CRITICAL RATES OF STELLAR MASS LOSS

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INTRODUCTION

Many of the effects of mass loss on OB stars have now been explored. Mass loss will cause a star to be overluminous for its mass (though less luminous than a star of its original mass) and, for moderate mass-loss rates, the luminosity decreases at the same rate as the mass contained in the convective core decreases causing the main sequence lifetime to remain unchanged (Chiosi and Nasi 1974, 1978, Deloore, DeGreve and Lamers 1977, Dearborn, Blake, Hainebach and Schramm 1978). Mass loss can also expose layers where ^{14}N has been enhanced via the CNO tricyle (Dearborn and Eggleton 1977) and, in extreme cases, can produce a stripped helium core resembling a Wolf-Rayet Star (Hartwick 1967). While many of these phenomena (in particular the composition change) are more sensitive to the total mass removed than the formalism used to represent the mass loss, significant differences will result for the same average mass-loss rate depending on whether the mass was removed early (near the ZAMS), or late (near core hydrogen depletion). In addition, there appears to be a critical mass loss rate which depends on initial mass and separates those models which continue to evolve in a relatively normal (though subluminous) manner, and those models which evolve to a Wolf-Rayet configuration.

CALCULATION

In earlier work (Dearborn et at. 1978) over thirty stellar tracks were evolved with different rates of mass loss for stars of 15, 30, and 60 $M_\odot$. A mass loss formula similar to that of McCrea (1962) was used:

$$M = -\mu \frac{\phi(T_e)\, L\, R}{M} \qquad \phi(T_e) = \frac{\pi}{\sigma T_e^4} \int_0^{\lambda_c} B(\lambda, T_e)\, d\lambda$$

where L R and M are the luminosity, radius, and mass in solar units. The constant μ is used to scale the mass loss rate and B is the Planck function. This formula differs from McCrae's in that it assumes only the luminous flux shortward of λ_c (2000Å) is effective at driving mass loss.

P. S. Conti and C. W. H. de Loore (eds.), Mass Loss and Evolution of O-Type Stars, 349–356.

The evolution of a number of the more interesting models has now been followed into carbon burning. At this point, the time remaining prior to core collapse (Arnett 1973) and resulting supernova is too short for mass loss to play any further role.

RESULTS

In order to better understand our calculations we begin by constructing a framework on which to compare the models. For this it is necessary to consider three timescales, the main sequence timescale without mass loss (τ_{ms}), the actual time spent on the main sequence (τ), and the average mass-loss timescale ($\tau_{\dot{m}} = \tau M_i/(M_i - M_f)$, where M_i and M_f are the masses at the beginning and end of the main sequence). Figure 1 is a diagram on which the vertical axis (τ/τ_{ms}) indicates how much mass-loss extends the life a model, and the horizontal axis ($\tau_{ms}/\tau_{\dot{m}}$) is an indicator of the mass-loss rate. There is to the right of this diagram an excluded region requiring total depletion of the mass of the star. The curved line on the diagram then shows the effects of different initial mass-loss rates on a 30 $M_\odot$ model.

As the mass-loss rate increase from zero the main sequence lifetime remains approximately the same until a critical mass-loss rate of

$$M_{cr} = 7.65 \times 10^{-10} \left(\frac{M}{M_\odot}\right)^{2.35} M_\odot/\mathrm{yr}$$

is reached. At this point the lifetime of the model begin to rapidly increase. Attempts to increase the mass-loss rate beyond this point cause the luminosity

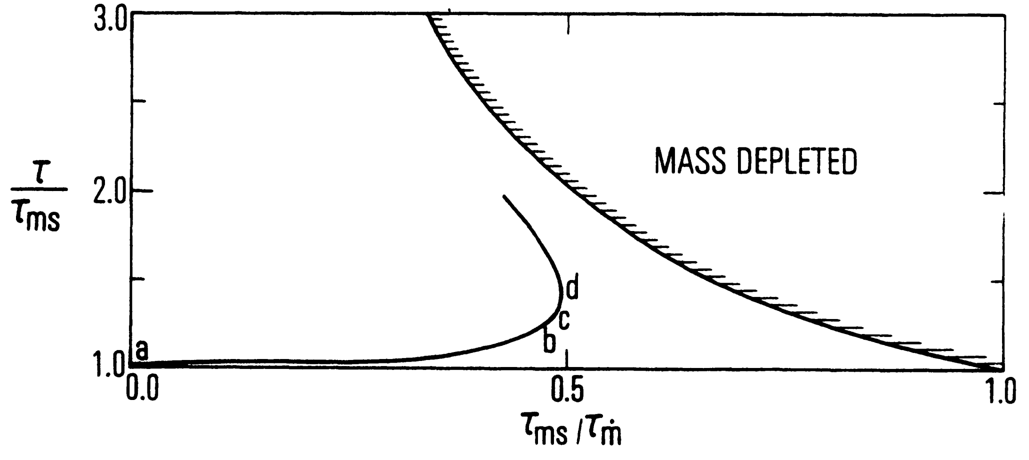

Fig. 1. This figure compares the mass-loss rate ($\tau_{ms}/\tau_{\dot{m}}$) to the lifetime of the mass losing star (τ/τ_{ms}) for a 30 $M_\odot$ star. For low to moderate rates of mass loss, the main sequence lifetime is unaffected. Eventually critical mass-loss rate is reached at which the lifetime begins to change. The positions of models a, b, c and d are marked.

of the star to decrease resulting in a lower mass-loss rate. If the mass-loss rate were not allowed to decrease, mass-loss rates higher than critical mass-loss rate would deplete the star of all mass.

In our case where mass-loss rate is allowed to decrease with luminosity, mass-loss rates initially higher than the critical mass-loss rate lead to the upper branch of the curve in Figure 1 which parallels the mass depleted region. The models on this upper branch are essentially stripped helium cores. This critical mass-loss rate then divides the models which evolve to Wolf-Rayet like configurations from those which evolve more normally.

Table 1 shows the physical parameters of some 30 $M_\odot$ models which were evolved to a presupernova configuration. Given are the scaling constant μ, the initial mass-loss rate $\dot{M}_i$, the final mass-loss rate (and the maxmum in case b) $\dot{M}_f$, the main sequence lifetime (Υ), the resulting core mass M_c, and the final stage. According to Conti (1978), the mass-loss rates used here to produce a Wolf-Rayet configuration are too low to produce a signature in the visible spectrum of a star, and therefore while these mass-loss rates are high, they are not unreasonable.

TABLE I

Model	μ	$\dot{M}_{initial}$	$\dot{M}_{final}$	$\bar{\dot{M}}$	Υ	M_c	Final State
a	0(x10^{-1})	0(x10^{-6})	0(x10^{-6})	0(x10^{-6})	6.0(x10^{6})	11.5	Red Giant
b	2	1.7	4.3	2.5	7.2	8.2	Red Giant
c	3	2.5	2.8	2.6	8.4	4.5	Wolf-Rayet
d	4	3.4	1.7	2.7	9.2	3.8	Wolf-Rayet

Mass loss in the red region was not considered, and may alter the final evolution of models a and b. To have a significant effect however, the mass-loss rate must be very high (~10^{-4} $M_\odot$/yr) and the star must spend sufficient time at this mass-loss rate to remove the envelope. The amount of time a star spends in the red prior to core collapse depends sensitively on the treatment of semi-convection, and is not a settled question. It seems however entirely possible that mass loss in the red could strip the remaining envelope off of model b resulting in a Wolf Rayet configuration.

Figure 2 shows the evolutionary tracks of models a, b, and c. Model b is subluminous compared to model a and the surface abundance of ^{14}N is enhanced 3 to 4 times its original value. Model c is substantially lower in luminosity than model a. In addition it undergoes two stages of ^{14}N enhancement in layers which are exposed where ^{12}C and then ^{16}O were converted to ^{14}N. This model begins as an O star, and evolves through an OB-N stage, an OB-N stage with ^{16}O deficient, a WN stage, a WC stage and finally a supernova. The temperature predicted by the models during the Wolf Rayet stages are unrealistically high because of the assumed boundary conditions. This does not affect the evolution of the models, but the surface temperatures are uncertain. Models c and d did supernova in the blue, and, not having a 10^{14} cm envelope to filter the energy, may have produce an x-ray or hard UV supernova such as has been proposed for the progenitor of the Cas A SNR (Chevalier 1976, Lamb 1978).

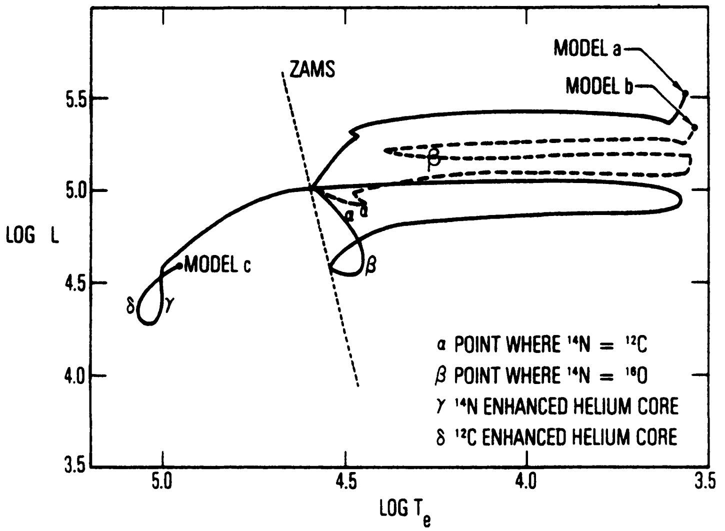

Fig. 2. This figure shows tracks in an H-R diagram for models a, b and c. The points are marked at which composition changes occur.

In addition a 60 $M_\odot$ star was evolved with a mass-loss rate sufficient to place it on the upper branch in Figure 1. It evolves directly to a Wolf-Rayet configuration without ever evolving to the red.

CONCLUSIONS

A critical mass-loss rate exists above which models result in a Wolf-Rayet configuration. Figure 3 shows the relation between initial mass and resulting helium core mass for stars losing mass at this critical rate. This shows that without mass-loss in the red, a 40 $M_\odot$ star is required to produce a 10 $M_\odot$ Wolf-Rayet star. Of course if sufficient mass is removed in the red, a 10 $M_\odot$ stripped core can result from a lower initial mass star which has lost mass at a rate below the critical rate during its main sequence lifetime.

In whatever manner a Wolf-Rayet star is produced, mass-loss rates of $\sim 10^{-5}$ $M_\odot$/yr such as have been reported here will have significant effect on the evolution of the star. Over the helium burning lifetime such a rate will remove the ^{14}N-rich helium envelope and expose ^{12}C-rich material once contained in the helium-burning core convection zone.

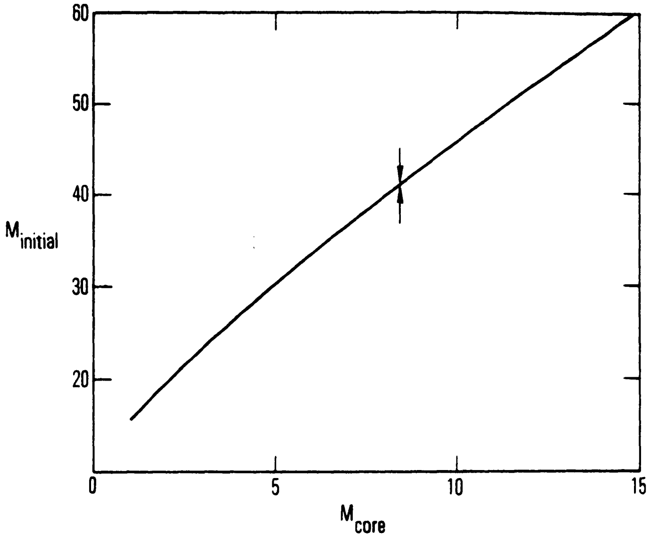

Fig. 3. This figure shows the resulting core mass for stars losing mass at the critical rate. A mass-loss rate of 10^{-5} $M_\odot$ /yr would expose ^{12}C rich layers in all of these cores over their helium burning lifetime. In fact such a mass-loss rate would cause stars less massive than those indicated by the arrow to be completely depleted of mass over their helium burning lifetime.

These ^{12}C-rich zones also can contain significant enhancements of ^{16}O from $^{12}C\ (\alpha,\gamma)$ ^{16}O. In the WC models we evolved, the ^{12}C achieved a mass fraction of ~0.08, while in the WN models the ^{14}N was enhanced only about 10 times normal.

Mass loss has a number of interesting effects on the nucleosynthesis in massive models. Because mass-loss reduces the core mass, less ^{14}N is trapped in the core for additional processing. Models which lose sufficient mass to become stripped cores yield about two times as much ^{14}N as a conservative ($\dot{M}$=0) model. The smaller core results in a smaller yield of metals to helium,because relatively more metals are trapped in the collapsed core during supernova. Model c yields $\Delta Y/\Delta Z$ of 3.0 in the ejected material instead of 0.5 obtained in case a. Due to both the smaller core size and the fact that mass loss causes the convective helium burning core to retreat, the C/O ratio is enhanced. Also when mass loss produced a WC star, it ejects a region which is ^{18}O enhanced (via $^{14}N\ (\alpha,\gamma)$ ^{18}O). Such an ^{18}O rich region exists in all massive stars, but there is some question as to whether it can survive the supernova shock without additional processing (Truran 1976, Dearborn, Tinsley and Scramm 1978). In WC stars we are probably seeing this material ejected.

Quantitative observations of the composition in OB stars can yield useful information on the amount of mass that has been lost. A ^{14}N enhancement of 3 to 5 times indicates a region has been exposed in which ^{12}C has been converted to ^{14}N. Higher ^{14}N enhancements requires much more extensive mass-loss in order to expose material originally in the convective core. It would be particularly interesting to look for ^{14}N in x-ray binaries where it is believed significant amounts of mass are lost. It is however important to make quantitative determinations in order to know at what level we are seeing (or not seeing) an anomaly.

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DISCUSSION FOLLOWING DEARBORN

Vanbeveren: Did I understand you correctly: did you follow really the CNO cycle step by step, layer by layer?

Dearborn: Yes.

Vanbeveren: In this case, how long does it take to reach the equilibrium abundances in the core during hydrogen core burning?

Dearborn: ^{12}C-^{14}N equilibrium is achieved throughout the core within 5% of the main sequence lifetime. The ^{16}O approaches equilibrium over a longer period. The envelope of course contains CNO processed material, but not in equilibrium.

Sreenivasan: Could you tell us the rate of mass loss you used in the track which makes two somersaults in the HR diagram?

Dearborn: The mass loss rate varied from 2.5 10^{-6} to 2.8 10^{-6} $M_{\odot} yr^{-1}$ with a time averaged mass loss rate of 2.6 10^{-6} $M_{\odot} yr^{-1}$.

Lamb: Given the rates for the triple-α and $^{12}C(\alpha,\gamma)^{16}O$ reactions wouldn't you expect the abundances of ^{16}O to be higher than that of ^{12}C in the later phases of mass loss from your model stars?

Dearborn: What you say would be correct for complete helium burning, but the region exposed here has only partial converted ^{4}He into ^{12}C and ^{16}O. In helium burning, ^{12}C is initially enhanced strongly over ^{16}O. Only after the ^{12}C is enhanced and ^{4}He begins to deplete does ^{16}O begin to overtake ^{12}C.

Chiosi: Would you please specify what θ^{2}_{α} was used in the computations of the 3α reaction network.
Secondly, I would like to know the fraction of lifetime spent by your models between the stage of complete removal of the H-rich envelope and the stage when 3α processed material is brought to the surface.

Dearborn: I used $\theta^{2}_{\alpha} \approx 0.06$. The fraction of the lifetime spent after the removal of the hydrogen-rich envelope depends on the mass loss rate. A higher mass loss rate produces a smaller core which has a longer helium-burning lifetime.

Van Dessel: I noticed you situated the WR stars in the region log T_{eff} = 5.0. This kind of high effective temperature is not confirmed by observational data. Could you comment?

Dearborn: The high effective temperatures are due to the static atmospheric model used as a surface boundary contition. A more accurate hydrodynamic approximation would result in lower effective temperatures. As this does not effect the nucleosynthesis and evolution of the interior I have not worried about it.

Moffat: You state that WN stars can evolve into WC stars. Does this also apply to WN 7/8 stars too, which appear to lie in a region of the HR diagram quite distinct from the remaining WN stars?

Dearborn: In any core helium burning star the carbon enhanced region is not that far below the hydrogen-helium discontinuity. If WN 7/8 stars are in this stage of evolution, the observed rates of $>10^{-5}$ $M_{\odot}$/yr should expose ^{12}C rich material in less than the core helium burning lifetime.

Massey: What are the lifetimes you get for the WN's compared to the WC's?

Dearborn: The relative lifetime of these two stages depends on the mass loss rate adopted. In this case the star spent six times as long as a WN star than as a WC star. The mass loss rate was however much lower than those talked of here. A higher mass loss rate could easily cause the WC lifetime to equal the WN lifetime.