WR 22 as a Core Hydrogen-Burning Wolf-Rayet Star? *

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Abstract: The analysis of an extensive sample of high resolution spectra of the Wolf-Rayet binary WR 22 recently allowed us to determine a minimum mass of 72 $M_\odot$ for the WN7 star. With such a high mass, WR 22 is expected to be a core H-burning star which has just evolved from a progenitor of at least 90-110 $M_\odot$.

1 Introduction

Given the similarities between some late Wolf-Rayet stars of the nitrogen sequence (WNL) and the Of stars, Conti (1976) suggested during a previous Liège Colloquium that such WNL's could represent an evolutionary link between the most massive single Of stars and the other Wolf-Rayet (WR) subtypes. This suggestion has been first theoretically investigated by Noels et al. (1980).

Unfortunately, the uncertainties on the evolutionary scenarios of single massive stars increase with the initial mass and, therefore, many different evolutionary sequences have been suggested (e.g. Langer et al. 1994, Meynet et al. 1994, Crowther et al. 1995b). Moreover, the real importance of mass transfer in massive O + O binary systems is not yet clear (De Greve 1991, Maeder & Meynet 1994). Since a key parameter for all these evolutionary models is the initial mass of the progenitor, an accurate observational determination of WR masses is crucial, particularly for those stars believed to be at the beginning of their WR phase.

2 WR 22 : the most massive WR star ever weighed

WR 22 (≡ HD 92 740), a bright ($V \sim 6.4$) WR of spectral type WN7+abs, is a member of the Carina OB1 association (Lundström & Stenholm 1984), and is classified as a single-lined spectroscopic binary (SB1) by van der Hucht et al. (1981, 1988). Previous determinations of

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the orbital parameters of WR 22 were made on the basis of photographic spectra and led to a rather eccentric ($e \sim 0.55$), 80.35 day orbit (Moffat & Seggewiss 1978, Niemela 1979, Conti et al. 1979). Until now, the only potential detection of a spectral signature of the secondary star in WR 22 has been reported by Niemela (1979) and Conti et al. (1979), who found some very faint absorptions on a few of their spectrograms taken when the Doppler shift between the lines of the WR and those of the companion was expected to be the highest.

In 1986, we initiated a long-term campaign with modern spectroscopic instrumentations available at the European Southern Observatory. A careful investigation of our high resolution spectra permit us to detect some features moving 180° out of phase with the lines of the WN7. Although rather weak, these absorption features allow a spectral classification of the secondary as a late O-type star (O6.5–O8.5) with a continuum-luminosity ratio at 5500Å $q = L_{\rm WR}/L_{\rm O}$ of about 8.2, suggesting a main sequence luminosity class for the secondary (Rauw et al. 1995).

Using the program of Wolfe et al. (1967), a least-squares radial velocity curve was derived for the WN7 star from the radial velocities (RV's) of the N IV λ4058 emission line as measured on our high quality spectra, allowing us to significantly improve the orbital parameters of WR 22. Since the absorption lines of the companion are rather weak, their RV's are plagued with large uncertainties of about 20 km s^{-1}. However, the RV's deduced from different lines are in good agreement with each other and can be used to derive the orbital parameters of the O star.

In this way, we find the minimum masses of both stars: $m_{\rm WR} \sin^3 i = 71.7 \pm 2.4\,{\rm M}_\odot$ and $m_{\rm O} \sin^3 i = 25.7 \pm 0.8\,{\rm M}_\odot$ (Rauw et al. 1995). Therefore, the WR star appears to be the most massive component of the system. The minimum mass of the WN7+abs component of WR 22 obtained here is significantly higher than any previous estimate.

3 Discussion and conclusion

The exceptionally high mass ratio $m_{\rm WR}/m_{\rm O} = 2.78$ and the high eccentricity of the orbit (0.559) of WR 22 point towards a WR + O system in which the WN7 primary has evolved from a very massive progenitor through mass-loss by stellar wind rather than through mass transfer by Roche lobe overflow.

The astonishingly high mass of the WN7 star ($m_{\rm WR} \geq 72\,{\rm M}_\odot$) and its high hydrogen mass fraction ($X_{\rm H} \sim 40\%$, Hamann et al. 1991, Crowther et al. 1995a) suggest that WR 22 is at the beginning of its WR lifetime and is most probably still a core hydrogen-burning star.

In fact, adopting a mean mass-loss rate of 6.9 10^{-6} ${\rm M}_\odot$/year during the O-Of stage of a star of initial mass 80 ${\rm M}_\odot$, Noels et al. (1980) find that 10% of the core H-burning lifetime would still be left, when the star enters the WNL phase, i.e. when sufficient material would have been lost to reveal at the surface the CNO equilibrium products of the initial convective core. These authors estimate the minimum mass to be lost before CNO processed material appears at the surface to be of the order of 19 ${\rm M}_\odot$ (for stars of initial masses between 80 and 100 ${\rm M}_\odot$). In the case of WR 22, this would imply a minimum mass of the progenitor of at least 90 ${\rm M}_\odot$. Crowther et al. (1995b) assume that WN7+abs stars have lost a higher fraction of about 35% of their initial mass. In the case of WR 22, this would lead to a progenitor of $\sim 110\,{\rm M}_\odot$.

Following Langer et al. (1994), the evolution of massive stars proceeds through the sequence O $\rightarrow$ Of $\rightarrow$ H-rich WN $\rightarrow$ LBV $\rightarrow$ H-poor WN $\rightarrow$ H-free WN $\rightarrow$ WC $\rightarrow$ SN. In this scenario, luminous H-rich late type WN stars are identified as core hydrogen-burning objects and the spectral sequence O $\rightarrow$ H-rich WNL reflects mainly an increase in the mass-loss rate.

According to Meynet et al. (1994), very massive stars with extreme mass-loss rates enter the WNL stage (as judged from surface composition) during the core H-burning phase and follow a downward track in the theoretical HR diagram before they end their core H-burning phase at

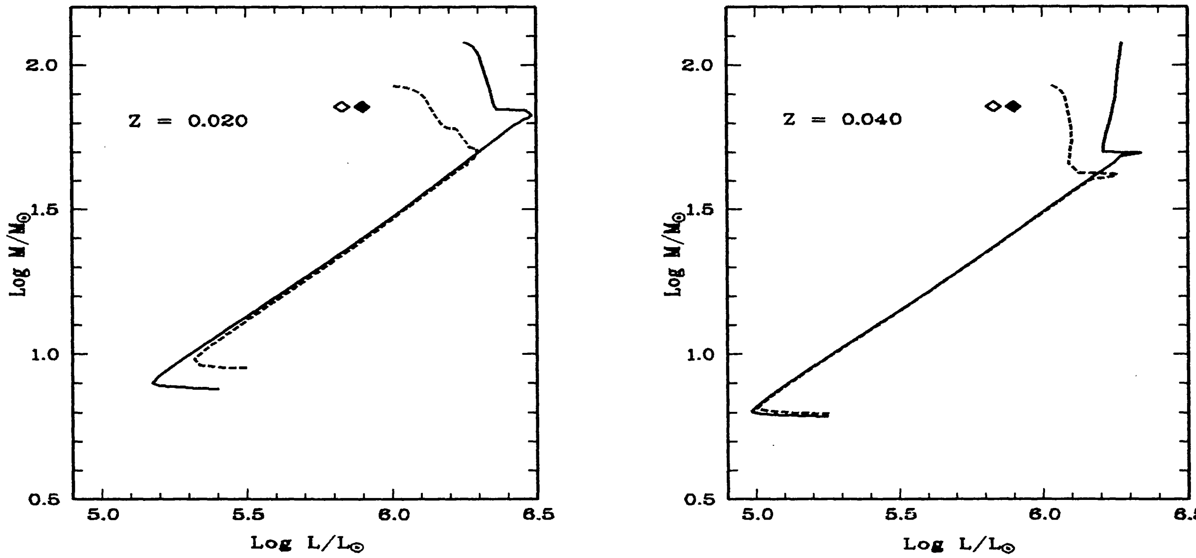
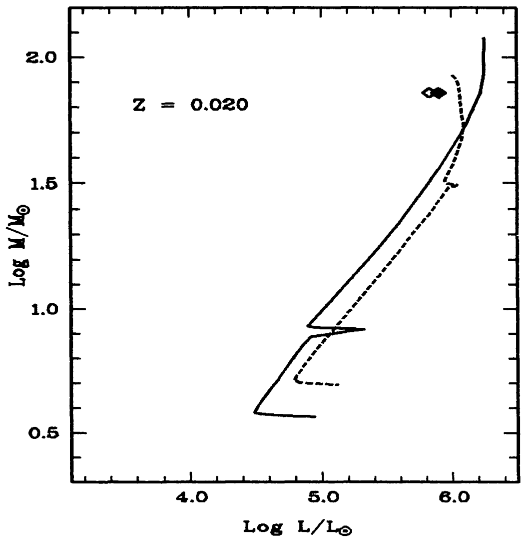


Figure 1: Mass-luminosity relation for the standard mass-loss rates and different values of the metallicity and initial mass. The evolutionary tracks are from Schaller et al. (1992) and Schaerer et al. (1993). The solid line and the dashed line are for $M_i = 120\,M_\odot$ and $M_i = 85\,M_\odot$ respectively. The position of WR 22 is indicated by an open diamond for the luminosity estimation of Crowther et al. (1995a) and a filled diamond for the value of Hamann et al. (1991). Note that the $85\,M_\odot$ model has not yet entered the WNL stage when it reaches a mass of $\sim 72\,M_\odot$ (see text).

a low luminosity. The evolutionary tracks computed by the Geneva group for a metallicity $Z \geq 0.020$ predict that stars of initial mass 120 $M_\odot$ and 85 $M_\odot$ are still core H-burning when they reach a mass of about 72 $M_\odot$. This conclusion holds for both, the standard and the enhanced mass-loss rates (Schaller et al. 1992. Schaerer et al. 1993, Meynet et al. 1994). However, while the models with $M_i = 120\,M_\odot$ are actually in the WNL stage (as judged from surface composition) once they reach a mass of 72 $M_\odot$, those of $M_i = 85\,M_\odot$ are still in the O-Of stage. Assuming a progenitor of $\sim 90-110\,M_\odot$ for WR 22, one would expect an intermediate situation between $M_i = 85\,M_\odot$ and $M_i = 120\,M_\odot$. Nevertheless, when comparing the observations to the theoretical tracks, one should keep in mind that, for the $120\,M_\odot$ model with high mass-loss rate, the mass-loss is so rapid that the evolution is qualitatively very different from the $85\,M_\odot$ model, thus casting some doubt on the validity of any interpolation. In any case, a brute force linear interpolation in the Geneva grids, on the basis of a star with $M = 72\,M_\odot$ and $X_H = 40\%$ at the surface favours initial masses of 105 to 110 or even 115 $M_\odot$, depending on the adopted metallicity and mass-loss rate.

Figures 1 and 2 show the position of WR 22 in the mass-luminosity plane together with the tracks of the Geneva group for different initial masses, metallicities and mass-loss rates. Hereinabove we have used the minimum mass for WR 22 together with the luminosities derived by Hamann et al. (1991) and Crowther et al. (1995a) from non-LTE analyses of the emission-line spectrum. While the absolute mass of the WN7 star is probably not too different from the minimum mass (WR 22 is an eclipsing binary, Gosset et al. 1991), the observed luminosities appear to be slightly lower than what is expected from the evolutionary tracks. However, the observed luminosities follow from assumptions over the distance and the absolute magnitude and, therefore, part of the observed difference could well result from uncertainties on these



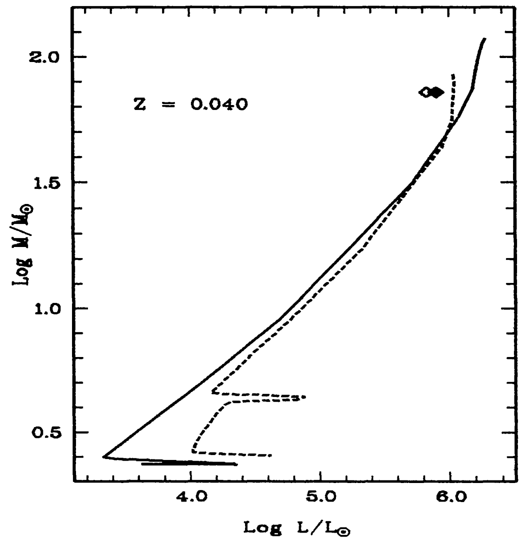


Figure 2: Same as Fig. 1, but for mass-loss rates enhanced by a factor of two. The evolutionary tracks are from Meynet et al. (1994).

parameters, although a true discrepancy with the models cannot be ruled out.

In conclusion, we have probably identified a representative of a rather poorly populated class of WR stars, even if the existence of such objects has been predicted many years ago (Conti, 1976). Indeed, while classical WR stars are highly evolved helium-burning descendants of massive O stars, we are here most probably dealing with a core hydrogen-burning object. This means that, while its core is still the one of a main sequence object, the external layers of WR 22 have been nearly completely peeled off, leading to reduced H and enhanced He and N abundances at the surface. At the same time, the star has developed a higher density wind than typical Of stars, giving it the external appearance of a WR object.

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