SESSION 7

WOLF-RAYET STARS IN EXTERNAL GALAXIES

Chairman: A.V. TUTUKOV

Introductory speakers: C. FIRMANI
A.F.J. MOFFAT

1. J. BREYSACHER and M. AZZOPARDI: Absolute magnitudes of Wolf-Rayet stars: The WN3 and WN4 sub-classes in the Large Magellanic Cloud.
2. Y. ANDRILLAT, M. DENNEFELD and J.M. VREUX: Near infrared observations of Magellanic WN stars.
3. M.M. SHARA and A.F.J. MOFFAT: The first detection of Wolf-Rayet stars in M 31.
4. I. LUNDSTRÖM and B. STENHOLM: Wolf-Rayet stars in open clusters and associations.
5. J. MELNICK: The Wolf-Rayet stars in 30 Doradus.
6. P.S. CONTI: Spectra of the Wolf-Rayet stars in 30 Doradus.
7. M. ROSA and S. D'ODORICO: NGC 604 - A giant H II region dominated by many WR stars.
8. S. D'ODORICO and M. ROSA: Wolf-Rayet stars associated to giant regions of star formation.
9. J.P. CASSINELLI, J.S. MATHIS and B.D. SAVAGE: The central object of the 30 Doradus nebula, a supermassive star.

OBSERVATIONS AND THE WOLF-RAYET EVOLUTIONARY SCENARIO

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Abstract. Results of a statistical analysis of massive stars and of WR stars show general agreement with the scenario that identifies the majority of the WR stars with the He-burning evolutionary phases. The duplicity, the morphological properties and the galactic distribution of the WR stars are valuable pieces of evidence that suggest correlations between the different WR types and the "channels" defined in the scenario. A rough analysis of the "traffic through each channel" is attempted.

1. WR AND O STARS

Since the researches of Smith (1968, 1973) the relationship between the WR stars with the stellar evolution and galactic structure, appeared as one of the most promising topics for a deeper knowledge of stellar structure and evolution. Further works on the evolution of binary stars (Van den Heuvel and Heise 1972; Tutukov and Yougelson 1973; Van den Heuvel 1976; Vanbeveren et al.1979) and single stars with mass loss (De Loore et al. 1977, 1978; Chiosi et al. 1978) have enriched this field and have permitted to work out a "scenario" that is an attempt to combine in one reasonable and flexible picture a wide range of theoretical and observational knowledge.

The rich compilation of data on WR stars published by Smith (1968a, 1968c) and Van der Hucht et al. (1981) make it possible at present to work out a rough statistical analysis in the solar neighborhood that later will be related to the statistical properties of the massive stars. On the basis of the distances published by Hidayat et al. (1981), with the exception of the WN8 stars (for which we assume $M_V \approx -6$,Conti 1979), a rough estimate of the average stellar density of each spectral type in the solar neighborhood can be made. The result is presented in Table I. For each spectral type the stellar density uncertainty ranges roughly between 30% and 50%; the WN6 spectral type has been subdivided into "early" and "late" groups as will be considered later.

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TABLE I

	WN							WC					
	4	5	6 E	6 L	7	8	9	4	5	6	7	8	9
kpc^{-2}	.08	.12	.10	.16	.18	.14	.02	.08	.30	.08	.22	.35	.25
	WNE .30			WNL .50									
	WN .80							WC 1.28					

The mass range of the WR progenitors can be estimated introducing the evolutionary time fraction corresponding to the WR stage and a reliable space density function in the solar neighborhood. About the WR stage it is interesting to bear in mind the controversy between the "object" and the "phenomenon" interpretation of the WR stars (Thomas, 1968). Many recent works have proposed arguments that support the "object" interpretation (de Loore et al. 1977; Chiosi et al. 1978 and references therein) or the "phenomenon" one (Underhill 1980; Sahade 1981). Unfortunately, the lack of atmospheric models does not permit a definitive choice in this controversy. We will adopt the "object" point of view for which the WR stars are advanced stages of the massive star evolution. On the basis of theoretical considerations, the WR stars can be related to a fraction of the stars in the He-burning phase and a lifetime of roughly 5% of the total evolutionary lifetime can be assumed in agreement with the recent evolutionary tracks (Chiosi 1978; Maeder 1981). For the massive stars the recent estimate of the stellar density function given by Lequeux (1979), has been adopted. From this assumptions it follows that a progenitor mass range: $M \geq 12\ M_{\odot}$ is compatible with the estimated WR stellar density in the solar neighborhood $N_{WR} = 2\ \mathrm{kpc}^{-2}$. Few comments are sufficient to emphasize the contradictory aspect of this result. 1) For the advanced stages of evolution the limit of 12 $M_{\odot}$ defines a magnitude $M_b \simeq -6.5$ that is 1 mag lower than the corresponding magnitude limit $M_b \simeq -7.5$ of the WR stars. 2) the H core mass for a 12 $M_{\odot}$ star is about 2 $M_{\odot}$, too small with respect to the masses of the WR stars ($M > 5\ M_{\odot}$, Massey 1980; van der Hucht et al. 1981). 3) For stars less massive than 15 $M_{\odot}$ the mass loss is insufficient for peeling out the hydrogen rich envelope (Chiosi et al. 1978).

If we compare directly the WR stellar density with the density of O stars $N_O \simeq 20\ \mathrm{kpc}^{-2}$ published by Cruz-Gonzâlez et al. (1974) we see that the major discrepancy is eliminated. This simple remark suggests that an alternative estimate of the space density of massive stars may be a clue to remove the inconsistency previously noted.

The difficulty to obtain space densities for massive stars arises mainly from the necessity to compare O star catalogues, whose completeness is rather good up to 2 kpc, with B star catalogues rather incomplete for the same distance limit. Further, both O and B type stars show inhomogeneities since they are generally found in associations. We will try to estimate new spece densities using a very simple method based on the following hypotheses: 1) The average distribution of the massive stars on the HR diagram is consistent with Humphrey's catalogue for associations (Humphrey 1978). 2) The number of stars in each mass range on the HR diagram can be reduced to a number density comparing the O stars number of Humphrey's catalogue with the O star density published by Cruz-González _et al_. (1974).

We have compared the spectral types earlier than 08 in order to estimate the space density for stars more massive than 60 $M_{\odot}$ and the complete O sample for stars more massive than 20 $M_{\odot}$. This procedure provides a very simple test to estimate and to reduce the effects produced by the different distributions of the stars "in" and "out" of the associations. The result is shown in Table II; the estimated uncertainty is of the order or less than 40%.

TABLE II

$M_{min}(M_{\odot})$	N(kpc^{-2})	5% N(kpc^{-2})
20	40	2.0
30	13.5	0.67
40	6.3	0.31
60	2.24	0.11

On the basis of the estimated stellar density the WR progenitors can be the stars whose masses are greater than 20 $M_{\odot}$. This conclusion is conforting because it removes the contradiction previously noted : 1) The bolometric magnitude corresponding to the advanced stages of the 20 $M_{\odot}$ evolutionary track with mass loss is $M_b \simeq -7.6$, roughly in agreement with the maximum bolometric magnitude of the WR stars. 2) The He-core-mass of a hydrogen shell burning, 20 $M_{\odot}$, star is roughly 5 $M_{\odot}$ in agreement with the minimum mass of the WR stars. 3) 20 $M_{\odot}$ is the minimum mass for which the mass loss is highly efficient to permit the loss of the hydrogen rich envelope (Chiosi _et al_. 1978).

Comparing with other results, our stellar density is between 3 times (20 $M_{\odot}$) and 2 times (60 $M_{\odot}$) that of the Lequeux estimate, and 1.5 times (20 $M_{\odot}$) the result of Miller and Scalo (1979) corresponding to the case b(t)= const. and $T_0 = 12\times10^9$ y.

2. DUPLICITY, MORPHOLOGY AND GALACTIC DISTRIBUTION OF THE WR STARS

Many "channels" have been proposed to produce WR from single stars (Conti 1976; Chiosi _et al_. 1978; de Loore _et al_. 1977, 1978, 1980; Maeder 1980, 1981; Noels and Gabriel 1981; Bressan et al. 1981) and from binary stars (Vanbeveren et al. 1979; de Loore 1980, Vanbeveren 1980). Very briefly we can summarize the main theoretical results with the following scheme.

Single Stars:

H-burning: Because of the high mass loss the nitrogen enhanced chemical composition appears at the surface during the MS evolution, the atmospheric conditions corresponding to this phase can be related to the WR phenomenon. This channel should be particularly efficient for the most massive stars, $M>60,100\ M_\odot$.

He-burning (YSG): For stars roughly between 30 and 100 $M_\odot$ the post MS evolution with mass loss proceeds very rapidly towards the red part of the HR diagram. The mass loss produces the helium ignition at low effective temperature when the mass loss (acustic flux?) is very efficient. During this phase the fractional mass of the hydrogen rich envelope is rapidly reduced below 0.6. This fact does not permit the star to continue toward the red supergiant zone of the HR diagram, but reverses the evolution towards high temperatures, during which the nitrogen enhanced chemical composition appears at the surface. Briefly we will call this channel post yellow supergiant phase.

He-burning (RSG): For less massive stars, possibly between 20 and 30 $M_\odot$, the evolution can proceed in a very similar way as in the previous case, but the star is able to spend an appreciable fraction of the helium burning lifetime in the red supergiant phase.

Binary Stars

The mass transfer in this case can play a very important role. If the supernova explosion of the primary star does not disrupt the system the WR phase can appear twice, the first corresponding to a WR+OB system, the second to a WR + collapsar runaway system. With the aim to analyze the "traffic through each channel" it is interesting to note few aspects related to the spectral types and the duplicity. Moffat (1980) analyzed the mass ratio of the double line WR binary stars. The main conclusions can be summarized in the following three points. 1) The early WR spectral types are roughly characterized by masses smaller than the ones of the late spectral types. 2) The masses of the WC stars are similar to those of the early WN stars (WNE). 3) The early spectral types (WN3, WC4) are more frequent in systems where the metallicity is low (LMC, SMC).

Figure 1 summarizes the most recent information about the duplicity of WN stars, and permits to make a simple analysis relating spectral types, duplicity and galactic distribution. The WN4-5 stars brighter than 10 mag are all single or double line binaries; the WN6 stars are also binaries if we consider that HD 191765 shows very clear spectrophotometric variability and a probable period (Bisiacchi et al.1981).

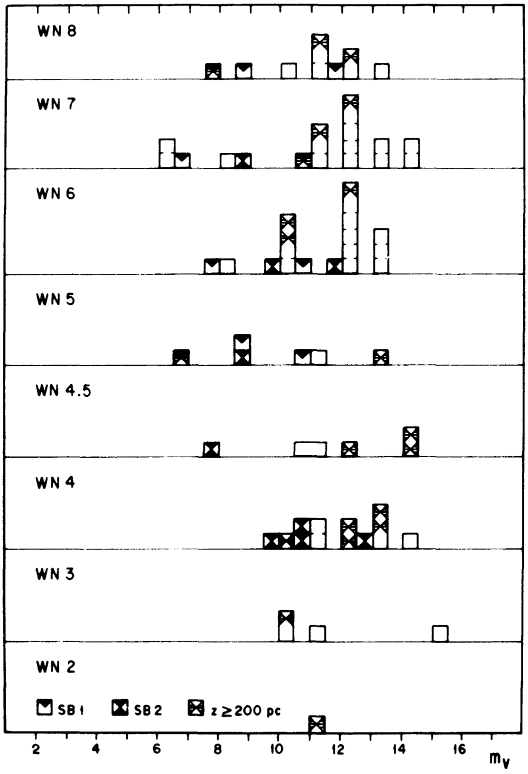


Figure 1. The duplicity and the distance from the galactic plane for each WR star are shown. The data are from the Sixth Catalogue (Van der Hucht et al. 1981) and recent unpublished observations.

The WN7-8 stars on the contrary show a rather normal duplicity. Between 10 an 11 mag the information on the duplicity is rather incomplete, the majority of the WN3-5 stars is binary or high above the galactic plane, which is an evidence that supports a runaway SB1 nature. The exceptions are: HD219460 (WN4-5) that shows a composite spectrum but its duplicity is subject to discussion; HD104994 (WN3) for which a careful spectrophotometric analysis should be highly desirable. The WN6 stars show one SB1, two stars high on the galactic plane and two single; of these, HD165688 is a good candidate to be SB1. Of the two WN7-8 stars one is a runaway SB1 and the other, single. The information on the duplicity of star fainter than 11 mag is highly incomplete. However, it is interesting to note that the WN2-5 stars show a distribution either far from the galactic plane, evidence of a runaway SB1 nature, while the WN6 stars show a distribution close to the galactic plane, as do also the WN7-8 stars. Summarizing, observations seem to lead to the following conclusions.

1. The WNL (>6) stars show a normal (possible low) degree of duplicity; the small number of WNL stars high on the galactic plane supports this conclusion.

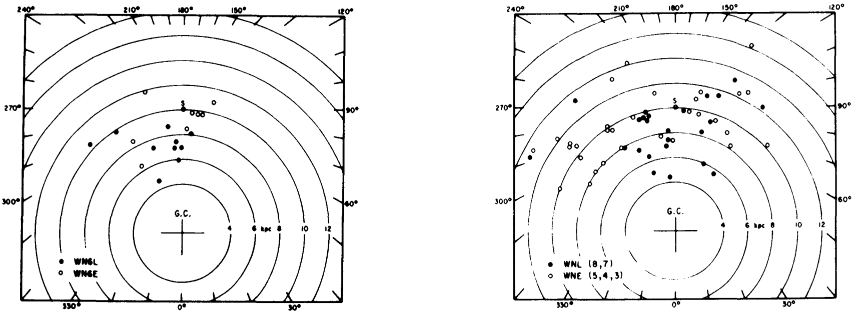
2. The WNE (<6) stars show a very high degree of duplicity; the fainter stars are far from the galactic plane in agreement with the possibility that they are WR + collapsar runaways.

3. The WN6 sample appears as the combination of two groups: E) The stars brighter than $m_V \simeq 12$, that appear to be binaries, high above the galactic plane, and that show high galactocentric distances; L) the stars fainter than $m_V \simeq 12$, that appear single, are close to the galactic plane, and show small galactocentric distances.

The galactic distribution of the WNE and WNL stars shows that the latter tend to be closer to the galactic center than the former. In Figures 2 and 3 the galactic distribution of each WN group is shown. Considering all these pieces of evidence it would appear reasonable to associate group E) with the WNE sample and group L) with the WNL.

New observations with the Lick 1-meter telescope and the IDS spectrophotometer carried out in collaboration with J. Wampler confirm the existence of two groups for the WN6 stars for a sample in the range of 0< ℓ^{II}< 90°complete up to $m_V \simeq$ 14. The WN6L stars show sharp lines similar to the WNL, while the WN6E show lines similar to HD 50896 and HD 192163. Our preliminary conclusion is that the WN stars appear distributed into two sequences or possibly three.

I) The WNL sequence with sharp lines that extends until WN6.



Figures 2 and 3. The galactic distributions of the WN6L and WN6E stars as discussed in the text. For comparison diagrams are shown separately for the WNL and WNE stars.

II) The WN6 and the WNE with broad lines and with the tendency to be SB1.

III) The WNE stars with intermediate broad lines that show a small ratio line continuum, evidence for a massive companion.

In Figure 4 we show the three blends: NV λλ4692-21 and N III λ4642 as well as He II λ4686; the spectra are labeled with the numbers of The Sixth Catalogue (Van der Hucht et al. 1981). Other interesting remarks related to these observations are as follows: 1) Among the WNL stars we observed an inhomogeneous hydrogen abundance; stars 120 and 123 show a strong deficiency of hydrogen and it is interesting to note that these stars have also small galactocentric distances. 2) We suspect that the WNL stars closer to the galactic center (e.g. HDE 318139-100) show broader lines than the others. These pieces of evidence are consistent with the fact that the WR stars closer to the galactic center show a more intense atmospheric activity.

It is important to emphasize that this discussion is based on very limited observational information; further work should be highly desirable.

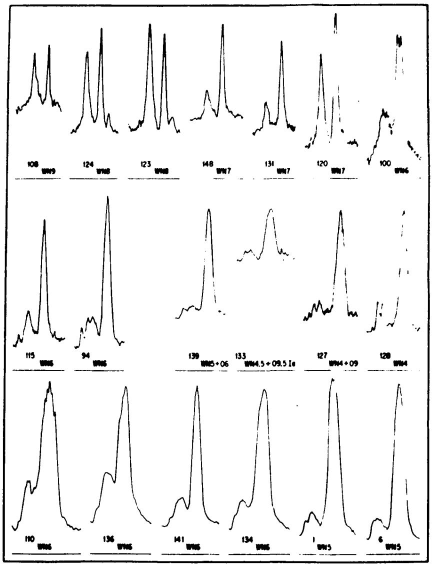


Figure 4. The NV λλ4602-21, the N III λ4642 and the He II λ4686 blends are shown for a sample of WN stars. The spectra are labeled with the number of The Sixth Catalogue (Van der Hucht et al. (1981).

The progenitors of the WNL stars have to be considered among the most luminous stars. On the basis of the space density defined earlier, the mass for the WNL progenitors has to be roughly $M > 30\ M_\odot$, if the WNL are He-burning stars (5% of the H-burning lifetime), or $M > 60\ M_\odot$ if they are H-burning stars (20% of the H-burning lifetime). The two channels in principle are possible. The models that include overshooting and diffusion (Maeder 1981; Bressan et al. 1981) are particularly interesting. The evolutionary tracks for stars with mass greater than 60 $M_\odot$ show that the nitrogen enhanced chemical composition produced by the CNO cycle, can appear on the surface before the exhaustion of the hydrogen at the centre. These models are extremely interesting and may explain the early O supergiants and the early ON stars (Bisiacchi et al. 1979, 1981). Concerning the possibility to produce WNL stars through this mechanism the following remarks can be made. 1) The morphological continuity from O to WNL stars is not completely clear. 2) The statistical continuity is poor. 3) The maximum WNL bolometric magnitude is $M_b = -8.5$, compatible with a 30 $M_\odot$ evolutionary track and not with one of 60 $M_\odot$. It appears very reasonable to interpret the supermassive WR stars associated with the giant H II regions as H-burning stars with $M > 100\ M_\odot$ (D'Odorico and Rosa 1981; Conti and Massey 1981). In this case the vibrational instability together with the overshooting can play a very important role (Maeder 1980). These considerations appear to provide enough evidence to support the idea that single WNL stars can be produced through the "YSG channel" and marginally through the "RSG channel".

The information about the WC stars is rather incomplete as compared with that of WN stars. Figure 5 has been made for the WC stars with the same criterion as in Figure 1.

As an immediate consequence we note that the frequency of the binary stars among the WC appears low. If we consider that the width

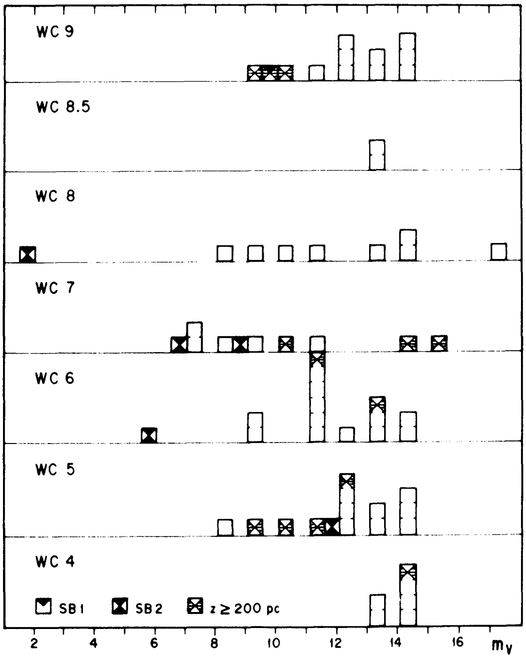


Figure 5. The binarity and the high on the galactic plane for each WC star are shown. The data are from the Sixth Catalogue (Van der Hucht et al. 1981).

of the lines make it difficult to detect binarity, a normal duplicity similar to that of the WNL stars is not impossible. From a morphological point of view the line/continuum ratio for the majority of the stars appears high with respect to the known binary systems and the time variability for the spectral line profiles tends to be smaller than for the WNE stars. A very well defined spectral sequence describes the majority of the stars; only few stars show rather broad lines in such a way that a parallel sequence is suspected. It is interesting to note also that the low binary frequency appears at the same time as the fraction of stars far from the galactic plane is rather small, particularly for the late spectral types, while the galactic distribution appears concentrated toward the galactic centre,specially for the late spectral types,in a similar way as for the WN single stars.

These properties support the idea that a "single star channel" produces WC stars. Considering the luminosities and the space densities of the WR stars, the WC phase related with this channel is probably more prominent than the WN phase. On the basis of the space density for massive stars, we are tempted to suggest that a "single WC star channel" can be related with the progenitors whose masses are in the range of about 20 to 30 $M_\odot$.

Few interesting points can be raised. The average absolute magnitude of the WC stars is $M_V \simeq -4.8$ and considering a BC$\simeq$ 3 we obtain $M_b \simeq -7.8$. This agrees with the advanced stage luminosity for the 20-25 $M_\odot$ evolutionary tracks (RSG channel, Maeder 1981). In the range 20 to 30 $M_\odot$ the number of RSG stars in the solar neighborhood is comparable with the number of WC stars. This is another evidence that supports the previous estimate of the progenitor mass range independently from the assumed stellar density function. The "RSG channel" has to be rather sensitive with respect to the mass loss. If we accept that the mass

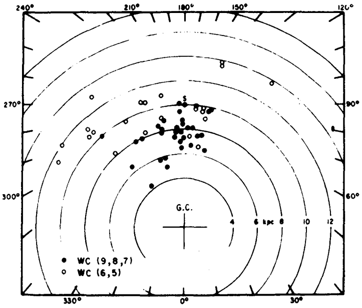


Figure 6. Galactic distributions of the WC (9,8,7) and WC (6,5) stars.

loss increases with metallicity, the concentration of the WC stars toward the galactic centre, as one can appreciate in Figure 6, can be easily explained. Finally, some dependence of the masses and the structures of the He-and C-rich nuclei on metallicity has to exist in order to favour the early spectral types (Moffat 1980) where the metallicity is lower. But one must not forget that also the "binary star channel" leads to the WC stars. Through this channel probably the WN phase is competitive with the WC phase, as the SMC appears to show. It is also necessary to emphasize that the old disk population O stars seem to be more abundant than normally thought; thus some WC stars (WN also?) may follow suit.

A particular attention has to be devoted to the binary systems. The high frequency of binary stars among the WNE stars supports the binary evolutionary scenario for which the main products of the evolution are hydrogen poor WR phases (de Loore 1980; Van Beveren 1980). The luminosity of the WNE stars corresponds to $M_b \simeq -7.5$, this suggests that the bulk of the WNE binary stars has progenitors between 20 and 40 $M_\odot$. The high efficiency of the mass loss mechanism makes the WNE lifetime longer than for single stars, and WC stars easier to be produced. Perhaps the observed low frequency of binary WNE stars with masses between 5 and 10 $M_\odot$ implies a short lifetime of the WNE phase when the progenitor masses are between 20 and 30 $M_\odot$, this is quite in agreement with the idea that the main product of the RSG channel are WC stars. It is possible that the WR spectral type in binary systems is related to their orbital parameters. Smith (1973) has suggested that the WC types are favoured when the separation is large. If we compare the WNE and WC binary periods the tendency of the WC periods to be greater than that of the WNE is remarkable. The only exception is HD 190918; this could be interpreted more in terms of a specific evolutionary phase, rather than of a binary mass transfer. Unfortunately the analysis of the orbital elements in the WR binary stars is affected by several factors that introduce a high degree of uncertainty. For example, the radial velocity curve of the WR component can be strongly affected by the profile deformations, the companion may be overluminous, and the orbital inclination angle in many cases is unknown. As a consequence mass estimates are rather uncertain and therefore the arguments presented above have to be considered only qualitative. With respect to the "single" WNE stars it is interesting to note that the majority are located far from the galactic plane, highly variable in their spectral line profiles, and in many cases the variability appears related to a very well defined period and with spectral variations similar to those of HD 50896 (Firmani *et al*. 1979; Firmani *et al*. 1980). These pieces of evidence support the suggestion that the majority of the "single" WNE stars are binaries with collapsed companions, for which the spiral-in mass loss mechanism could have played an important role. Recently the analysis of the period of HD 50896 (3.7^d, Firmani *et al*. 1979) has shown a variation, $\dot{p}$= -180 s/y (Moffat 1981; Moffat *et al*.1981). A simple interpretation of this is that in 2000 y the collapsed companion of HD 50896 will fall on the WN5 component and one explosion similar to a SN event could happen. This fact opens the possibility that some of the WN + collapsar systems will shrink, producing a SN by collision. This phenomenon can in part explain the apparent scantiness of the WC + collapsar stars.

3. WR STARS AND METALLICITY

The peculiar distribution of the different WR spectral types in the Galaxy can be related mainly to the stellar formation rate or to the metallicity of the different regions. At present it is rather uncertain whether the star formation rate is different or not in the Galaxy, the LMC and the SMC. Studies carried out by Vangioni-Flam *et al*. (1980) and Dennefeld and Tammann (1980) seem to show that the stellar formation rate is rather similar in the three galaxies, but some criticism has been advanced by Bertelli and Chiosi (1981). Until more information is available this argument will be a matter of controversy.

A comparison of the distributions for different O-stars groups in the Galaxy permits to test the relative influence of the stellar formation rate and the metallicity on the HR diagram. A very simple test is shown in Figure 7. Here the ratio of space densities, estimated up to 1.5 kpc from the Sun, versus galactic longitude has been represented. The estimates refer to sectors of 60° in ℓ^{II}; in Figure 7 we define the main sequence stars earlier than O8 as OV E. The stellar density ratio O V E/O V shows a rather constant distribution that suggests a rate of star formation isotropic around the Sun. The space density ratio O I/O V shows a very high anisotropy toward the ga-

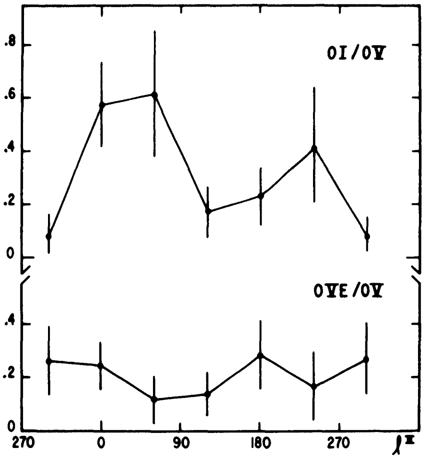


Figure 7. Ratios between the OI and OV stellar densities and between the OV E and O V stellar densities, estimated at 1.5 kpc far from the Sun on each 60° arc-sector of ℓ^{II}. O V E means main sequence O stars earlier than O V 8. The uncertainty is assumed on the basis of a normal distribution.

lactic centre. Bisiacchi et al. (1978, 1980) have suggested that this reflects the influence of the metallicity on the mass loss in the sense that a higher metallicity increases the mass loss and consequently decreases the surface gravity. Some kind of influence of the metallicity on the stellar structure (e.g., overshooting) cannot be ruled out.

This interpretation is qualitatively consistent also with the red supergiant galactic distribution. From Humphrey's catalogue (1978) the ratio, red supergiant density/OB supergiant density, estimated for $M_b<-6$, is 0.02 in the Sagittarius arm, 0.06 in the local arm, and 0.15 in the Perseus arm. Where the metallicity and the mass loss are smaller, the time spent by the star in the RSG phase is shorter in agreement with the evolutionary tracks with mass loss (Chiosi et al. 1978, Maeder 1980).

On the basis of similar arguments Maeder et al. (1980) point out one anticorrelation between WR and RSG in the Galaxy and in the MC's, whereas Bisiacchi and Firmani (1980) emphasized the correlation between O supergiants and WR in the Galaxy.

We will try to explore this effect in more detail with respect to the three systems, the Galaxy, the LMC and the SMC. We will distinguish the WC from the WNL case and also we will try to eliminate the cases where the mass transfer in binary systems may have played an important role. The catalogues published by Russeau et al. (1977) and Azzopardi and Vigneaux (1975) are being used for the LMC and SMC respectively. For the WR stars we considered the paper of Vanbeveren and Conti (1980) and references therein.

TABLE III

	sample 100 stars M>20			sample 100 stars M>30		
	WC	RSG (20-30)	YSG (20-30)	WNL	RSG (>30)	YSG (>30)
G	3	2·4	5:	4·2	4	4
LMC	.7	4·4	—	3·5	5	5
SMC	0	—	—	0	5:	9

Table III shows the results. We considered a sample of 100 stars with masses greater than 20 $M_\odot$ for the WC case, and a sample of 100 stars with masses greater than 30 $M_\odot$ for the WNL case; in this way the numbers give directly the percentage of the total lifetime spent in each phase. We tried also to estimate the numbers of the stars (YSG) later than B5 and earlier than the red supergiants, in order to include in Table III the majority of the He-burning stars and to exclude the contribution of the H-burning stars. In the WC case we introduced only the RSG and YSG with masses between 20 and 30 $M_\odot$. Where the selection effects are considered important the numbers have been omitted. A future work will try to improve these results.

The main conclusion from Table III can be summarized as follows: 1) The number of the WR stars is of the same order as the number of the other He-burning stars with the same progenitors. 2) From the Galaxy to the LMC the WC number decreases and the RSG number increases. 3) From the Galaxy through the LMC the WNL number decreases, meanwhile the RSG and YSG numbers increase and the sum is rather constant. 4) In a general sense the fraction of the He-burning stars roughly agree with the evolutionary times. 5) This behaviour is qualitatively similar to the one obtained from the comparison of zones of the Galaxy with different metallicity.

4. CONCLUSIONS

There exists a general agreement between 0 and WR stars by number. The masses involved for the WR progenitors have to be greater than 20 $M_\odot$. For this to occur it is necessary to introduce a new stellar density function for the massive stars.

The WNL and WC stars have to be produced mainly through single star channels. If the WR phenomenon is related to the He-burning evolution a rough estimate of the progenitor mass range is $M > 30\ M_\odot$ for WNL stars and $20\ M_\odot < M < 30\ M_\odot$ for the WC ones. The possibility that WNL are H-burning stars has been discussed and the conclusion is that only a minor fraction of the most luminous stars can evolve through this phase. A transition through a WN phase previous the WC phase is possible but has to be very fast and probably related with hydrogen poor WN stars.

The WNE stars have to be produced mainly through a binary star channel whose progenitor mass range is $20\ M_\odot < M < 40\ M_\odot$. A fraction of the WNL and WC stars can also be related with this channel in the sense that mass transfer could have played an important role. It is possible that the WR spectral type in binary systems could be correlated with the orbital parameter as also with the specific evolutionary phase of the star. Further observations are necessary to improve this analysis.

The zones of high metallicity are related to a high atmospheric activity, a high efficiency of the single star channels and a tendency to produce later WN and WC spectral types.

As a concluding remark, we may add that the observations seem to confirm rather well the scenario discussed earlier, but extensive observational work is needed. Some crucial points related to the evolutionary tracks have to be clarified, in particular the post red supergiant phases. Above all further theoretical work has to be devoted to atmospheric models.

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DISCUSSION FOLLOWING FIRMANI

Chiosi: I have one comment. I like the scenario you have proposed in the sense of internal consistency. You did not mention a point I consider rather important. In order to get the scenario one has to use a certain amount of mass loss during the hydrogen and helium burning phases. If we adopt the rates of mass loss that one estimated for WR stars in general then these rates and the lifetimes that are involved in the helium burning phase are such that a lot of material has to be lost. There are only few computations leading to the WC stage, and they were stopped at the middle of the core helium burning phase because, if they were continued till the end, no remnant would be left.

Firmani: The evolution during helium burning is not very well known. So the theoretical explanation for the WN and WC stages is already difficult.

Abbott: Generally it is assumed that the helium burning phases last roughly for about 10% of the hydrogen phase. You use 5%. How does this effect the general conclusions?

Firmani: On the base of evolutionary tracks I was convinced that not the total helium burning lifetime corresponds with the WR phase. Therefore in my opinion 5% is a reasonable fraction, perhaps even a little high because red supergiant statistics and WR statistics support this assumption.

Conti: As Dr. Garmany showed very briefly yesterday we came to the same conclusion about that large number of higher mass stars. This conclusion does not depend at all seriously on the effective temperature scale unless the effective temperature scale is in error by much more than 10%, which is improbable. You come then unescapably to the conclusion that the number of massive stars is somewhat more than expected, given the present data in the literature on the initial mass function.