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THE NATURE OF THE WOLF-RAYET PHENOMENON: MASS LOSS CLOSE TO THE EDDINGTON LIMIT

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RESUMEN

Con los nuevos modelos de atmósferas Wolf-Rayet hidrodinámicos de Postdam (PoWR) hemos obtenido los primeros modelos de vientos totalmente auto-consistentes para estrellas Wolf-Rayet. Para las estrellas más masivas, esto sucede ya hacia el final de su estadío en secuencia principal, esto es, aún en la fase de quema de hidrógeno. Objetos menos masivos alcanzan la fase Wolf-Rayet luego de iniciada la quema de helio. Por medio del análisis espectral con modelos hidrodinámicos estimamos las masas de dos estrellas WNL, extremadamente luminosas, ricas en hidrógeno, de la región de Carina OB 1. Estas estrellas, con masas actuales de al menos 80–100 $M_{\odot}$, son los descendientes directos de las estrellas más masivas en la Galaxia.

ABSTRACT

With the new Potsdam Wolf-Rayet (PoWR) hydrodynamic atmosphere models we have obtained the first fully self-consistent wind models for WR stars. We find that WR-type mass loss is initiated when stars approach the Eddington limit. For the most massive stars this happens already at the end of their main-sequence lifetime, i.e. still in the H-burning phase. Less massive objects enter the Wolf-Rayet stage after the onset of He-burning. From spectral analyses with hydrodynamic models we estimate the masses of two extremely luminous, H-rich WNL stars in Carina OB 1. With present masses of at least 80–100 $M_{\odot}$, these stars are the direct descendants of the most massive stars in the galaxy.

Key Words: stars: mass loss — stars: winds, outflows — stars: Wolf-Rayet

1. THE GALACTIC WN STARS

In a recent re-analysis of the galactic WN sample with line-blanketed model atmospheres (Hamann et al. 2006) we found two distinct groups of objects which are chiefly distinguished by their luminosities (see Figure 1). The first group, with luminosities above $\sim 10^{5.9}\ L_{\odot}$, consists of H-rich WNL stars which are located to the right of the ZAMS. The second group is dominated by H-free objects of early to intermediate subtype. These stars show much lower luminosities ($L_{\star} \sim 10^{5.2}$–$10^{5.8}\ L_{\odot}$) and higher temperatures.

The relatively large number of extremely luminous H-rich stars in the first group already implies that we are dealing with very massive stars in the phase of central H-burning (i.e. with a long lifetime). The stars in the second group are most probably in the much shorter He-burning phase. The upper luminosity limit for this group ($\sim 10^{5.8}\ L_{\odot}$) roughly agrees with the upper luminosity limit for galactic red supergiants ($\sim 10^{5.6}\ L_{\odot}$; Levesque et al. 2005) and the Humphreys-Davidson limit for red and yellow supergiants ($\sim 10^{5.9}\ L_{\odot}$; Humphreys & Davidson 1979). This could mean that our two groups do in fact belong to different evolutionary channels, namely extremely massive H-burning WNL stars in a pre-LBV phase, and less massive post-RSG/YSG stars in the phase of central He-burning.

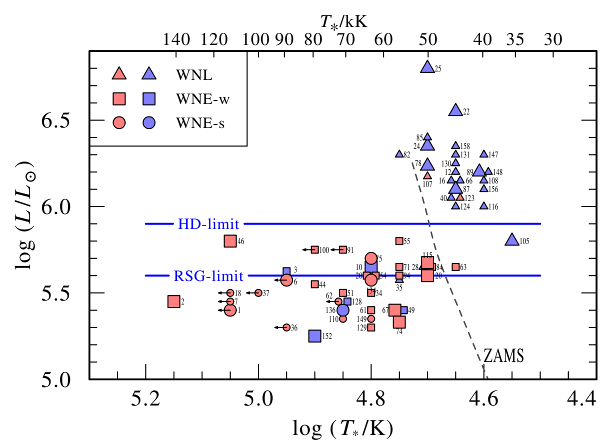

Fig. 1. Revised stellar parameters for galactic WN stars. Empirical HR-diagram from Hamann et al. (2006).

The large difference between the luminosities of both groups shows that H-burning objects need much higher luminosities to drive WR-type winds

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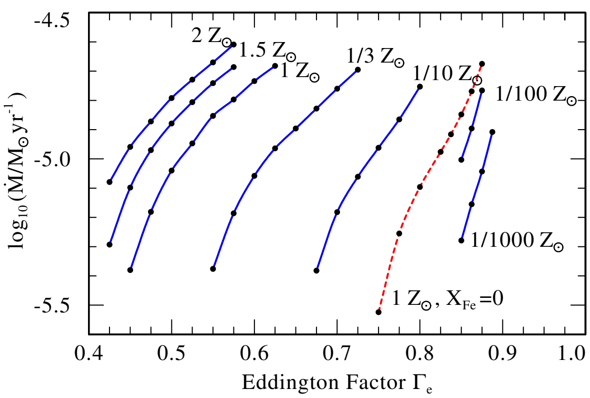

Fig. 2. Dependence of WNL star mass loss on Γ_e for a wide range of metallicities (Z). The results from Gräfener & Hamann (2007) show that large WR mass loss rates can even be maintained at very low Z if the stars get close enough to the Eddington limit.

than He-burning stars. Already this observational evidence indicates the importance of high L/M ratios for WR mass loss. Because of their lower masses, He-burning stars reach high L/M ratios at considerably lower luminosities than H-burners.

2. HYDRODYNAMIC ATMOSPHERE MODELS

Model computations with a new generation of self-consistent hydrodynamic model atmospheres (Gräfener & Hamann 2005, 2006, 2007) confirm this scenario. When stars approach the Eddington limit, their effective surface gravity is reduced. By this, the density scale height is increased, and the stars tend to develop optically thick stellar winds. For such winds the sonic point is located at large optical depth, close to the point of zero effective gravity. In contrast to classical OB star winds, the resultant mass loss thus depends on the temperature and density in these layers, and on the Eddington factor $\Gamma_e \equiv \chi_e L/4\pi c G M$ (see also Nugis & Lamers 2002).

Our WR wind models in fact show a rather strong dependence of $\dot{M}$ on Γ_e (see Figure 2). This leads to an extreme sensitivity of the emergent spectra on the L/M ratio, because the emission line fluxes typically scale with the square of the wind density. Detailed spectral analyses with our hydrodynamic models thus allow to constrain the masses of WR stars, if the distance towards the objects are reliably known. In particular, our models help to distinguish between H-burning and He-burning objects.

As a first test of such an approach we have modeled two H-rich WNL stars with weak emission lines in the Carina region, WR 22 and WR 25. Apart from our argumentation in §1, the low mass loss rates of these stars indicate that they might be in the H-burning phase. Indeed, we obtain relatively large stellar masses from our hydrodynamic models. With an adopted distance modulus of $m - M$=12.1 we get $10^{6.3}$ $L_\odot$ and 78 $M_\odot$ for WR 22 (WN 7h), and $10^{6.5}$ $L_\odot$ and 136 $M_\odot$ for WR 25 (WN 6h), respectively. Both objects are wide binary systems with faint OB star companions. The mass estimates from the orbital elements generally confirm our results. For WR 22 Rauw et al. (1996) find $M_{\mathrm{WR}} \sin^3 i = 72\ M_\odot$, and for WR 25 Gamen et al. (2008) finds $M_{\mathrm{WR}} \sin^3 i \approx 80\ M_\odot$ (see also Gamen et al. 2006). While WR 22 is an eclipsing binary with $\sin i \approx 1$, Pollock derives a small value of $\sin i$ for WR 25, making this star an extremely massive object.

Interestingly, WR 25 is the second evolved object in the young OB cluster Tr 16, in addition to η Car. Its location at the top of the main-sequence of this cluster, with a luminosity only 0.3 dex below η Car (Hillier et al. 2001), strongly supports its evolutionary stage as an LBV progenitor. Note that our results depend on the adopted distance. For WR 25 we determine 110 $M_\odot/10^{6.4}$ $L_\odot$ (with $m - M$=11.8 according to Hillier et al. 2001), and 210 $M_\odot/10^{6.7}$ $L_\odot$ (with $m - M$=12.55 according to Massey & Johnson 1993), respectively. The derived masses are consistent with H-burning stars in late phases of their main-sequence evolution. Our models thus suggest an evolutionary sequence of the form O → WNLh → LBV for very massive stars, whereas less massive objects should follow the sequence O → RSG/YSG → WN → WC.

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DISCUSSION

N. Walborn - There are four evolved objects (in addition to Eta Car) in the Carina Nebula, as I described in the previous discussion. WR 22 is at the western edge of the Nebula, however, and WR 24 is in Collinder 228 in the southern part of the Nebula. They could have moved to those locations from Trumpler 16 with modest velocities in 2 Myr.

N. Walborn - On the distance issue: I believe Massey's result of well over 3000 pc is due to numerous Tr 16 B-type ZAMS stars (as well as the O-type ZAMS in Tr 14). With $R = 3$, the Tr 16 O stars yield 2500-2800 pc; however, there is evidence that $R > 3$ and may differ toward different stars, which is to be determined. WR 25 is especially sensitive to this issue, since it lies behind a dust lane and has $V \sim 8.5$, as opossed to $V \sim 6.5$ for the other two WNL's near the edge of the Nebula. The three stars have similar absolute magnitudes. The most reliable distance may be that derived from kinematics of the Eta Car shell, which is geometrical and independent of extinction or absolute magnitudes. As derived, originally, by Hilllier & Allen, and recently in more detail by Nathan Smith, it is 2200–2300 pc, again implying $R > 2$ for the OB stars.

S. Owocki - How much of the driving in your models is due to continuum and how much due to lines?

G. Gräfener - At the critical point the continuum contributes about 75%. Nevertheless, the mass loss is determined by the increase of the mean opacity due to Fe lines.

A. Maeder - Your two groups of WN stars are very interesting and they show that different filiation may exist. You are pulling WNL before LBV. In view of their chemical composition, this may also be the inverse, because they essentially share the same domain of He/H ratios.

G. Gräfener - According to our models the H-rich WNL stars have large masses and should be in the H-burning phase. I did not want to exclude the possibility of the He-burning WNL stars. These would presumably appear as more He-enriched strong-lined objects.

A. Moffat - WNL stars show large spread in H-content (probably correlated with luminosity L). So perhaps you should consider the scenario O $\rightarrow$ WNLh $\rightarrow$ LBV $\rightarrow$ WN $\rightarrow$ WC where WN includes WNL without H, instead of what you proposed: O $\rightarrow$ WNL $\rightarrow$ LBV $\rightarrow$ WN $\rightarrow$ WC.

G. Gräfener - This is exactly what I meant. The group of over-luminous very massive WNL stars appears spectroscopically as weak-lined WNLh stars.

P. Massey - I was unaware of this controversy over our distance determination to Tr 14. Our result comes from spectroscopic parallaxes of about 30 OB stars, and we derive a very coeval age of about 2 Myr. I do not understand Nolan's and Virpi's argument that the early B's are ZAMS and hence less luminous at M_V that what I assumed. As far as I know early B's do not change their M_V by factors of 2 in a million years. If you adopt much smaller distance modulus, then the ages of these stars are going to be a lot less than 1 Myr. So then how did you form these WR stars on Eta Caineæ?

G. Gräfener - For WR 25 we have determined $R = 5.0$ and $E(B-V) = 0.59$ from the UV to IR flux distribution. With these values the star is only 0.3 dex fainter than Eta Car, i.e., it is a possible LBV progenitor. This result is independent of the adopted distance.

V. Niemela - E. Fernández Lajús (see poster) has observed eclipsing binaries in the η Car field, and he obtains a distance of 2.2 kpc for these binaries, which also turned out to be ZAMS stars, smaller and less luminous than normal O stars.

G. Gräfener - So this is in favor of a smaller distance to the Carina region.