MASSIVE STARS BURNING HELIUM: THE NUMBERS OF WR STARS AND RED SUPERGIANTS IN GALAXIES

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1. INTRODUCTION

We have calculated evolutionary models of massive stars in the range 15-120 $M_\odot$ from the zero-age sequence up to the end of the carbon burning stage (Maeder, 1981). Three sets of models with different mass loss rates $\dot{M}$ have been computed; the adopted parametrisation of $\dot{M}$ is fitted on the observations and thus the expression for $\dot{M}$ differs according to the location of the stars in the HRD.

In this short note we concentrate on the location of the He-burning stars in the HRD. The helium burning phase, which lasts 8 to 10 % of the MS phase, is spent mainly as red supergiants (RSG) and as WR stars (note that for low mass loss, the time spent as A-G supergiants becomes longer). An important result of the models is that, at a given luminosity, the ratio t_R/t_{WR} of the time t_R spent as an RSG to the time t_{WR} spent as a WR star is strongly decreasing with increasing mass loss rates in both the MS and RSG phases.

In this connection, let us mention some observational results found by Maeder, Lequeux and Azzopardi (MLA, 1980).

2. THE NUMBERS OF WR STARS AND RED SUPERGIANTS IN GALAXIES

Table 1 gives, as a function of the galactocentric distance R, the surface densities projected onto the galactic plane of blue supergiants, red supergiants and WR stars and some ratios discussed below. The basic data used by MLA are those by Humphreys (1978), Smith (1973) and van der Hucht et al. (1980). The 4 main facts to be pointed out are:

- The ratio N_R/N_{WR} of the numbers of red supergiants to WR stars decreases by about a factor 90 from the galactic zone centred at 12 kpc towards the zone centred at 8 kpc. This is quite an extreme variation, much larger than that of N_R/N_B.

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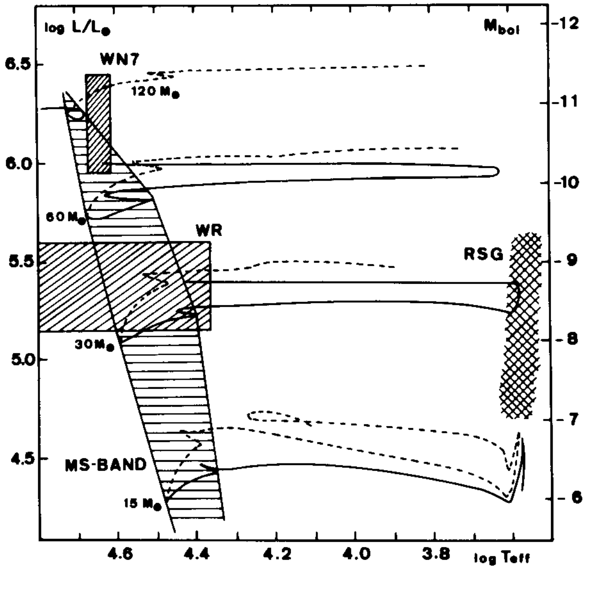
Table 1

R(kpc)	$\frac{N_B}{kpc^2}$	$\frac{N_R}{kpc^2}$	$\frac{N_{WR}}{kpc^2}$	$\frac{N_R}{N_{WR}}$	$\frac{N_R + N_{WR}}{N_B}$
11-13	25.6	4.11	0.32	13.0	.17
9-11	26.6	2.08	1.42	1.5	.13
7- 9	21.3:	0.44:	3.11	0.14:	.17:

- As shown in Table 1, the sum (N_R+N_{WR}) of the numbers of red supergiants and WR stars remains nearly constant with galactocentric distance when normalized to the number of blue supergiants. Such constancy, occurring despite the very large variations of N_R and N_{WR}, is quite striking as noted by MLA (1980).
- The N_R/N_{WR} ratio is related to chemical abundances, as shown by MLA. Indeed, if physically significant, such a relation must also be verified by the Magellanic Clouds, which have relatively low metal contents Z. Indeed, from the available data, MLA found that the galactic relation between N_R/N_{WR} and Z is also verified by the SMC and LMC; the obtained relation is N_R/N_{WR} = 251·exp (-5.16 $Z/Z_\odot$).
- The N_R/N_{WR} ratio is thus an extremely useful indicator of metal abundances, since both RSG and WR stars are very bright objects visible up to large distances in our and in external galaxies.

3. THE HELIUM BURNING PHASE AS WR AND RED SUPERGIANTS

Let us consider the evolution of a 30 $M_\odot$ star (cf. Fig. 1). After having left the main-sequence, the star reaches the red supergiant (RSG) stage,



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where it ignites helium in its centre to form a ^{12}C, ^{16}O core. Due to mass loss, the hydrogen-rich envelope is progressively lost and the surface of the helium core formed during the MS comes close to the stellar surface. Then the star tends to leave the RSG stage and moves bluewards in the HR diagram where it may be observed as a WR star with ^{4}He and ^{14}N enrichment. Two facts are worth being noted: -1) If at a given luminosity, $\dot{M}$ is larger (both on the MS and RSG phase), the time t_R decreases. Consequently, the duration t_{WR} increases, since the total duration t_{He} of the He-phase does not change significantly with mass loss. -2) The relative duration of t_R decreases with increasing luminosity; this accounts for Humphreys' observations (1978) on the behaviour of N_R/N_B with luminosity.

Stars with initial masses $\gtrsim 60\ M_\odot$ appear to lose enough mass so as not to spend any significant time at the RSG stage and this explains why the maximum luminosity of RSG is about 2 magnitudes lower than that of the brightest O stars. Conversely, a 15 $M_\odot$ star does probably not lose enough mass to enable the surface of its core to reach the stellar surface and the star may thus never become a WR star. This allows to understand the existence of a lower limit to the absolute luminosity of the WR stars.

We interpret the change of the ratio N_R/N_{WR} with galactocentric distance and metal content by the following connections: $Z\uparrow \rightarrow \dot{M}\uparrow \rightarrow t_R/t_{He}\downarrow \rightarrow N_R/_{WR}\downarrow$. The second of these connections is just the one discussed above and for which quantitative relations are available; in order to obtain the first one, further improvements in models of stellar winds are still needed. Thus we suggest to interpret the strong variations of N_R/N_{WR} as the result of the effects of chemical abundance on the mass loss rates, which in turn strongly influence the relative duration of the RSG and WR phases (cf. MLA, 1980). The noticeable constancy of the ratio $(N_R+N_{WR})/N_B$ easily follows, since this ratio is proportional to t_{He}/t_H, which has a low dependence on mass loss.

It is clear that the scenario for forming WR stars is certainly not unique. However, the above results do suggest that a large fraction of WR stars effectively is in a post-RSG stage. In particular, binarity could not be the leading factor for forming WR stars. As an argument, we note that there are no WR stars at a luminosity lower than $10^5\ L_\odot$, where contact binaries evidently exist.

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DISCUSSION

CHIOSI: I qualitatively agree with the very interesting results you have presented, however I wonder if I can also agree quantitatively. I feel in fact that by adopting Barlow's and Cohen's mass loss rates for supergiant stars to estimate the amount of mass lost during the main sequence phase, one would certainly overestimate the mass lost by these stars, thus severely affecting the evolutionary behaviour of subsequent phases. We cannot in fact ignore here that different laws of mass loss rates have been suggested according to which very little mass is expected to be lost even though the rate increases by more than one order of magnitude. I have the impression that those models which are expected to live near the main sequence band and therefore should represent the WR stars do not spend very much time in the area of blue yellow supergiants. I think that at least part of the core the burning phase should take place in this range of effective temperatures.

MAEDER: I shall first emphasize that the rates of mass loss I used are quite compatible with the observed ones, as indicated for example by Lamers et al. (1979) who showed that the rates by Barlow and Cohen should be increased by a factor of about 2. By the way, may I point out that my main sequences rates are still lower than the ones you were using in your α = .90 computations; for red supergiants my rates are smaller by a factor of 5 to 10. As it was shown by many observation and in particular by those of Peter Conti, there is a large scatter in mass loss rates even for stars identically classified. Therefore in order to interpret an HR diagram in which stars of many clusters are present, one has to make a population synthesis with an appropriate mixture of models with various mass loss rates. When doing this, by means of transparencies, there seems to be stars almost everywhere in the HRD; however, I agree that a very detailed quantitative analysis of the exact numbers of the blue-yellow supergiants has still to be made.

ANDRIESSE: This is a comment. From your work we get the strong impression that red giants of normal metal content lose significantly more mass than otherwise similar stars of low metal content. This fits in the framework of the fluctuation theory of mass loss, where differences in chemical composition lead to differences in mass loss. In my Erice-paper you can find a figure showing that the trend is correctly predicted.

FALK: Almost every evolutionary calculation for massive stars with and without mass loss indicates that the stars will spend most of their time in two distinct regions. The MS phase and blue-yellow supergiant region. That is, there should be a reduced number of stars between the two regions. However, Humphrey's observations do not show a gap. This gap could be filled in by slow blueward evolution during the core He burning phase such as that shown by my track with initial rate of 5.0×10^{-7} $M_{\odot}$/yr. Extended blue loops for stars which become RGS's may also fill in this gap.

MAEDER: I am of the opinion that any careful comparisons between observations and models must the based on cluster sequences preferably to any mixture of stars from everywhere in the galaxy, although the composite HR diagram of galactic stars has its own high intrinsic value. Another point is that it would certainly be an fruitful tendency to attempt to interpret everything in stellar evolution in terms of mass loss. My own feeling is that the absence of the gap in the observations could result from other hydrodynamic processes such as convective overshoot and diffusion.

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