OBSERVATIONAL AND EVOLUTIONARY ASPECTS OF WOLF-RAYET STARS

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Some of these results are part of a more extended investigation on WR stars that will appear in four papers, i.e. Vanbeveren and Packet (1979), Vanbeveren and Conti (1979), Vanbeveren and Doom (1979), Vanbeveren and de Loore (1979).

## 1. THE BINARY STATUS OF WR STARS

Many authorities proclaimed that all WR stars are members of close binary systems with OB type companions (see e.g. I.A.U. Symp.n°43). Arguing that fainter stars were less well studied Kuhi (1973) only considered northern systems brighter than $m_V$=10m. In this sample 73% of the WR stars are binary components. Due to the very low disruption probability during the supernova explosion of the low mass component in a massive binary (De Cuyper et al., 1976) classical evolutionary theory predicts that there should be as many WR+OB type systems as there are WR+compact star systems (de Loore et al., 1975). If 73% WR+OB systems would be real, the evolutionary predictions would give serious problems. Fortunately, the proposed 73% is probably largely overestimated. P.S. Conti made spectra with the 4m telescopes at the observatories of Kitt Peak and Cerro Tololo of nearly all the galactic WR stars and those in the LMC studied by Smith (1968). One of the important results to remember here is that very few additional stars were found to have absorption lines that had not been listed as such by Smith already. On the other hand, the $m_V$ of many of the brightest WR stars is dominated by a companion. In the fainter WR stars the continuum is dominated by the WR star itself. Therefore if one decides only to consider systems brighter than $m_V$=10m one preferentially includes the binaries and this biases the statistics. The new measurements show a binary frequency ~40(±10)% for the Galaxy and for the LMC considering the whole sample now and using the criterion : binary means absorption lines present.



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It can be remarked that these numbers do not exclude the possibility of the existence os a low percentage of single WR stars.

## 2. THE EVOLUTIONARY STATUS OF WR STARS

According to Willis and Wilson (1978) early WN and WC stars show pure (He,Z) layers. This indicates that these stars should be in the He burning stage. Stellar wind mass loss during H burning is not enough to bring these pure (He,Z) layers to the surface. In WR binary systems the remaining hydrogen will be removed during the Roche lobe overflow process (RLOF). In Figure 1 the position in the HR diagram of early WN and WC stars is shown according to Willis and Wilson (1978 and private communication). The position of the late type WN stars is taken according to P.S. Conti (I.A.U. Symp.n°83). On the other hand also evolutionary tracks are shown for a $40M_\odot$, $60M_\odot$ and $100M_\odot$ star. During core hydrogen burning mass loss by stellar wind is taken into account (N=300, cf. Vanbeveren and de Loore, this symposium). As most of the massive binary systems will evolve through a case B of mass transfer (Vanbeveren et al., 1979), the primary reaches its Roche lobe after core hydrogen burning. We remark that the remnant mass after RLOF is largely independent from the period and the mass ratio of the system

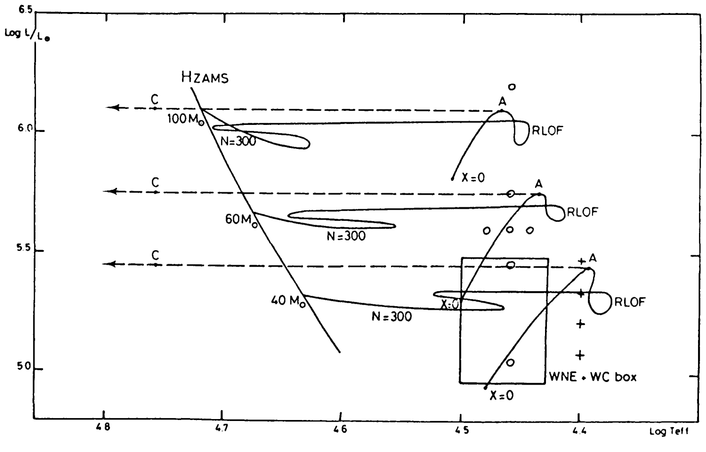


Figure 1. Evolutionary tracks for primaries of binary systems with initial ZAMS masses of $40M_\odot$, $60M_\odot$ and $100M_\odot$. During the hydrogen core burning, mass loss by stellar wind is taken into account (N=300). Point A denotes the end of the Roche lobe overflow. The dashed lines are the tracks with a non-extended, hydrostatic radius determination. The observed WN7 stars (o), the WN8/9 stars (+) and the WNE+WC box are indicated.

(De Grève et al., 1978) and of the mass and angular momentum loss from the system during RLOF (Vanbeveren et al., 1979). After RLOF the surface H abundance ≃0.2 almost independent from the stellar mass (Vanbeveren and De Grève, 1979) so that this stage may account for the late WN stage. The observations reveal that WR stars lose mass by stellar wind at very high rates (typically a factor 10 higher than in O and Of stars). After RLOF the evolution was further carried on including mass loss rates of this order. A mass loss rate formula proportional with luminosity was used. The remaining hydrogen is removed and pure He layers appear at the surface: an early WN star is formed. The hydrogen burning shell dies out very fast and the luminosity decreases, explaining the observed luminosity difference between late type and early type WN stars.
There remains however a large discrepancy: after RLOF the evolutionary tracks cross the HR diagram towards the very high temperature range of the He main sequence in a time scale of the order of $10^4$ years. The number of WR stars relative to the number of OB type stars indicates that the WR stage should last for the whole He burning phase. So, according to evolution we would expect to see most of the early WN stars and WC stars in a temperature range around ~90 000K and this is much higher than observed (T≃30 000K). A possible reason for this discrepancy may be the treatment of the atmosphere in evolutionary programs. The outer layers are treated as a planparallel, non extended, gray and hydrostatic atmosphere. In WR stars none of these assumptions are correct. Although the energy production in the core (and thus the luminosity) is nof affected, a correct treatment would result in larger radii and thus lower $T_{eff}$ values. Considering the position of the early WN stars and WC stars in the HR diagram, it cannot be excluded that the real He main sequence for massive stars is situated at lower $T_{eff}$ values than the hydrogen ZAMS.
The evolution after core hydrogen burning was performed including different stellar wind mass loss rates. It is possible to put some limits on these rates. First the mass loss rate may not be too high because in this case we would see layers that were in the He burning core in a previous

| $M(M_\odot)$ | $t^{min}_{He}(10^5 yrs)$ | $t^{max}_{He}(10^5 yrs)$ | $\Delta M_{min}(M_\odot)$ | $\Delta M_{max}(M_\odot)$ |
|---|---|---|---|---|
| 10 | 3.4 | 5.3 | 4 | 6 |
| 17 | 2.2 | 3.1 | 5 | 7 |
| 32 | 1.0 | 2 | 6 | 10 |

Table 1. Minimum and maximum values for the total mass removed from the star during core He burning. The corresponding He burning lifetimes are indicated.

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stage containing too much carbon as observed in WC stars. On the other hand, in order to see carbon enhanced layers at least once during He burning and taking into account with the WR distribution, i.e. n(late WN)/n(WR)~0.1 (Moffat and Seggewiss, 1979) and n(WN early)≃n(WC) we can determine a lower limit. It is encouraging that both numbers generally do not differ by more than a factor 2. In Table 1 some of these mass loss rates ar shown.

## 3. THE CHEMICAL ABUNDANCES

In this section we try to determine theoretically the CNO abundances in the surface layers of the remnant stars after RLOF (corresponding with late type WN stars) and in the surface layers of the early WN stars. Therefore the whole CNO cycle was followed in detail in the layers of a 40, 60 and 100 $M_\odot$ star. This mass range covers the WR mass range $8M_\odot < M_{WR} \leq 35M_\odot$. The results are shown in Figure 2. As can be noticed the results for N/He, C/He and O/He are almost independent from the stellar mass, the difference being

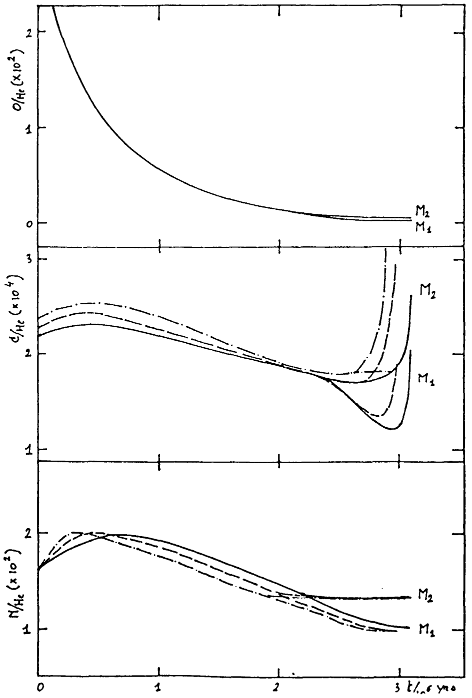


Figure 2. The variation of the N/He, C/He and O/He ratios in the mass layers $M_1$ and $M_2$ corresponding resp. with the layer X=0.2 (just after RLOF) and with the layer X=0 (early WN). The end of each curve indicates the N/He ratio at the moment the layer appears at the surface. Different stellar masses are considered, i.e. $40M_\odot$ (full line), $60M_\odot$ (dashed line) and $100M_\odot$ (dashed-dotted line).

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largest for C/He because C is most sensitive to temperature variations in the layers considered. The CNO abundances in WR stars should therefore be largely independent from their mass. The correspondence of the theoretical calculations with the abundances in 3 early WN stars and 1 WC star determined by Willis and Wilson is amazingly good if their model with $T_{eff} \simeq 30\ 000K$ is considered (which I recall is the most probable one).

## 4. EVOLUTIONARY MODELS FOR SOME KNOWN WR SYSTEMS

For a number of WR systems where estimates of the masses are available evolutionary models were constructed using the stellar wind mass loss rates obtained in section 3. Using interpollation formulas given by Vanbeveren and De Grève (1979) one can calculate the mass a star had just before RLOF. More details are given in a paper by Vanbeveren and de Loore (1979). In order to be consistent with the overabundance of unevolved systems with large mass ratios, a large mass loss from the system during RLOF is necessary. On the other hand, as it may be expected that more massive systems will evolve through a case B system (Vanbeveren et al., 1979) also a large angular momentum loss is needed. Striking also is the fact that all the WR stars considered here result from initial ZAMS masses larger than $\sim 50M_{\odot}$. This is quite different as what has been found by Smith (1973). From a statistical investigation she found that all OB type stars with masses larger than $25M_{\odot}$ should evolve into a WR star. However this conclusion was based on the use of the initial mass function of Sandage (1957) and very crude estimates of hydrogen and helium burning lifetimes. Since that time things have been improved. Using the initial mass function of Lequeux (1979) one finds that only 1/5 of the stars with masses larger than $25M_{\odot}$ should evolve into WR systems. Only by using $50M_{\odot}$ as a minimum mass one obtains that all OB stars with masses larger than $50M_{\odot}$ should evolve into WR stars.

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DISCUSSION FOLLOWING VANBEVEREN

Friedjung: I wish to make a somewhat provocative remark. Wolf-Rayet stars are very badly understood--we do not understand the nature of the wind. The significance of $T_e$ is not simple if one has in many layers optically thick winds, rather than a hydrostatic photosphere. How can one then make evolutionary calculations for objects so badly understood? Are you sure your calculations refer to Wolf-Rayets? It should also be noted that the University College London group obtained a high Wolf-Rayet mass loss rate from IUE observations.

Vanbeveren: The origin of the high stellar wind is indeed badly understood whereas the determination of an effective temperature is extremely difficult as well. However these problems are not so important for evolutionary calculations of WR stars. As has been done for the evolution of O stars including stellar wind, we have used a parameter equation for the stellar wind in WR stars in order to determine general evolutionary characteristics during the burning. On the other hand, a different treatment of the outer layers in evolutionary computations will not alter the behavior of the core of the star determining the whole evolutionary pattern. Thus although the effective temperature is badly known, this does not affect general evolutionary characteristics as there are the surface CNO abundances, the behavior of the luminosity, the timescales, the calculations of the masses before RLOF, the mass of the star itself so that a comparison with observations is very reliable. The determination of a maximum mass loss rate after RLOF is independent of the atmospheric treatment as well. The reason for the difference between these maximum values and the values obtained by the London group is unclear to me for the moment. If the values of the London group are correct then there should exist a large number of stars having carbon abundances in their outer layers of the same order as the He abundance. This is not observed.

Morton: It is strange that the Willis-Wilson effective temperatures are essentially the same for all WN types. The Zanstra calculations I made show that there are some WN5 stars with surrounding nebulae where $T_{eff} \approx 50000K$ consistent with what we have just heard about the central star of NGC 6888.

Vanbeveren: I would be very happy if the observed $T_{eff}$ values for WR stars were higher than the values obtained by Willis and Wilson. There is something in the determination of $T_{eff}$ for WR stars that we do not yet understand. Even the 50000K for some WN5 stars would not resolve the problem I mentioned i.e. from evolutionary calculations we would expect to see most of the WR stars at $T_{eff} \approx 90000K$. Therefore I considered different parameters to make a comparison, parameters that are only marginally affected by the treatment of the atmosphere.

Holm: A couple of years ago Joe Cassinelli and I compared UV and optical spectrophotometry of HD 50896 with a model extended Wolf-Rayet atmosphere having a temperature of $50,000^oK$. The agreement was quite good. The temperature of this atmosphere is about $20,000^oK$ hotter than a plane-parallel atmosphere which also fits the observed energy distribution.