their mass and chemical composition. In Galactic scale, we estimated that the population release \(~0.507 \, M_\odot\) every year. Within the same period of time with the occurrence of Galactic supernova, they would have similar mass contribution as a single massive star supernova. Since this work was carried out in the optical regime only, further multi-wavelength study with also higher resolution is required to provide wider perspective on WR stars contribution to the Galactic ISM.

Acknowledgments
We are grateful to the staff of Bosscha Observatory for the time and assistance in the use of NEO-R1000 spectrograph. This research is carried out under P3MI 2019 and we thank them for their research grant.

References
[1] Niedzielski A and Skorzynski W 2002 Acta Astronomica 52 81-104
[2] van der Hucht K A 2001 New Astronomy Reviews 45(3) 135-232
[3] Kanarek G C 2017 Diss. Columbia University, Dissertation Abstract International 78-05(E) 159
[4] Malasan et al. 2016 Indonesian Journal of Physics 27(1) 1-8
[5] Valdes F 1992 A.S.P Conference Series 25 417
[6] Moore C E 1945 Contributions from the Princeton University Observatory 20 1-110
[7] Kirshner et al. 1987 The Astrophysical Journal 315 135-139
[8] Hamann W R and Gräfener G 2004 Astronomy and Astrophysics 427(2) 697-704
[9] Schmutz W et al. 1989 Astronomy and Astrophysics 210 236-248
[10] Nugis T and Lamers H 2000 Astronomy and Astrophysics 360 227-244
[11] Kwitter K 1984 The Astrophysical Journal 287 840-844
[12] Pineault S and Terebey S 1997 The Astrophysical Journal 113 433-438
[13] Kwitter K 1981 The Astrophysical Journal 245 154-162
[14] Moore D B et al. 2000 The Astronomical Journal 119(6) 2991
[15] Cappa C E et al. 2003 Symposium-International Astronomical Union 212 596-603
[16] Meynet G and Maeder A 2005 Astronomy and Astrophysics 429 581
[17] Tammann et al. 1994 The Astrophysical Journal Supplement Series 92 487-493
[18] Sukhbold et al. 2016 The Astrophysical Journal 821(1) 38.
[19] Sander A et al. 2012 Astronomy and Astrophysics 540 A144