ON THE SIGNIFICANCE OF MASS LOSS FOR THE EVOLUTION OF MASSIVE STARS

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It is shown that mass loss by stellar wind with rates observed in O, B-stars cannot change qualitatively their evolution in the core hydrogen-burning stage. The effects, that are usually attributed to the mass loss, can be explained by other causes: e.g., duplicity or enlarged chemically homogeneous stellar cores.

The significance of mass loss by stellar wind for the evolution of massive stars was studied extensively by numerous authors (see e.g. Chiosi et al. (1979) and references therein). However, the problem is unclear as yet. There does not exist any satisfactory theory of mass loss by stars. Therefore one is usually forced to assume that mass loss rate depends on some input parameters. If one assumes that the mass outflow occurs under a continuum radiation pressure, then

$$\dot{M} = -\alpha \frac{L}{V_\infty c} \tag{1}$$

where L is the luminosity, V_∞ is the terminal velocity of the outflowing matter. $\alpha = 1$ corresponds to the case when all momentum carried by the radiation is absorbed by the matter (Cassinelli and Castor, 1973). Equation (1) is essentially the same as proposed by Fesenkov (1949) and Massevitch (1949). It follows immediately from (1) that the total amount of mass that could be lost by the star during its core hydrogen-burning stage is (Massevitch et al. 1979)

$$\frac{\Delta M}{M} \approx 0.2 \ \alpha \ . \tag{2}$$

We have computed the evolution of 16, 32, 64, 128 $M_\odot$ stellar models with mass loss rates given by (1) for values of α = 0, 1.5, 3, 10. Evolutionary tracks of models are shown in Fig. 1, where we have also indicated positions and mass loss rates of several observed early

C. Chiosi and R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, 265–270.

spectral-type stars (Barlow and Cohen, 1977). The

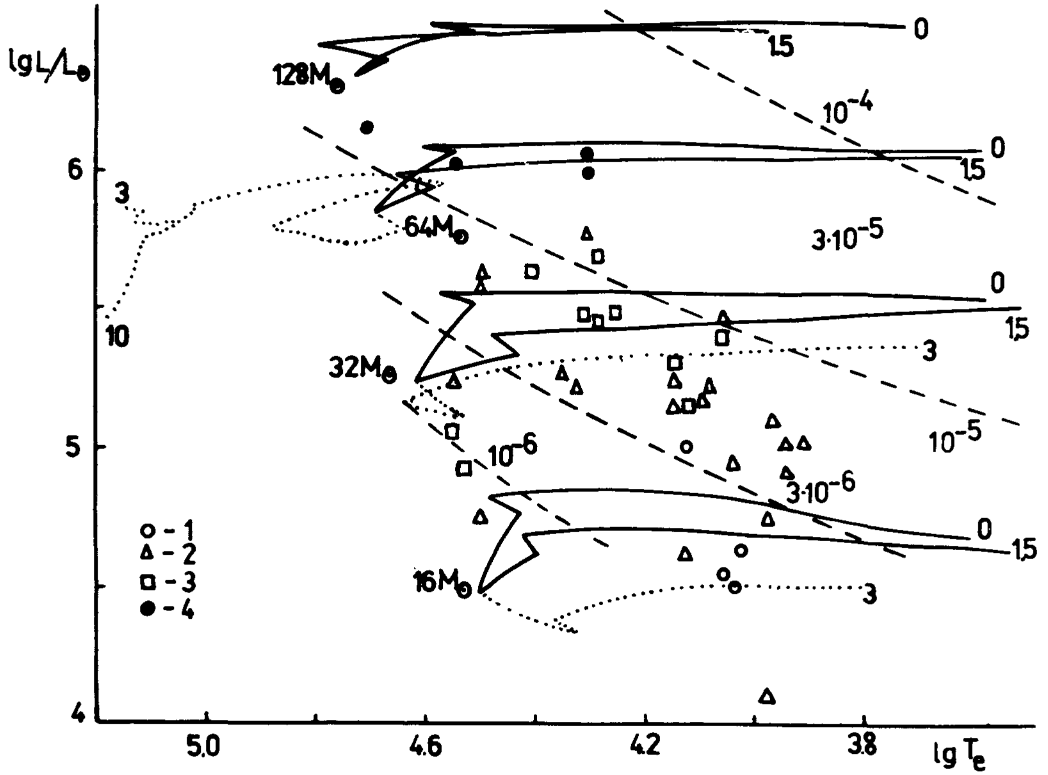

Figure 1. Evolutionary tracks of mass losing stars in the Hertzsprung-Russel diagram. Numbers near the ends of tracks indicate values of α in eq. (1). Dashed lines are constant mass-loss rate curves. 1 - $\dot{M} < 5\ 10^{-7}\ M_\odot/yr$, 2 - $5\ 10^{-7} \leqslant \dot{M} \leqslant 10^{-6}\ M_\odot/yr$, 3 - $10^{-6} < \dot{M} \leqslant 5\ 10^{-6}\ M_\odot/yr$, 4 - $\dot{M} > 5\ 10^{-6}\ M_\odot/yr$

comparison with observational data shows that observed M correspond to $\alpha \simeq 0.4 - 0.5$. If mass loss rates are so low, stars are not able to lose any significant amount of matter during the core hydrogen-burning and later stages. One has to conclude that mass loss does not alter the evolution of stars.This statement remains valid even if real mass loss rates are about ~(1.5 -2) times higher than given by Barlow and Cohen (1977) as argued by Conti and Garmany (1979). Observed mass loss rates are too low to uncover the layers where hydrogen is depleted to a considerable degree and where all carbon is converted into nitrogen in the CNO-cycle. The same conclusion was reached by Czerny (1979). Such a low mass loss rate also makes it impossible to attribute the broadening of the upper main-sequence strip in the Hertzsprung-Russel diagram to mass loss. Two alternative solutions of the latter problem are possible: a difference of stellar opacities from the usually assumed Cox opacities (Stothers and Chin, 1977) or increase of the size of the homogeneous stellar core, due to some still unclear reasons (Massevitch et al., 1979). It is well known that the O, B- components of binary X-ray sources have luminosity excesses about 1^m. These excesses that are usually attributed to mass loss also could be explained by enhanced cores (Massevitch et al., 1979).

Observed $\dot{M}$ are also insufficient to explain the absence of blue supergiants later than B3 with $M_B \lesssim -9.5$ by mass loss (Hutchings, 1976).

Conti (1976) assumed that apparently single WN7/WN8 stars are formed by means of mass loss from Of-stars, which they closely resemble in many aspects. The results of our computations show that for observed $\dot{M}$ ($\alpha \simeq 0.5$) stellar models do not have properties of WR stars (surface chemical composition, luminosity excess) when they cross the region of the Hertzsprung-Russel diagram lgTe $\approx$ 4.4 - 4.7, occupied by WR stars according to Conti (1976). The more so they do not evolve into the high temperature region of the Hertzsprung-Russel diagram (lgTe = 4.8 - 5.0) occupied by WR stars according to Rublev and Cherepaschuk (1974). A star could become a WR star if it loses almost all its hydrogen envelope. As shows relation (2) this is possible only if $\alpha \gtrsim 2 - 4$. This is confirmed by computations of evolution of a 64 $M_\odot$ star, which had reached the WR region when $\alpha \gtrsim 3$ (see Fig. 1). The reasons for such a high $\dot{M}$ are unclear, especially if one takes into account that stars with high $\dot{M}$ have to originate in the same region of the H-R diagram, where stars with a 5 - 6 time lower $\dot{M}$ are situated. Even if the real values of $\dot{M}$ are 2 or 3 times higher than given by Barlow and Cohen (1977) (cf. Hutchings (1977)), they are not high enough to provide the loss of the whole hydrogen-rich envelope during the core hydrogen-burning stage. However, let us mention that components of close binaries not filling their Roche lobes have values of $\dot{M}$ higher than single stars (Hutchings, 1976).

One can propose (Tutukov and Yungelson, 1980) the following solution of the problem of absence of supergiants later than B3 with $M_B \lesssim -9.5$ and of formation of at least a part of the "single" WN7/WN8 stars within the evolutionary scenario for massive close binaries (Tutukov and Yungelson, 1973a, Yungelson and Tutukov, 1974). Pressure on dust particles in the surrounding gas-dust envelopes puts a limit on the masses of both young single stars and components of binaries of about 50 $M_\odot$ (Kahn, 1974). Mass exchange increases the masses of secondaries in binary systems up to 70-90 $M_\odot$. Due to the large difference in the luminosities of components it is difficult to discover the duplicity of the system. In the course of evolution the primary becomes a neutron star, but a systems as a whole obtains a spatial velocity up to 100 Km/sec.

Stone (1979) and House and Kilkenny (1978) have discovered that high spatial velocities are typical for most luminous and massive "single" stars in the Galaxy. The presence of unseen relativistic component determines the evolution of those stars after they expand, fill their Roche lobes and begin to lose matter. The rate of accretion onto a compact star is limited. Therefore a common envelope forms around the system (Paczynski 1976). The common envelope could be lost in the thermal time-scale $\sim 10^4$ years if the following condition is satisfied (Tutukov and Yungelson 1979): $M_c\, m/r_c > M_*^2 /R_*$, where M_c is the mass of the stellar core, m is the mass of the compact companion, M_* is the total mass of the star, R_* is its radius. The typical mass loss rates from the envelopes $\dot{M} \sim 10^{-3}$ M_o/yr coincide with $\dot{M}$ observed in unique non-stationary blue supergiants like P Cyg, Car, S Dor. Loss of the envelope leads to formation of a WN star. A lost envelope with a size $\sim$ 1pc could be observed for $\sim 3\cdot10^4$ years. This is 5 to 10 per cent of the lifetime of a star with $M \gtrsim 50M_o$ in the core Heburning stage. The quota of WN stars with envelopes among all WR stars is also several per cent. There are known several "single" WN stars with high value of $|z|$, anomalously low mass-function f (m), variable radial velocities and envelopes, that may present evidence for the existence of relativistic companions: HD 147 406 (WN7, $|z|$ = 1302 pc, f(m) = 0.32 M_o), HD 50896 (WN5, $|z|$ = 279 pc, f(m) = 0.015 M_o), HD 192 163 (WN6, $|z|$ = 65 pc, f(m) = 0.00024 M_o), M1-67 (WN8, ΔRV = 184 Km:sec) (Moffat and Seggewiss, 1979, Moffat and Isserstedt, 1979). Barlow et al. (1980a) have discovered in the spectrum of WR star Sanduleak 3 lines of ultra-high exitation with the time-scale of variability $\sim$ 150 sec. This also can indicate the existence of a relativistic companion. According to Moffat and Seggewiss (1979b) the numbers of WN7/WN8 stars with variable and constant radial velocities are equal. Therefore at least half of the stars of that type could be formed in binary systems.

Tutukov and Yungelson (1973b) have shown that if the mass loss rate by a WR star $\dot{M} \gtrsim 10^{-6.4}$ $(M_{WR}/M_o)^{1.3}$ M_o/yr, then during the core He-burning stage the layers enriched by C and He are uncovered and the WN star becomes a WC star. High mass loss rates by WR stars ($\sim 10^{-5}$ M_o/yr) are confirmed by observations of Barlow et al. (1980b). Binaries with $P \lesssim 20^d$ that contain a blue supergiant with a relativistic companion merge and probably become (infra)red supergiants. Part of them can be identified with OH/IR stars with high spatial velocities.

The absence of red supergiants with $M_B \lesssim -9.5$ that is usually ascribed to the changes of evolution caused by mass loss (Chiosi et al. 1978), can be a consequence of the screening of those stars by dust particles, formed in cold outflowing envelopes. As a result these stars become infrared sources with corresponding luminosity. If such an envelope exists at the instance of a Supernova explosion and $\dot{M} \gtrsim 10^{-4}$ M_o/yr, such a Supernova could be discovered only in the infrared (Tutukov and Yungelson, 1978). This may influence the statistics of Supernovae and also may open some new possibilities for their discovery.

From the said above one may draw the following conclusion.

1. The observed mass loss rates by O, B-stars could provide the loss of no more than ~10 per cent of total stellar mass. This is unable to change qualitatively the stellar evolution in the core H-burning stage.

2. A part of effects that are usually ascribed to the mass loss: absence of supergiants with $M_B \lesssim -9.5$, luminosity excesses of optical counterparts of X-ray sources, formation of WN7/WN8 stars can be explained by other reasons. These are: impossibility of formation of single stars more massive than 50 $M_\odot$, duplicity, enhanced size of chemically homogeneous stellar cores (in binaries?).

3. It is necessary to point out that although mass loss by O,B-stars does not significantly influence their evolution, the mass loss by stelar wind is able to sustain the luminosity of X-ray sources in massive binaries, to provide the formation of interstellar "bubbles", to provide the dynamics of interstellar gas.

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https://doi.org/10.1017/S0252921100094859 Published online by Cambridge University Press

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DISCUSSION

BASU: As far as I have understood, you assume in your model that radiation pressure in the only agent for driving the stellar wind. Can we do that? Some apparently single WR stars may turn out to be binaries. But can we draw a general conclusion like this from such a simplified model of mass loss? If there is a relativistic component, can that not be detected by some means, such as X-ray emission, etc.?

YUNGELSON: In our treatment is a free parameter that could be estimated either from theoretical considerations or from observational data. As any reliable theory of mass loss is still absent, our expression for $\dot{M}$ is only a convenient formalism for computations, that is not related to any mechanism of mass loss. Our computation showed that mass loss with rates observed in most O, B-stars is not able to change qualitatively evolution of massive stars in the core hydrogen burning stage. The average $|Z|$ for single WR stars is almost two times higher than the average $|Z|$ for binary WR stars. Therefore is seems to us that a sufficient part of apparently single WR stars are binaries with unseen companions. The absence of observable X-ray emission from WR stars can be caused by several reasons: WR star does not fill the Roche lobe and therefore the capture of matter is inefficient; large optical thickness of stellar wind from WR star.