ORIGIN AND EVOLUTION OF WOLF-RAYET STARS

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ABSTRACT

The larger part of close binary components with initial mass exceeding ~20 $M_{\odot}$ becomes WR stars in the core helium burning stage. Some of the most massive WR stars may be products of evolution of single massive stars with initial masses exceeding ~50 $M_{\odot}$ if the mass loss in the infrared supergiant stage is effective enough. The Ledoux criterion of convective stability seems more promising to explain the observed properties of WR stars.

Up to now 159 massive Wolf-Rayet stars have been found in our Galaxy (van der Hucht et al., 1980). According to Moffat and Isserstedt (1980) almost half of all bright ($m_V \lesssim 12^m$) WR stars have OB companions. Massey (see van der Hucht et al., 1980) concluded that only about a quarter of all WR stars have massive OB companions. Orbital periods are from $1\overset{d}{.}6$ to 113^d, mass ratios are from 0.25 to 2. Since the observed duplicity rate must be doubled in order to take into account invisible low mass relativistic companions (Tutukov and Yungelson, 1973), one gets that from 50 to 100 per cent of all WR stars are binaries. Thus, regretfully up to now observations only cannot answer a very important question: are all WR stars binaries? There are four WR+WR systems (de Loore, 1981) which constitute about 2.5 per cent of all known WR stars. The theory of evolution gives the possibility to connect the relative number of such systems with the relative number of binaries having the initial mass ratio between 0.9 and 1. But before numerical estimations it is necessary to be sure that all WR+WR systems among observed WR stars have been found.

High luminosities of WR stars suggest helium as their main constituent. Helium core arises in the course of evolution of an initially hydrogen star. There are two possibilities to lose the hydrogen rich envelope: by mass exchange in close binaries or due to intense stellar wind. Evolutionary tracks of mass losing stars are displayed in Fig.1 together with positions of two WR stars - components of eclipsing close binaries. Dense circumstellar envelopes of WR stars make the estimates

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of surface temperatures and luminosities of single WR stars extremely uncertain. To get a hot helium WR-like remnant, it is necessary that the star should fill the Roche lobe in the core hydrogen exhaustion phase, or in the hydrogen shell burning phase if the Ledoux criterion of convective stability is valid. Then the surface hydrogen content of the remnant is ~0.2, as observed.

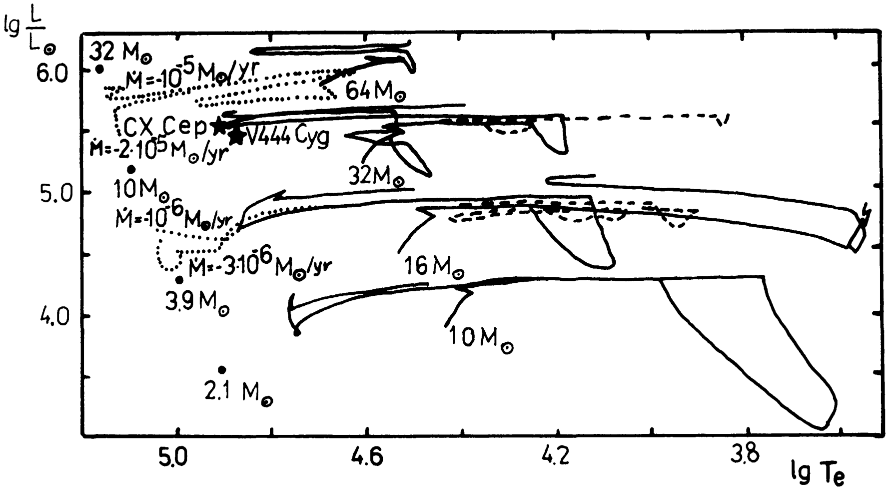

Figure 1. Evolutionary tracks of mass losing stars in the HR diagram. The solid line marks evolution of primary components with the Ledoux criterion, dashed line with the Schwarzschild one (Tutukov et al.,1973; Tutukov and Yungelson,1978). Tracks of the 5 $M_\odot$ helium star and the 64 $M_\odot$ hydrogen star with mass loss by wind is shown by dotted lines (Tutukov et al.,1973; Massevitch et al.,1979). Positions of helium star models are shown by dots (Tutukov et al., 1973). Asterisks are positions of WR stars: of V444 Cyg (Cherepashchuk and Khaliullin,1972) and of CX Cep (Lipunova and Cherepashchuk,1981).

If the Schwarzschild criterion of convective stability is assumed, the surface temperature of remnants of components with initial masses 16 $M_\odot$ and 32 $M_\odot$ remains rather moderate. We had found that if the initial mass of a star exceeds ~19 $M_\odot$, it fills the Roche lobe during the larger part of the core helium burning stage. Therefore, intense additional mass loss is necessary to get a WR-like remnant in this case. But high enough mass loss rates are not observed for blue supergiants (see Fig.2). To get a single helium star, it is necessary to lose the hydrogen rich envelope. The mass losing star may be an (infra)red supergiant (Bisnovatyi-Kogan and Nadyozhin, 1972) or a blue hot star (Conti, 1976). The evolutionary track of a 64 $M_\odot$ star with intense mass loss is displayed as an example in Fig.1. Now we compare the observed mass loss rates for different stars with the rates necessary to lose the hydrogen rich envelope or to uncover carbon rich shells of stars. Fig.2 shows that single OB stars do not lose hydrogen rich

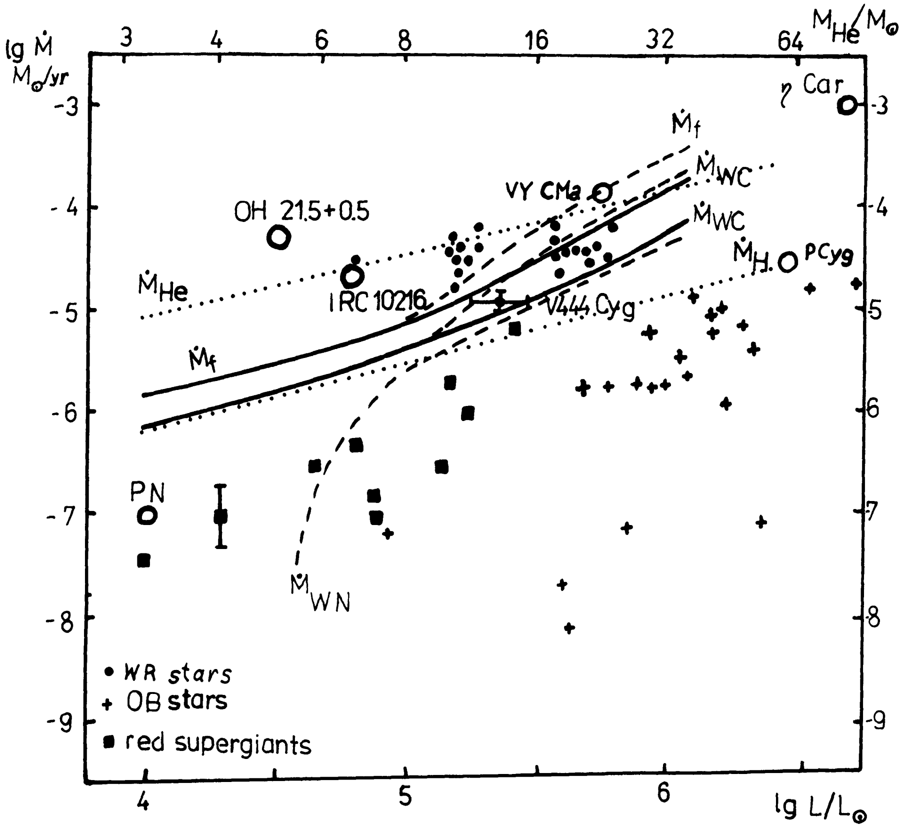

Figure 2. The luminosity-mass loss rate diagram. Sources for red supergiants are due to Sanner (1976), for OB stars (Abbott et al., 1980), for WR stars (Barlow et al., 1980), for OH 21.5 + 0.5 (Werner et al., 1980), of IRC 10216 (Fazio et al., 1980), of V444 Cyg (Kornilov and Cherepashchuk, 1980), of VY CMa, P Cyg, planetary nebulae (PN)(de Jager, 1980), of η Car (Davidson and Ruiz, 1975). Minimal mass loss rates necessary for uncovering nitrogen and carbon enriched shells are indicated by lines $\dot{M}_{WN}$ and $\dot{M}_{WC}$, respectively. Mass loss rates necessary for the loss of all mass of star during core hydrogen of helium burning stages are marked by $\dot{M}_H$ and $\dot{M}_{He}$ respectively. The solid line is for the Ledoux criterion and dashed line for the Schwarzschild one. $\dot{M}_f$ are the mass loss rates necessary for loss of all mass of the WR star during core helium burning stage.

envelopes during the core hydrogen burning stage. For this reason OBN stars are rare. The observed mass loss rates of core helium burning red supergiants are $10-10^2$ times lower than the rate M_{He} necessary for the loss of the hydrogen rich envelope of a single star during the core helium burning stage. But a red supergiant with mass loss rate exceeding $\sim 10^{-8}(L/L_o)^{1/2}$ M_o/yr becomes an infrared supergiant due to dust formation in its atmosphere. Mass loss rates by three infrared supergiants VY CMa, OH 21.5 + 0.5, IRC 10216 seem to be high enough for the loss of envelopes, if the duration of the infrared stage is comparable to the duration of the core helium burning stage. But present estimations of the mass loss rate by such objects are still uncertain within factor ten. It is also possible that some stars with very high mass loss rates are common envelope close binaries. Thus the possibility of single WR star formation is still open.

The existence of red supergiants with luminosities up to ~10^6 $L_{\odot}$ indicates directly that most of the stars with initial masses lower than ~50 $M_{\odot}$ do not lose hydrogen rich envelopes during core hydrogen and helium burning stages. But more massive single infrared supergiants still remain as the most probable progenitors of single WR stars. In this case part of young WR stars must be surrounded by ring nebulae that are remnants of hydrogen rich envelopes. About 15 per cent of all apparently single WR stars are really surrounded by such envelopes. But the large mean z-coordinate (Moffat and Isserstedt, 1980), high space velocity, absence of the association of single WR stars with young stellar clusters (Mikulashek, 1969), the presence of invisible low mass components in three such systems lead to the conclusion that at least 6 out of 9 observed stars of this type are the products of massive close binary evolution. It is also possible that all apparently single WR stars are close binaries with relativistic companions. If however WR stars may be products of evolution of massive single stars, then the primary components of wide binaries may also transform into WR stars like single stars. The lost envelope would be observed for ~5.10^4 yrs around a WR+OB system as a usual ring nebula. If one assumes that about half of massive binaries are wide ones, then about five WR+OB stars should have ring nebulae around them. But not a single nebula of this type is observed.

Observed mass loss rates for WR stars are high enough to display carbon-enriched matter (see Fig.2). We should remark that these values of $\dot{M}_{WR}$ are still unreliable and probably several times overestimated, as the comparison with $\dot{M}$ for the WR component of eclipsing star V444 Cyg shows. The observed rates are high enough for considerable mass loss during the helium core burning stage ($\dot{M}_f$) for WR with the luminosity below ~3.10^5 $L_{\odot}$.

Now we shall estimate the minimal initial mass M_{min} of components of close binaries that transform into WR stars. Taking the galactic stellar birthrate function $dN \simeq (M_{\odot}/M)^{2.5} dM/M_{\odot}$, helium burning time $T_{He} \simeq 1.6.10^7\ M_{\odot}/M$ years and assuming that half of all massive stars are components of close binaries, we get the number of WR stars in the Galaxy: $N_{WR} \simeq 3.10^6\ (M_{\odot}/M_{min})^{2.5}$. 158 WR stars were found within one sixth of the volume of the Galaxy. Thus the total number of WR stars is ~10^3. We can conclude that all components of close binaries with mass exceeding ~25 $M_{\odot}$ must become WR stars if all observed WR stars are binaries. A similar value results from the minimal luminosity of WR stars (see Fig.2). Besides M_{min} should be of the order of the minimal mass of OB companions of WR stars in binaries, which is ~20 $M_\odot$ (van der Hucht et al., 1980). The lower limit for the WR mass is ~7 $M_\odot$ (see the upper part of Fig.2).

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