A Study of Wolf-Rayet Stars Formed VIA Chemically Homogeneous Evolution

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Abstract

Using the stellar evolution code—Modules for Experiments in Stellar Astrophysics (MESA)—we investigate the evolution of massive stars with different rotational velocities and metallicities towards Wolf-Rayet stars. In our simulations, the initial rotating velocities are taken as 0, 250, 500, and 650 km s\(^{-1}\), and the metallicities equal to 0.02, 0.014, 0.008, 0.006, 0.004, and 0.002. We show our rapid rotation models in the HR diagram compared with the observations. We find that the rotational mixing is less efficient at high metallicity, and these stars become Wolf-Rayet (WR) stars when the helium in their center is ignited. However, rapid rotating massive stars at low metallicity can easily evolve into WR stars due to the rotation resulted in chemically homogeneous evolution. This can explain the origin of single WR stars in galaxy at low metallicity. In our models, the observed SMC WR stars are consistent with the single-star evolution models. However, at higher metallicities our single-star evolution models can only explain the luminous, hydrogen-rich WN stars and O stars (which are classified as WR stars previously).

Key words: stars: evolution – stars: rotation – stars: Wolf-Rayet

Online material: color figures

1. Introduction

Wolf-Rayet (WR) stars are, typically, helium-burning stars who have lost a substantial part of their hydrogen envelope via stellar wind or mass transfer through Roche lobe overflow in close binary systems, and they are fusing helium or heavier elements in the core (Chiosi & Maeder 1986; Maeder & Conti 1994). Usually, they are hot (log(T\(_{\text{eff}}\)/K) \(>\) 4) and luminous stars (log(L/L\(_{\odot}\)) \(>\) 5.0). Spectroscopically, distinguished from normal stars, WR stars are objects with strong, broad emission lines (Beals 1940), in which the broadening of lines is caused by the large expansion velocity in the expanding stellar wind and their emission characteristic is mainly because of the powerful deviations from local thermodynamical equilibrium (Todt et al. 2015). Based on the relative intensity of the spectrum, WR stars can be cursorily classified into three subtypes: WN, WC and WO, depending on whether the spectrum was dominated by lines of nitrogen, carbon or oxygen, respectively. WR stars with both WN and WC characteristic are classified as WN/WO stars. There are about 642 WR stars in our Galaxy, including 357 WN stars, 273 WC stars, eight WN/WC stars and four WO stars (Crowther 2015).

As one of the closest galaxies to Galaxy, the Large Magellanic Cloud (LMC) allows a detailed spectroscopy of its brighter stars (Hainich et al. 2014). The forth catalogue of population I WR stars provides about 134 WR stars in LMC (Breysacher et al. 1999), and recently 13 more WR stars in the LMC were discovered by Massey et al. (2015). There are 12 WR stars currently known in the Small Magellanic Cloud (SMC) (Massey et al. 2014), and 5 out of the 12 stars are in confirmed binary or multiple systems based on their RV curves (FMG) (Shenar et al. 2016).

WR stars are very important objects. They are dominant sources of energy and nuclear synthesis products such as helium (He), carbon (C), oxygen (O), and other \(\alpha\) elements to their surroundings thanks to their strong stellar winds (Eldridge & Vink 2006). They are also the progenitors of type Ib/c supernovae (SNe) due to their lack of H and long gamma-ray bursts (LGRBs) (Galama et al. 1998; Ensmann & Woosley 1988; Hjorth et al. 2003; Woosley & Bloom 2006). And their evolution towards core collapse is critically determined by mass loss (Yoon 2017).

After years of observational and theoretical efforts, basic concepts about massive stars have been established and provide a good guide to their observed properties from the aspects of single star and binary system. One of the most known picture of stellar evolution is “Conti scenario” (Conti 1975). He first proposed that a massive O stars may lose a significant amount of mass of envelope through stellar wind and reveal the core H-burning or later He-burning products (if there is sufficient...
additional mass loss) at its surface, this evolutionary stages are spectroscopically identified with WN and WC types (Crowther 2007). Nowadays, it is argued that this process is occasionally aided by Roche lobe overflow in close binaries and/or episodic mass loss during the LBV stage (Smith & Owocki 2006; Massey et al. 2015).

However, the true evolution conditions of WR stars are still not completely understood owing to some indeterminate issues, such as the interior mixing processes and stellar mass-loss processes which perplex the massive stellar evolutionary models all the time (Chiosi & Maeder 1986; Hamann et al. 2006a). The strong mass-loss rate ($\dot{M}$) of the order of $10^{-5} M_\odot$ yr$^{-1}$ is an important feature of massive stars (van der Hucht 2001). It is closely related to the stellar luminosity and effective temperature with the relation that the higher the luminosity is, the more violent the mass-loss rate behavior (Jaeger et al. 1988). The prescriptions of WR mass-loss rates adopted in stellar evolutionary models before are very large (Maeder 1987; Langer 1989; Hamann et al. 1995). Although Meynet et al. (1994) obtained a good agreement with the observed WR populations for the metallicities ranging from that of the SMC to twice the solar metallicity at high mass-loss rates. The consideration of wind clumping in later empirical estimates resulted in much lower values (Hamann & Koesterke 1998; Hamann et al. 2006b; Crowther 2007; Sander et al. 2012). One of the most striking results among these many studies is the prescription that mass-loss rate should be reduced by a factor of 2 to 3 than that applied before because WR winds are optically thick and inhomogeneous (Nugis & Lamers 2000; Hamann & Koesterke 1999).

Moreover, observations and theoretical researches indicate that stellar wind strongly depends on metallicity and behave as a power law, $\dot{M} \propto Z^m$, in which $m$ is the index ranging from 1/2 to 0.94 (Garmany & Conti 1985; Pinjor 1987; Castor et al. 1975; Abbott 1982; Pauldrach et al. 1986; Vink et al. 2000, 2001). Therefore, theoretically, mass-loss rates for WR stars at low metallicities would perform much lower than those at high metallicities. As a consequence, stellar wind will be too weak to strip off their H-rich envelope to evolve into WR phase. Some works suggest that WR stars at low metallicities could be formed by the means of mass transfer through Roche Lobe Overflow in close binary systems (Bartakos et al. 2001; Maeder 1982; Vanbeveren et al. 1998).

Nevertheless, this conjecture was pushed down by the works of Foellmi et al. (2003a, 2003b) and Foellmi (2004), which indicate that even at low metallicity, such as the SMC and LMC, a large fraction of the WR stars may originate via the single-star scenario, similar to that in the Milky Way. Therefore, another process must be at work.

A practicable channel to form WR stars from single stars without invoking mass loss is supplied by the scenario of chemically homogeneous evolution (Maeder 1987; Langer 1992; Yoon & Langer 2005; Schootemeijer & Langer 2018), which means stars evolving with a nearly uniform chemical composition from the centre to the surface. Homogeneously evolution can be triggered by various mechanisms (Georgy et al. 2015): a) internal mixing inside the stars induced by convective movements of materials in the convective regions (Maeder 1980; Yusof et al. 2013); b) mixing progress in the radiative regions, such as rotational mixing (Zahn 1992; Maeder 1987). The proposal of this scenario is attribute to the less role of mass loss in producing WR at low metallicity, and the observational evidence of the large-scale structures harboured in certain WR stars also indicated that a rotating velocity may be existed (St-Louis et al. 2007; Crowther 2007).

Besides, as one of the quantitative measurements of nuclear burning times and the importance of mass loss during various stages of the stars lifetimes (Eldridge et al. 2008), the reproduce of WC/WN number ratio of WR stars is momentous but difficult owing to our uncertainty of their surface temperatures and luminosities. While the rotating models could reproduce them to some degree. Meynet & Maeder (2003) discussed the effects of rotation on WR stars at solar metallicity and found that the theoretical predictions of the number ratios of WR stars matched the observations well when the effects of rotation are accounted for. By contrast, the standard non-rotating models did not agree with these observed rates. The studies of massive single-star evolution considering both mass loss and rotation also show a well reproduction of the observed variation of type Ib/Ic SNe with respect to type II SNe fractions with metallicities (Meynet & Maeder 2005). Evolutionary models obtained from the new Geneva Population Synthesis code which take rotational mixing into account slighting the discrepancy between the synthetic and observed population than the older tracks without rotation (Hamann et al. 2006b). In addition, the works by mixing single and binary star populations got a better agreement between the observational values and their predicted values (Vanbeveren et al. 2007; Eldridge et al. 2008).

It is clear that stellar rotation plays an essential role in massive star evolution, influencing the output such as stellar lifetimes, evolutionary tracks, surface abundances, pre-supernova status and even the deaths and contributions to interstellar medium (Meynet & Maeder 2005; Maeder & Meynet 2010). High-rotational velocity of stars can be accompanied by their births or acquired through the accelerating mechanism induced by tidal forces, material accretion or merging of stars (Petrovic et al. 2005b; Petrovic et al. 2005a; de Mink et al. 2009, 2013; Tylenda et al. 2011; Dervişoğlu et al. 2010; Song et al. 2016). It is needed to provide the large number of core angular momentum required for explosion to become LGRBs as the death of the most massive stars especially at low metallicity (Martins et al. 2013). Georgy et al. (2012) suggests that about half of the observed WR stars and at least half of the Type Ib/Ic SNe may be produced through the single-star
evolution channel predicted by their rotating stellar models at 
\( Z = 0.014 \).

Recently, thanks to work by the Potsdam WR group, we now have a much better understanding of where the WR stars in the HR diagram. Their comparison of tracks to the WR stars indicated that while models could reproduce the WC/WN ratio they could not reproduce locations in the HR diagram (e.g., Sander et al. 2012). Lately Eldridge et al. (2017) have shown that with binary models they can reproduce the observed HR diagram locations as well as the WC/WN ratio at different metallicities. Also Shenar et al. (2016) have shown that the WR stars in the SMC can be reproduced by standard single-star models as well as binary models while binary models are required at higher metallicities to explain the luminosity.

Considering above, in this work, we study how rotation leads to the quasi-chemically homogeneous evolution therefore modifies the evolution of a given initial mass star towards the WR phase in single-star evolutionary scenario. And we test our rapid rotating models against the observed WR locations in the HR diagram.

In Section 2 a brief summary of the physics adopted in our models is given, in Section 3 we present the effects of rotation on stellar evolution and show the HR diagram of most known WR stars in MW, LMC, and SMC. And a synthesis of the main results is presented in Section 4.

2. Model

In this paper, we employ the open-source stellar evolution code MESA (version 8848, Paxton et al. 2011, 2013, 2015) to simulate the structure and evolution of rotating massive stars. Brott et al. (2011) had produced several grids of evolutionary models for rotating massive stars. Using similar parameters with those in Brott et al. (2011); Zhu et al. (2017) investigated the effects of the core-collapse supernova ejecta on rotating massive star. Following Brott et al. (2011) and Zhu et al. (2017), the Ledoux criterion is used for convection, mixing-length parameter \( \alpha_{\text{LMIT}} \) and an efficiency parameter \( \alpha_{\text{SEM}} \) for semi-convection are taken as 1.5 and 1.0, respectively.

The mass-loss rates we use in our code are the same with Brott et al. (2011). For stars hotter than about 25 kK with surface hydrogen mass fraction of \( X_S > 0.7 \), we use the wind recipe of Vink et al. (2001). Vink et al. (2001) gave the formulae of mass-loss rate for massive stars. If the massive star is rapidly rotating, the mass-loss rate would be enhanced, which was given by Langer (1998):

\[
\dot{M} = \left( \frac{1}{1 - \Omega / \Omega_{\text{crit}}} \right)^{\beta} M_{\text{ini}} = 0, \tag{1}
\]

where \( \Omega \) and \( \Omega_{\text{crit}} \) are the angular velocity and the critical angular velocity, respectively, and \( \beta = 0.43 \) (Langer 1998). For hydrogen-poor hot stars with \( X_S < 0.4 \), we use the WR mass-loss recipe from Hamann et al. (1995), reduced by a factor of ten. The mass-loss rate results from a linear interpolation between Vink et al. (2001) and Hamann et al. (1995) for \( 0.4 < X_S < 0.7 \). We use the highest of the values given from the prescriptions of Vink et al. (2001) and Nieuwenhuijzen & de Jager (1990) when the stars cooler than the critical temperature for the bi-stability jump (~25 kK).

When stars evolve into RSG phase (the central hydrogen is exhausted and the effective is lower than 10k K), we use the mass-loss rate given by Nieuwenhuijzen & de Jager (1990), which does not depend on metallicity. Simultaneously, rotational mixing induces various instability, such as dynamical shear instability, Solberg-Hisland instability, secular shear instability, Eddington-Sweet circulation, and the Goldreich-Schubert-Fricke instability (Spiegel & Zahn 1970; Zahn 1974, 1975; Wasiutynski 1946; Goldreich & Schubert 1967; Fricke 1968; Endal & Sofie 1978; Pinsonneault et al. 1989; Heger et al. 2000). Considering these instabilities provides an alternative procedure to restrict the class of angular velocity distributions considered which is needed for the calculation of a static model (Spiegel & Zahn 1970). Following Brott et al. (2011) and Zhu et al. (2017), the ratio of the turbulent viscosity to the diffusion coefficient \( (f) \) and the ratio of sensitivity to chemical gradients \( (f_i) \) are taken as 0.0228 and 0.1, respectively (Heger et al. 2000; Yoon et al. 2006).

Mass-loss rate and these instabilities are affected by the metallicity \( (Z) \) (Heger et al. 2000). Considering the relevant metallicities used by most studies are \( Z = 0.014 \) to 0.020 for the MW, for the LMC \( Z = 0.06 \) to 0.008 and \( Z = 0.002 \) to 0.004 for the SMC, we take the two critical values for each galaxies, respectively, that is to say, the initial abundance of hydrogen \( (X) \), helium \( (Y) \), and metal \( (Z) \) used in our models are: \( Z = 0.02 \) and 0.014 for the MW, \( Z = 0.008 \) and 0.006 for the LMC and \( Z = 0.004 \) and 0.002 for the SMC, the corresponding initial helium mass fractions \( Y \) are given by the relation \( Y = Y_F + \Delta Y / \Delta Z \cdot Z \), where \( Y_F = 0.23 \) and \( \Delta Y / \Delta Z = 2.25 \) are the the primordial helium abundance and slope of the helium-to-metal enrichment law respectively (Meynet & Maeder 2005; Maeder & Meynet 2001), \( X = 1 - Y - Z \). Meanwhile, we also calculate three groups of models by referring to the work of Brott et al. (2011): \( X = 0.7274, Y = 0.2638, Z = 0.0088, X = 0.7391, Y = 0.2562, Z = 0.0047, \) and \( X = 0.7464, Y = 0.2515, Z = 0.0021 \) to make a comparison with Brott et al. (2011)’s models for the Galaxy, LMC, and SMC and make a preliminary test of our results respectively. All other elements (including C, N, O, Mg, Si, Fe) follow the solar abundances in Asplund et al. (2005).

3. Results

Based on Meynet & Maeder (2003), whether a single star can evolve into a WR star, its rotating velocity is crucial. Therefore, we take different initial rotating velocities to investigate its effects on stellar evolution. In order to compare
with results in Brott et al. (2011), we set the specific initial surface velocities \( v_i = 0, 250, 500 \) and 650 km s\(^{-1}\) in different models, respectively.

### 3.1. Evolutionary Tracks

Figure 1 shows the evolutionary tracks in HR diagram compared with Brott et al. (2011) for initial masses of 25, 40, 50, and 60 \( M_\odot \) from left-top to right-bottom. The solid colorful lines are our models and the dotted colorful lines represent the models of Brott et al. (2011), different \( v_i \) is represented by different colors which are shown in the legend.

(A color version of this figure is available in the online journal.)

Brott et al. (2011) only calculated the evolution of the rotating massive stars on main sequence. In this work, we compute the evolution from the beginning of hydrogen burning to the end of carbon and oxygen burning and enlarge the range of the metallicity. Considering the input parameters in this paper are similar to Brott et al. (2011), we compare our evolutionary tracks with these in Brott et al. (2011). There are some differences, especially for stars at higher mass and rotating velocity. They may result from some uncertainties on simulating massive stars with high rotating velocity in the different codes (Zhu et al. 2017). For instance, the different opacity used between us and Brott et al. (2011), the lower opacity in our models contributes to the fact that they are hotter and more compact (Cantiello et al. 2009; Götberg et al. 2017).

### 3.2. Evolve to WR Stars

Most of WR stars observed are in the Galaxy and the LMC, only 12 are from SMC. They are plotted in Figures 2, 3 and 4. The observational data of WN, WC, and WO stars in the Galaxy come from Hamann et al. (1995); Hamann et al. (2006b); Liermann et al. (2010); Sander et al. (2012); Martins et al. (2008) and Tramper et al. (2015). The observational data of WC and WN stars in the LMC originate from Crowther et al. (2002); Hainich et al. (2014); Crowther & Smith (1997);
Figure 2. Positions of WRs observed in the MW and the evolutionary tracks of massive stars with different masses (from the bottom to the top the stellar masses are 25, 40, 60, 80, and 100 $M_{\odot}$, respectively). The black lines represent the pre-WR phase (defined as $X_s > 0.3$), the red lines for WN ($10^{-5} < X_s < 0.3$), while the blue lines for WC sequence ($X_s < 10^{-5}$). The dashed and solid lines represent non-rotating and rapidly rotating models, respectively. Different types of WR stars are showed with different icons given in the legend. The observational data of WN, WC, and WO stars in the Galaxy come from Hamann et al. (1995), Hamann et al. (2006b), Liermann et al. (2010), Sander et al. (2012), Martins et al. (2008), and Tramper et al. (2015), respectively.

(A color version of this figure is available in the online journal.)

Figure 3. Same as Figure 2, but for $Z = 0.008$ (left) and 0.006 (right). The observational data of WC and WN stars in the LMC originate from Crowther et al. (2002), Hainich et al. (2014), Crowther & Smith (1997), Tramper et al. (2015), and Koesterke et al. (1991). The nine WN3/O3s observed by Neugent et al. (2017) are also included.

(A color version of this figure is available in the online journal.)
Tramper et al. (2015) and Koesterke et al. (1991). The nine new type of WR stars WN3/O3 stars in the LMC observed by Neugent et al. (2017) are also included, which spectroscopically resemble a WN3 and O3V binary systems but visually too faint to be WN3+O3V binary systems. Despite some of the stars listed with a WN classification in the BAT99 catalog have been reclassified as O-types stars (e.g., Taylor et al. 2011; Niemela et al. 2001; Crowther & Walborn 2011; Evans et al. 2011), they are also collected in our sample, and we call them as O-type stars in the following sections. In the SMC, almost all known WR stars belong to the WN sequence excepting the binary system SMC AB 8 whose primary belongs to WO type, and their parameters adopted here are from Hainich et al. (2015) and Shenar et al. (2016). The hydrogen-rich and hydrogen-free WN stars are separated out with solid triangle and hollow triangle in HR diagrams, respectively.

Considering the distribution of metal abundance in galaxies is inhomogeneous, for instance, the metallicities in galactic disk are higher than that in galactic nucleus and halo, and the strongly dependence of metallicities on galactic age, for example, the young massive stars in the LMC may reach nearly solar values (Piatti & Geisler 2013; Hainich et al. 2014). We adopt the two thresholds of metallicities for each of the galaxies. Figures 2, 3, and 4 show the evolutionary tracks of non-rotating and rapidly rotating massive stars for different Zs.

Based on the works of Smith & Maeder (1991); Meynet & Maeder (2003) and Groh et al. (2013), a massive star evolves into a WR star when the hydrogen abundance \( X_\text{H} \) around its surface is less than 0.3, and it may become a late-type WR star (WC star \( X_\text{C} > X_\text{N} \), and surface abundances (by number) such as \( \frac{C+O}{He} < 1 \) or WO star \( X_\text{C} > X_\text{N} \) and \( \frac{C+O}{He} < 1 \)) when \( X_\text{H} < 10^{-5} \). According to Figure 2, WN stars with low effective temperature can originate from massive stars at high metallicity. For these massive stars, majority of their angular momentum were taken away by their severe stellar winds, which can rescue the rotation, and making it difficult to produce efficient chemical homogenous evolution. There is not significant difference between the evolutionary tracks for these massive stars evolving into WR stars without rotating velocity and with highly rotating velocity. However, rapid rotation can lead to efficient chemical homogenous evolution for the massive stars at low metallicity, for instance, the LMC and SMC models as shown in Figures 3 and 4. The evolutionary tracks of these massive stars without rotation and with rapid rotation are completely different. The massive stars at low metallicity and low rotating velocity hardly evolve into WR stars, but these with high rotating velocity rapidly become WR stars. This can explain the origin of single WR stars in the low-metallicity galaxy. Their evolutionary tracks pass through the zone covered by WN stars with high effective temperature in Figures 3 and 4. Although these tracks also cover several WC stars, even several WO stars, our results can hardly explain the origin of the WR stars located in the left-bottom zone. However, the binary models computed by Göttberg et al. (2017) indicating that much of them may evolved from rapid rotating star that are produced by spin-up during mass transfer in binary systems. In addition, we can see that some WN and WC stars are cooler than predicted by our stellar evolution

![Figure 4](image-url)
models, which has been also proposed by Eldridge et al. (2017); Hamann & Gräfener (2003) and Sander et al. (2012), this may be attributed to the inflating of the envelope caused by clumping in the outer convective zone of the star (McClelland & Eldridge 2016; Gräfener et al. 2012). Simultaneously, one should notice that there are the errors for the observations due to some factors (for example distance: the distances of the majority of WR stars are not well established.).

We find that there is a temperature offset between the hydrogen-rich WR stars and our quasi-homogeneous evolutionary models, this is because that hydrogen-rich WR stars usually show signature of hydrogen in their atmospheres which is inconsistent with chemically homogeneous evolution (Shenar et al. 2016). The nine WN3/O3s discovered by Neugent et al. (2017) known as a new class of WR stars are shown in LMC models in Figure 3 with red circle symbols. We can see that they can be mostly but not all reproduced by our rotating models, and our results is similar to that of Eldridge et al. (2017) who considered that their both single and binary models agree well with the observed luminosity, temperature and surface composition of WN3/O3s. This indicates that they may be typical WR stars but with different mass-loss rates.

Besides, as revealed in our paper and the works of Brott et al. (2011) and Koenigsberger et al. (2014), rotating stars at low metallicities are more likely to induce chemically homogeneous evolution. Koenigsberger et al. (2014) proposed that the binary system contained in multiple system HD 5980 in the SMC is the product of quasi-chemically homogeneous evolution with little or no mass transfer. However, it is found that quasi-chemically homogeneous evolution does not seem consistent with AB 5, either with AB 3, 6 and 7, since the temperature of the primary is overpredicted by more than 2σ (Shenar et al. 2016; Eldridge et al. 2011; Eldridge & Stanway 2012), and we can get the same conclusion from Figure 4. This is because of the lower value of $T_{\text{eff}}$ adopted in our work compared to that used by Koenigsberger et al. (2014) (Shenar et al. 2016). Eldridge et al. (2017) proposed that AB2, whose location matches quite closely to their 40 $M_{\odot}$, quasi-chemically homogeneous evolution track, is perhaps the candidate for a quasi-chemically homogeneous evolution (by mass transfer) star. Although we can't get the same conclusion from Figure 4 directly, this possibility can not be ruled out cause the velocity (650 km s$^{-1}$) we shown is too high enough to lead to chemically homogeneous evolution (compared with 400 km s$^{-1}$ proposed by Brott et al. 2011 and Heger et al. 2000).

4. Conclusions

WR stars are very important objects because they are related to the type Ib/Ic SNe, and LGRBs. They also affect the chemical compositions of interstellar medium. In this work, we investigate the possibility of a single star evolving into WR star due to rotation and compare our rapid rotation cases with observations in HR diagrams. The rotation has few effects on the evolution of massive stars at high metallicity that is because the rotation rate and efficiency of the mixing process is slowed down due to the enhancements of stellar-wind mass and angular momentum loss, and these stars become WR stars when the helium in their center is ignited. However, the mass loss induced spin-down, which stops the efficient rotational mixing, is reduced at lower metallicity. Since then rapid rotating massive stars can easily evolve into WR stars due to the trigger of the rotational induced chemically homogeneous evolution. From our models, we find that in the SMC the observed WR stars are consistent with the single-star evolution models. However at higher metallicities our single-star evolution models can only explain the luminous, hydrogen-rich WN stars and O stars. In the LMC and the Galaxy all the WC and WO stars are significantly fainter, and for the WC stars cooler, than our model tracks. The same is also true for a significant fraction of the WN stars. It is therefore likely that the majority of these stars are the result of binary evolution (e.g., Eldridge et al. 2017). Perhaps, it may be also because that our models about rapidly rotating massive stars are still beyond real ones. Simultaneously, the observational errors (such as distance) also lead to disagreement. There is a long way to go before we can understand WR stars.

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