THE VARIOUS SCENARIOS LEADING TO WR STARS: THEIR RELATIVE IMPORTANCE AND THE ROLE OF MIXING

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1. CATALOGUE OF SCENARIOS FOR WR STARS

Over the last 40 years WR stars have been associated with almost all possible evolutionary stages. Hereafter are listed those scenarios which may be considered as most relevant in view of recent surface abundance determinations (cf. Willis, this meeting).

Scenarios with mass loss:

-1. Conti's scenario (1975): sequence leading O → Of → transition WN → WN → WC stars as a result of mass loss.

-2. Quasi-homogeneous evolution at the verge of vibrational instability: this instability has been studied by many authors (e.g. Appenzeller, 1970). Due to mass loss, stars with initial $M \gtrsim 100\, M_\odot$ may evolve in a succession of quasi-homogeneous structure (never large composition differences between core and surface) always keeping at the edge of vibrational instability (cf. Maeder, 1980). This scenario is likely to be the rule for the most massive O and WR stars and also gives the same sequence as above.

-3. WR as post-red supergiants (RSG): sequence leading O, Of stars → RSG → WN (early) → WC stars. This scenario mainly concerns initial masses in the range 20-60 $M_\odot$ (see Maeder, 1981a,b and this book).

-4. Binary evolution with mass transfer: mass transfer and mass loss reveal bare cores (cf. de Loore, 1980 and this book).

Scenarios and processes of mixing:

Although strong emphasis has been laid on the role of mass loss over recent years, internal mixing can also play a leading role in WR star formation.

-5. Meridional circulation: the general view is that circulation cannot penetrate varying molecular weight barriers, which therefore insulate different regions in a star with respect to their rotation (cf. Kippenhahn and Thomas, 1981). Some rapidly rotating stars may, however, not be far from mixing.

-6. Mixing by shear instability: the shear between adjacent layers in differentially rotating stars may give rise to turbulent mixing for velocity gradients higher than some critical value given by Townsend's criterion (cf. Zahn, 1974). In the course of evolution a star is likely

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to keep at the verge of shear flow instability (cf. Schatzman, 1977; models by Schatzman and Maeder, 1981). If the velocity gradient in a star were larger than that given by Townsend's criterion, transport by turbulent currents would lower it down to the critical gradient. On the opposite, even initially small velocity gradients could rapidly rise to the critical value as a result of external losses of angular momentum. This type of mixing may play a major role in the formation of WR stars (cf. Maeder, 1981c).

-7. Convective overshoot: extensive studies of this process have been made (cf. Maeder, 1976). This effect (incorporated in calculations of § 4) may contribute to the formation of WR stars.

2. IMPORTANCE OF MASS LOSS IN WR FORMATION

a) MS mass loss: according to interior models, for obtaining stars with surface ratio H/He < 2, it is necessary that the average mass loss rates $\langle\dot{M}\rangle$ are larger than $1.2 \cdot 10^{-11} (L/L_\odot)^{0.83}$; different multiplicative coefficients correspond to different H/He ratios. Comparing this minimum $\langle\dot{M}\rangle$ with recent rates (Conti, this meeting) we note that only stars with $M_{bol} < -10.8$ (corresponding to $M > 115\ M_\odot$) may lose enough mass to become WR stars. This scenario may only account for 0.04 WR kpc^{-2} (mass spectrum by Lequeux, 1979), while the observed frequency in the solar neighbourhood is 1.4 WR·kpc^{-2}. Thus, mass loss on the MS is only able to explain a minute fraction of the observed WR stars.

b) Mass loss in the RSG stage: on the basis of our models and by making similar estimates as above, we find that the post-RSG scenario may account for 0.5 WR·kpc^{-2}, which indicates that mass loss in the red may produce a sizable fraction of the observed WR stars.

3. CASE OF BINARIES. GALACTIC CHANGES OF THE BALANCE BETWEEN SCENARIOS

The frequency of binary WR (visible and invisible) is estimated to be about 50 % (cf. Massey, this meeting). From data by van der Hucht et al. (1981), Breysacher (1981), Azzopardi and Breysacher (1981) it may be noted (Maeder, 1981c) that the number ratio (binary WR/all WR) increases through a sequence of locations with decreasing metallicity Z: 1) zone towards galactic centre, 2) solar neighbourhood, 3) anticentre, 4) LMC and 5) SMC. For example in the zone number 1, the fraction of observed binaries is 17 %; on the opposite in the SMC all the observed WR stars appear binary. Now, in zone 1 the overall WR frequency is 3.1 WR·kpc^{-2}, while it is as low as about 0.05 WR·kpc^{-2} in the SMC. Hence the fraction of binary WR seems smaller just where the frequency of WR is larger. Tentatively, we make the following suggestion: in the SMC only the binary channel hardly succeeds in WR formation and the other channels play a minor role. In zone 1 the various other channels are very active and they contribute, in addition to binary WR stars, to make the overall WR frequency quite large.

In addition to the above example many other properties of WR stars rather continuously change in the sequence of zones 1 to 5 which suggests that the "traffic" through the various channels leading to WR stars strongly changes with initial metallicity Z and thus galactic location.

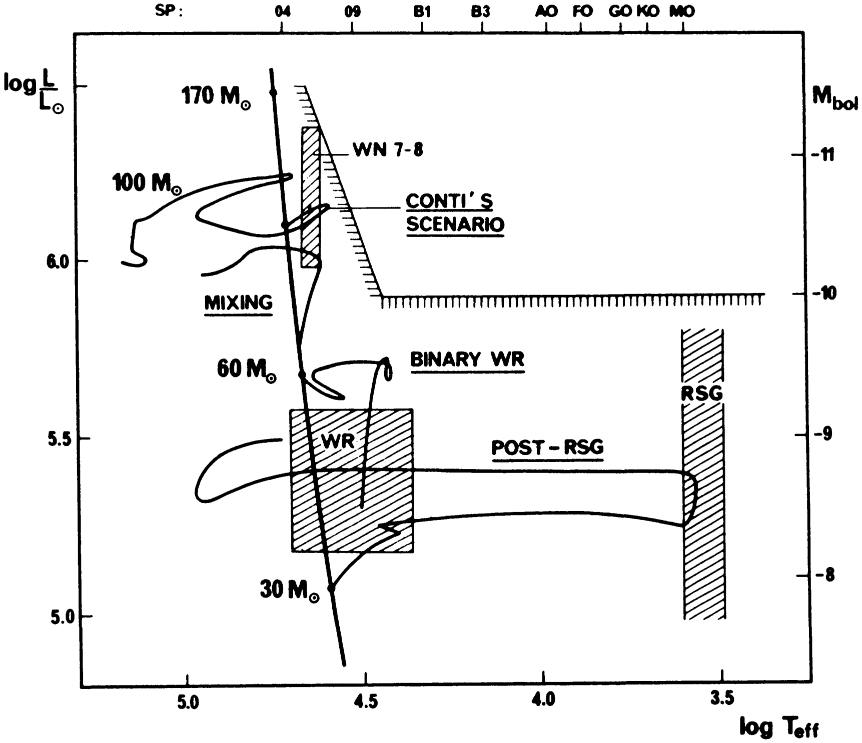

Fig. 1 : Illustration of the tracks of 4 important scenarios for forming WR stars: 1) Conti's scenario, tracks by Noels and Gabriel (1981). 2) Scenario with mixing due to shear instability (present work). 3) Scenario with binary mass transfer (cf. de Loore, 1980; Vanbeveren and Conti, 1980). 4) Formation of WR stars as post-RSG (cf. Maeder, 1981b). The schematic location of WR stars is indicated (cf. Conti, 1975) as well as the upper envelope of stellar distribution in the HR diagram and the location of RSG.

4. THE ROLE OF MIXING

The mixing by shear flow is characterized by a diffusion coefficient $D = R_e^* \nu$, where R_e^* is some critical Reynolds number of the order of 10^2 (cf. Schatzman and Maeder, 1981) and ν is the viscosity (molecular and radiative). The radiative viscosity varies like $\nu_{rad} \sim T^4/\kappa\rho^2$ (κ: opacity) and it is about 10^6 times larger in a 60 $M_\odot$ star than in the Sun, making the diffusion by shear flows quite important in massive stars. The table on the next page shows the timescale τ_{mix} for mixing by shear instability. τ_M is defined here as the time to lose half of the stellar mass with current mass loss rates on the MS; finally t_{MS} is the MS lifetime. We find that internal mixing by shear instability has, for all stellar masses, a larger effect on MS evolution than mass loss and also that the timescale for mixing is smaller than t_{MS} for $M > 60\ M_\odot$.

initial M	τ_{mix}	$\tau_{\dot{M}}$	t_{MS}
15 $M_\odot$	152.2	-	11.55
30 $M_\odot$	28.8	100:	6.78
60 $M_\odot$	6.3	12	4.22
120 $M_\odot$	1.6	2.4	2.93

Evolutionary models including simultaneously the effects of -mass loss, -convective overshoot and -shear flow mixing following the details of CNO abundances are now in progress. Fig. 1 illustrates one evolutionary track with mixing together with tracks for other important scenarios. The first main results coming out of these models are the following ones: 1) with the 3 combined effects the stars with $M > 50\ M_\odot$ evolve quasi-homogeneously to the left of the MS. 2) The models show a larger core surrounded by a smoother H-distribution. 3) During the evolution the change of the ratio $^{14}N/^{12}C$ is more progressive, therefore accounting for stars with intermediate characteristics. 4) No semi-convection is present. 5) For $M < 50\ M_\odot$, mixing considerably extends the MS band. 6) Mixing also significantly favours the formation of WR stars as post-RSG.

Mixing may thus supply for the recognized deficiency (cf. § 2) of MS mass loss in bringing O stars directly towards transition WR for $M \gtrsim 50\ M_\odot$, thus contributing to about 0.22 WR kpc^{-2}.

We must note that these results on mixing do not at all contradict Conti's evolutionary sequence; on the contrary mixing and mass loss allow the beautiful evolutionary sequence proposed by Conti to occur.

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DISCUSSION FOLLOWING MAEDER

Lortet: It might be one of the main topics for to morrow afternoon general discussion to define provisory families of WR stars, in connection with possible different theoretical scenarios. For instance, WN8 stars probably follow a different evolutionary path compared with WN7 stars.

Maeder: I agree that establishing a correspondence between WR subtypes and evolutionary channels could be an important step in our understanding of WR star evolution. However, the things might not be so simple in the sense that some WR subtypes may contain products of various channels and various initial masses as it is suggested by the large scatter of the observational properties within a given subtype.

Firmani: What initial mass function have you adopted for your statistical estimate?

Maeder: We used the Lequeux IMF. I was pleased to see in your paper with Dr. Bisiacchi that you have a continuous transition in surface abundances. When only mass loss is present this is a rather discontinuous event.