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THE WOLF-RAYET STARS

(Invited Paper)

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RESUMEN

Se discuten algunos aspectos de la problemática de las estrellas Wolf-Rayet relacionados con su composición química, estado evolutivo y la dicotomía aparente en dos secuencias espectrales.

ABSTRACT

Aspects of the problems of the Wolf-Rayet stars related to their chemical composition, their evolutionary status and their apparent dichotomy in two spectral sequences are discussed.

Key words: STARS-WOLF RAYET – STARS-BINARIES – STARS-EVOLUTION

I. GENERAL CHARACTERISTCS

I propose to discuss in this invited talk only a few aspects of the problem of the Wolf-Rayet stars which are relevant because of some recent results and because of the trend in today's research on the subject.

To start let me remind you that Wolf-Rayet spectra are characterized by the fact that they display *broad emission lines,* which could be as broad as 100 A, and represent a *wide range of excitation and ionization.* Moreover, *the excitation level of the line spectrum is generally much higher than that of the continuum.*

The Wolf-Rayet spectra are also characterized by correlations that are related to the widths of the lines. These well known correlations can be briefly stated as follows:

a) *The higher the ionization, the narrower the line.*
b) Among the WC's, *the earlier the subclass, the broader the emissions.*

Since I have utilized the label WC perhaps I should recall the dichotomy that appears to exist among Wolf-Rayet spectra and led Beals to propose in 1935 two sequences in the classification scheme of the objects, namely, the WN and the WC sequences. The two sequences came about because it was noticed that when N was present in the spectrum, C and O were apparently absent, and viceversa. Actually, it is now clear that, in the two sequences, the presence of an element like N or C does not exclude the presence of C and O or of N; only the relative strengths are different (cf. Sahade 1980*a*).

What I have already mentioned does not give the complete characterization of Wolf-Rayet spectra. As we know, in the extended electron envelope that surrounds Wolf-Rayet stars, the *excitation temperature* at least in the region responsible for the photographic spectrum *decreases outwards* and the *matter accelerates outwards.* The second variation law describes the type of velocity field that we have and implies an inverse correlation between the radial velocities and the excitation potentials of the upper level of the lines, if we are considering violet absorption borders.

To complete the picture I should perhaps add that I have suggested (Sahade 1980*b*), from ultraviolet data, that the extended electron envelope that surrounds Wolf-Rayet stars is a sort of a chromosphere-corona formation with two maxima of the excitation temperature T_e, one of them located very close to the stellar surface and the other one located at a certain distance from the star, beyond the zone where the diluted lines of He I, that are present in Wolf-Rayet spectra, originate. Willis (1980) has contested the existence of a second T_e maximum because he believes that the excitation conditions are frozen throughout the extended envelope and, therefore, that the fact that we see higher excitation lines arising closer to the star is just a reflection of optical depth effects in the winds. Such a belief does not seem to be supported by the observational evidence. Moreover, to interpret the behavior of lines arising in the outer layers of the extended envelope one should not forget that the outward velocity at some point will cease to increase.

II. CURRENT "DOGMAS" ON WOLF-RAYET STARS

When discussing Wolf-Rayet stars and trying to understand them from an evolutionary point of view there are some strong beliefs or dogmas that are

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considered as the pillars of such discussions and considerations.

a) *Typical or "Canonical" mass*

Because of the fact that for years the best studied Wolf-Rayet star was V444 Cygni, a WN5 + O6 close binary system, that yielded a mass of about 10 $M_\odot$ for the WN5 component, we were led to the belief that such a figure represented the normal or typical mass for a WR star. However, a recent study of γ^2 Velorum (Niemela and Sahade 1980) that suggested a minimum mass of 17 $M_\odot$ for the WC8 component gave a warning against such a practice. Other large masses were subsequently found and the whole available material led Sahade (1980*a*), Massey (1980*a*) and Niemela (1980) to state that there is no such thing as a typical mass for a Wolf-Rayet star. Moreover, there seems to be no one-to-one relationship between mass and WR subclass (Sahade 1980*a*; see also Massey 1980*a*).

Table 1 illustrates the present situation in regard to the masses of Wolf-Rayet stars.

b) *Chemical Composition of Wolf-Rayet Stars*

Because of the apparent lack of H lines in the spectrum, it is generally believed that we are actually dealing with H-deficient objects, that is, with objects that are in the stage of releasing energy from He-burning in their cores.

In regard to this belief, I would like to point out a few facts. First, that H is present in absorption and in emission in a number of WR objects. Table 2 lists the cases that are available in the literature. The H absorptions that are observed in the photographic region originate in the photosphere of the star, while the emissions should arise in the extended envelope. The first statement results from the examination of the location of the values from H on the plot of the radial velocities from absorption lines and violet absorption borders against the excitation potential of the upper level of the line (Sahade 1980*b*). As for the emissions in the photographic region the detection technique consists of plotting the flux of the Pickering lines versus the principal quantum number of the upper level of the transition (Smith 1973; Underhill 1980*a*). Another evidence for the presence of H in emission, in the spectrum of γ_2 Velorum, for instance, is the fact that the V/R variations of the emission features that were found at the position of the Balmer and He I lines were not present in He II (N. de Monteagudo and Sahade 1970, 1971; Niemela 1973).

The information that refers to the ultraviolet has been recently provided by Willis (1980) from *IUE* high resolution material on seven WN and three WC stars: the conclusion that Ly-α is present at 1215 A in the stars that are so indicated in Table 2 comes from the fact that

TABLE 1

BINARIES WITH WOLF-RAYET COMPONENTS (MINIMUM MASSES)

HD or MR	Star	Spectral type	P (days)	$\mathcal{M}_W \sin^3 i$ ($M_\odot$)	$\mathcal{M}_O \sin^3 i$ ($M_\odot$)
63099	···	WC+O7	14.7	5	19
113904	θ Muscae	WC6+O9.5/B0 Iab	18.3	(0.4)	(10.5)
152270	···	WC6−7+O5	8.8	2	5
97152	···	WC7+O7 V	7.9	4	6
193793	···	WC7+O5	?	–	–
68273	γ_2 Velorum	WC8+O9 I	78.5	17	32
168206	CV Serpentis	WC8+O8−9 III−V	29.7	11	22
94546	···	WN4+O7	4.9	8	23
193576	V444 Cygni*	WN5+O6	4.2	9.5	24
90657	···	WN5+O6	8.2	9.5	22
190918	···	WN5+O9.5 I	112.8	0.7	3
MR 114	CX Cephei*	WN5+O	2.1	5	12
186943	···	WN5+O9 V	9.6	9	19
193928	···	WN6	21.6	–	–
211853	GP Cephei*	WN6+O	6.7	25:	40:
311884	MR 42	WN6+O5 V	6.3	> 40	> 47
192163	···	WN6	4.5	–	–
214419	CQ Cephei*	WN7+O?	1.6	23	19
MR 111	···	WN7	22.1	–	–
92740	···	WN7	80.3	64:	24:
228766	···	WN7+O7.5 I	10.6	–	–
197406	···	WN7	4.3	–	–

* Eclipsing variable.

TABLE 2

PRESENCE OF H IN WOLF-RAYET SPECTRA

		Absorption		Emission		
HD or MR	Sp	Pg	UV	Pg	UV	IR
MR 119	WN8			*		* (P_γ)
96548	WN8	*	*		*	
177230	WN8	no				*
92740	WN7	*	*		*	
93131	WN7	*	*		*	
93162	WN7	*				
151932	WN7		*	*	*	
191765	WN6		*	*	*	*
192163	WN6		*	*	*	*
193077	WN5	*		*		*
187282	WN4			*		*
9974	WN3	*		*		
68273=γ_2 Vel	WC8			*		#(P_β)
192103=V1042 Cyg	WC8		no	*	no	*
156327	WC7	*				
192641	WC7	*				*
183793	WC7	*				*
165763	WC5		?		?	*
MR 89	WN7					*
228766	WN7					*
197406	WN7					*
214419=CQ Cep	WN7					*
165688	WN6					*
211853=GP Cep	WN6					*
4004	WN5					*
193576=V444 Cyg	WN5					*
193928	WN5					*
MR 114=CX Cep	WN5					*
190918	WN4.5					*
219460	WN4.5					*
186943	WN4					*
211564	WN3					*
MR 82	WC9					*
MR 90	WC9					*
168206=CV Ser	WC8					*
190002	WC7					*
16523	WC6					*
17638	WC6					*
165763	WC5					*
169010	WC5					*
195177	WC5					*
213409	WC5					*
In LMC: 4 WN7, 2 WN8, 2 WN9				*		

e correlation diagram between radial velocity and citation potential of the line only holds if one assumes at the element present H and not He II.

The observation of Paschen lines in emission has been ported, in the case of γ_2 Vel, by Barnes, Lambert and tter (1974) who did high resolution spectral observations with a Michelson-type interferometer in the interval 0.9-1.7μm and detected the presence of $P\beta$. The rest of the infrared observations listed in Table 2 are due to Kuhi (1968*a*), who carried out photoelectric measurements of the intensities of strong infrared lines, among them $P\gamma$.

We can, therefore, conclude that at least some H is present in the spectrum of a number of Wolf-Rayet stars of both sequences.

Secondly, we do not normally observe photospheric lines in Wolf-Rayet stars and, when we see them, like those of H, then they are weaker than expected. Now, the emission line profiles in Wolf-Rayet spectra do suggest that the envelope is opaque in the lines, and, therefore, it seems logical to conclude that it is the opacity of the envelope that prevents us from "seeing" through it and observe lines that are formed in the photospheric layers (Sahade 1980*b*). Very recently, Massey and Conti (1981*a*) have investigated the spectrum of "the WN8 standard star HD 177230" and have remarked that "the WN5 star HD 193077 [the same is true in the case of the WN3 object HD 9974 (Massey and Conti 1981*b*)] was shown to have a thin envelope, and still have an appreciable amount of hydrogen present" while the WN8 star HD 177230 have "a thick envelope, no detectable hydrogen and no photospheric absorption lines". Massey and Conti preferred to interpret the different behavior of the two stars in terms of their ideas on the evolutionary history of Wolf-Rayet stars, but to me an obvious possible conclusion of their results is exactly what I had argued in order to explain the weakness of the photospheric lines, when present, or their absence. Moreover, the fact that HD 177230 displays Pγ in emission, also invalidates Massey and Conti's argument.

In short, the evidence is that the chemical composition of the WN and WC stars does include H. The question is then whether or not the composition is "normal". And now we come to our third point, that of the abundance determinations in Wolf-Rayet stars. I do not think we could derive meaningful photospheric abundances because the envelope is thick in the lines; moreover, the absorptions that are normally seen do not arise in the photosphere but are violet absorption edges of the emission lines that originate in the extended envelope. Neither we could derive abundances from the emission lines because of the fact that the envelope is characterized by a velocity law, an excitation temperature law and a density law, and we do not know as yet how these parameters vary with distance to the star nor at which distances from the star the regions where each line is formed, are located.

Regarding the presence or absence of H emission arising in the extended envelope, the fact that there are two maxima of T_e makes it possible to conceive a structure of the envelope such that H lines would not necessarily be formed. In this context, let us mention that Willis (1980) states that the lack of H in HD 50896 (WN5) may be the result of an ionization effect because no low ionization elements are observed either.

Lastly, I should recall that Underhill (cf. 1973) has been always skeptical about the question of the H-deficiency of Wolf-Rayet stars, and lately Underhill (1980*a*) has stressed the fact that the location of the Wol Rayet stars in the H-R diagram corresponds to tl region of the stars that are in the stage of H-burning their cores.

So, in regard to the second dogma, at least we oug to be cautious and not state so firmly that Wolf-Ray stars are H-deficient objects. After the exercise obtaining abundance figures by considering that tl Wolf-Rayet envelopes are completely transparent in tl lines, Ambartsumian (1958) warned that "the estima made above of the relative abundance of hydrogen ar helium in the atmospheres of Wolf-Rayet stars is rath rough, since it does not take into account the possib opacity of the envelopes of Wolf-Rayet stars to radiatic in the lines of the subordinate series of the ator concerned, or of certain other factors."

c) *Evolutionary Considerations*

Since the "second dogma" I have just discussed h been considered for the last four decades or so as a so of an established, unquestionable fact, practically evolutionary considerations are based on such a premis

Currently, it is believed that massive close binari evolve into Wolf-Rayet binaries which, in turn, are tl ancestors of massive X-ray binaries (van den Heuv 1973), and that the Wolf-Rayet component of tl former becomes, after a supernova explosion, the cor pact component of the latter, the companion being OB supergiant. Further evolution would lead to a secor Wolf-Rayet stage, where we would have a short peric binary combining a Wolf-Rayet star and a compa neutron star (de Loore *et al.* 1975). This picture, whic identifies helium stars with Wolf-Rayet stars, is su plemented by the scheme that Conti (1976) suggested the 1975 Liège Colloquium, namely, that "O sta become Of stars if they are sufficiently massive ar luminous and a substantial wind begins to blow... moreover, Of's would become first the so-called "tran tion objects" between Of's and WN's and then, succe sively, late WN's, early WN's and, eventually, WC which are considered to be in a more advanced stage evolution.

On the picture that I have described very concisel the two sequences are understood as arising because tl large mass loss that the objects are supposed to ha undergone, have brought up to the surface material fro the core, where the CNO cycle would be at work in W stars, thus accounting for the "N overabundance", ar the triple-alpha process would be at work in WC sta thus accounting for the "C over-abundance".

As I have mentioned, in the whole picture, heliu stars that result in the course of the evolution of tl more massive component of the assumed initial systen are identified with Wolf-Rayet stars. It seems to me th by doing this we are not stepping on solid ground, f three reasons, namely.

1. As I have already shown, it is far from certain that /olf-Rayet stars are He stars.

2. Even if they were, it does not seem reasonable to ssociate outrightly He stars with Wolf-Rayet stars ecause stars are not only defined or characterized by heir chemical composition.

3. As Niemela (1979) has remarked, if WC stars are howing in their surfaces the products of He-burning, we /ould not be finding any H in their spectra.

As I said at the meeting held in Trieste last September would feel happier if, in all the evolutionary considera-ions that are made, the word "if" is used in the ppropriate places.

In regard to Conti's scheme, I am not certain that it inds support in the observational facts. Niemela (1979), or instance, has pointed out that if WN's evolve into VC's we must not find WC stars that are much more nassive than the WN's; in addition, Massey and Niemela 1980) have stressed the fact that "the masses known for VC stars are not significantly lower than those for WN tars". Actually, the values of the masses and of the radii hat have been determined for the O as well as for the Volf-Rayet stars do not seem to lend support to the vhole evolutionary scheme that is being accepted Sahade 1980*a*; Sahade and Zorec 1980).

One of the arguments that have been mentioned ately in support of the suggestion that O stars evolve nto Wolf-Rayet objects is the frequency of binaries mong the two types of objects. Massey *et al.* (1980) tate that "the total percentage of WR binaries (includ-ng those with collapsed companions) may be $\leq$ 50%, he same as found for O stars" by Garmany *et al.* (1981). Such a percentage, however, is what is consid-ered as the "normal" percentage of spectroscopic bina-ies along the main sequence (cf. Batten 1973).

d) *"Second Wolf-Rayet Stage"*

Going back to the evolutionary history that starts with massive close binary system, one feature that arose mmediate attention and interest is that of the "second Volf-Rayet stage ". In this stage we are supposed to have short period single-lined binary. This binary may be ocated at some distance from the galactic plane, due to he recoil velocity of the system in the case of an symmetric mass ejection produced by a supernova xplosion that did not disrupt the physical system of the wo stars. A hasty search for possible candidates and an nalysis of them began immediately. Moffat and Seg-gewiss (1980) have produced a list of 20 likely "runaway VR candidates" and already 6 of them –as far as I am ware– have been reported as Wolf-Rayet binaries with possible compact companions. These six objects are: HD 50896 (WN5), HD 96548 (WN8), HD 164270 WC9), HD 192163 (WN6), HD 193077 (WN5 or WN6), nd HD 197406 (WN7).

The first object of the list was announced as a 3.76-day binary by Firmani *et al.* (1979), on the basis of periodic profile variations found on spectra taken with high signal-to-noise ratio. The principle used was similar to the one that had been suggested by N. de Monteagudo and Sahade (1970, 1971) to detect binaries among Wolf-Rayet stars. Further work on HD 50896 has been done by Firmani *et al.* (1980).

HD 96548 has been investigated by Moffat and Isserstedt (1980); HD 164270, by Isserstedt and Moffat (1980) and HD 192163 by Koenigsberger *et al.* (1980), as quoted by Lamontagne *et al.* (1980). HD 193077 has been discussed by Massey (1980*b*) who concluded that it is probably a single WN5 star, although the possibility of "a binary system with a highly eccentric orbit or an extremely long period cannot be completely excluded". The new discussion of HD 193077 by Lamontage *et al.* (1980) suggests that it is probably a triple system formed by a close pair, with a WN6 object and a neutron star as components, and an O main sequence star. In regard to HD 197406, a single-lined WN7 binary inves-tigated by Bracher (1966), it has been postulated as a Wolf-Rayet binary with a compact companion by Moffat and Seggewiss (1979*a,b*).

Let me make some comments in regard to these objects and the interpretation of the results. In the first place, I should say that it is extremely desirable to make an effort to try to ascertain whether single or apparently single Wolf-Rayet stars are actually binary objects. Thus we would be contributing towards the answer to the questions: a) which is the actual percentage of binaries among Wolf-Rayet stars or, are all Wolf-Rayet stars binary systems?, and, particularly, b) are the evolution-ary ideas described above confirmed by the observa-tions, or do we need another evolutionary scheme or another approach to explain the observations? More-over, when one is dealing with single-lined binaries it is legitimate to play with the mass-function values to have a feeling as to the mass configurations that are reason-able and perhaps set limits to the different possibilities.

Now, the papers and preprints that I have been able to read, which did not include the one on HD 192163, left me with the strong feeling that the observations have been analyzed and discussed under the conviction that the objects in study are indeed the cases that are expected in the "second Wolf-Rayet stage" of the evolution of massive close binaries and no alternative explanations are offered.

The investigation of the stars I have listed is indeed not easy. At least four of them are characterized by variations in the level of the continuum, in the line profiles, in polarization and in radial velocities. Some of the features suggest a certain periodicity which appear to be shared by the photometric as well as by the spectroscopic data. However, there are lines that yield different amplitudes or different mean velocities in differ-ent epochs, and, in some cases, there are phase shifts of the order of 180° between different curves. In some cases, the way data have been analyzed is not free from criticism.

In HD 50896 there are "central absorptions" and "violet absorption edges", and it may be very important for the understanding of the object to try to discuss the possible origin of those central absorptions as well as the different behavior in radial velocity of emission lines and their violet absorption borders.

In the case of HD 193077 it is argued that it is more reasonable to postulate that the hydrogen absorption lines come from a third body because, otherwise, the γ derived from N IV emission would be $\sim 130\,\mathrm{km\ s^{-1}}$ more negative than the γ derived from the absorptions, and such a difference would be much larger than it is usually the case. But this will depend on the velocity of the layer or region where N IV is formed, relative to that of the photosphere. It is also argued that HD 193077 would be the only WN6 star where one sees photospheric H lines, and actually the list of Wolf-Rayet stars showing photospheric H lines covers practically the whole range of subclasses in both sequences. And the additional argument that the high rotational velocity suggested by the H absorptions would imply non-synchronous rotation and, therefore, a case that would not conform with what one would expect, can be answered by recalling several cases among Algol systems where there is no synchronization between rotation and orbital motion (cf. Struve 1950).

Finally, I would say that some of the velocity curves that result from the observations do not seem to suggest precisely orbital motion, and add that, if one takes into account the mass values that are possible to find among Wolf-Rayet stars, the mass-functions that are derived, with the limitations inherent to the problem, do not lead to the conclusion that the possible companion to the Wolf-Rayet star is necessarily a neutron star.

All my remarks aim at suggesting that it might be better not to draw conclusions and make generalizations at this stage, and that all the listed objects deserve further, patient and thorough investigation based on an adequate amount of suitable observational material secured through an appropriate stretch of time. It may very well be that we are concerned here with a group c Wolf-Rayet objects that have in storage information thа migh prove to be extremely important for a bette understanding of Wolf-Rayet stars, in general, and c their evolution.

III. SURROUNDING NEBULAE

One of the "theoretical predictions" for the "secon Wolf-Rayet stage" in the evolution of massive clo binaries is that "the system will appear as a sing Wolf-Rayet surrounded by a massive slowly expandir shell of matter (the expelled hydrogen-rich envelope) (van den Heuvel 1976). Up to late 1979, the know Wolf-Rayet stars that appeared surrounded by a rir nebula were all apparently single WN stars. As consequence, the fact that HD 164270, which is a WC object, appears not to be associated with a ring nebu was interpreted as the result "of its relatively advance age, having already passed through the WN stage an dispersed any such nebula into the interstellar medium (Isserstedt and Moffat 1980).

Table 3 lists the Wolf-Rayet stars associated with rir nebulae, that were known up to late 1979. All of the where WN, apparently single objects.

Lortet *et al.* (1980) found in Carina a ring-shape filamentary nebula that surrounds the WC6 obje HD 92809, and called attention to the fine, filamenta "ring" structure of NGC 6357 = Sh 2-11, shown in tl light of Hα + [N II] (Goudis 1977), that is arour HD 157504 (WC6), and to "the north-eastern part of S 2-54 around" HD 168206 = CV Serpentis (WC8 + O 9 III-V), which suggests the existence of a hollow co between the star and the nebulosity.

A similar technique to the one that permitted tl discovery of the ring structure around HD 157504 h permitted the extension of the list of Wolf-Rayet sta associated with ring-like nebulae. This has been achieve by Heckathorn and Gull (1980) by using Parker *et a*

TABLE 3

WOLF-RAYET STARS ASSOCIATED WITH RING NEBULAE[a]

HD	Sp	Nebula	Diameter (pc)	Shell velocity (km s^{-1})
50896	WN5	S308; RCW 11	–	–
56925	WN5	NGC 2359	8	55
89358	WN5	NGC 3199	16	30
96548	WN8	RCW 58	–	–
117688	WN7	RCW 78	–	–
147419	WN6	RCW 104+106	36	–
191765	WN6	S109	–	–
192163	WN6	NGC 6888	10	50-60
MR97	WN7	L 96	–	–

a. Known up to 1979.

979) *Emission Survey of the Milky Way*, which was ade with narrow-band interference filters effective for) III] 5007, Hα + [N II] 6570, [Si II] 6730 and Hβ. ɛckathorn and Gull found that a significant fraction of e 164 presently catalogued Wolf-Rayet stars (van der ıcht *et al.* 1980) of *the two sequences*, are associated ith such ring-like nebulae. I have not been able to see e full paper and, therefore, I cannot give more details ›w, but it is important to point out that the observa- ›nal evidence that has become available offers a picture at is different than the one on which we were basing ır speculations and arguments.

Regarding the shape of the ring nebulae, Johnson and ›gg (1965) had suggested that it is due to the matter at is ejected by the star and sweeps up the interstellar aterial in the star's vicinity. Seggewiss (1977) further ought that the filamentary structure of the nebulae ay arise as the result of variable stellar wind.

In this discussion related with the association of ɔlf-Rayet stars with ring nebulae, we should report an ditional observational fact which refers to the Mage- nic Clouds. In the Large Magellanic Cloud, Chu and ısker (1980) have identified eight ring nebulae, asso- ıted with Wolf-Rayet stars, all of them of the WN ɋuence; they are listed in Table 4. These nebulae are orphologically similar to the galactic ones, but their :es are 2-20 times larger. Although Chu and Lasker nsider Johnson and Hogg's explanation for the genesis ring nebulae as a plausible one, they think that nother obvious possibility is that the two kind of ›jects (the WR stars and the ring nebulae) merely have common origin in the star-forming processes". Now, ıce "the LMC contains other large ring-like objects at are not obvious supernova remnants" they conclude that "apparently, conditions in the ISM of the LMC are more favorable to the appearance of large ring (or bubble) nebulae", that is, "the ISM in the LMC may have significant spatial differences from that of the Galaxy".

Chu and Lasker carried out a similar search for ring nebulae associated with WR stars in the Small Magellanic Cloud, which was unsuccessful.

We should end our reference to the Magellanic Clouds by mentioning that Prévot-Burnichon *et al.* (1980), from an investigation in *UBV* and *R*, claim that 100% of the Wolf-Rayet stars in the Large Magellanic Cloud are associated with gaseous nebulae.

Going back to Wolf-Rayet stars in our Galaxy, we should recall that a number of them –we have a list of about 32– are central stars of the so-called planetary nebulae, a number which represents above 11% of the total of planetaries. As far as we know today, the Wolf-Rayet central stars are mostly WC objects.

Normally when one deals with central stars of planetary nebulae, one thinks in terms of Population II and very low mass stars. However, the question of the masses is completely open (cf. Sahade 1980*a*), and, regarding the population, planetary nebulae form, according to Peimbert (1978), a mixed group where we can find from Population I through extreme Population II objects. Therefore, the fact that a star is the central object of a planetary nebula should not necessarily mean that it is a Population II object.

It might be convenient to repeat here that the questions of attaching the planetary nebula label to an object is apparently not a clear-cut one. At least the morphology alone does not help. As examples in support to our assertion, we can mention S308 that was

TABLE 4

RING NEBULAE ASSOCIATED WITH WOLF-RAYET STARS IN THE LARGE MAGELLANIC CLOUD (Chu and Lasker 1980)

Star[a]	Sp	Nebula[b]	Diameter (pc)
WS 7=HDE 268847	WN3-5[c]	DEM 45	...
WS 17	WN4[e]	DEM 137	...
WS 19=HD 36063	WN6[e]	DEM 165	...
WS 22=HDE 269485	WN4[e]	DEM 174	...
WS 28	WN3[e]	DEM 208	200
HDE 269748	WN3(+OB?)[d]	DEM 231	24×16 (elliptical)
HV 5947	WN3+O[e]	DEM 240	...
HDE 270149	WN4[e]	DEM 315	25 (inner shell) 100 (outer shell)

a. WS: Westerlund and Smith 1964.
b. Davies, *et al.* 1976.
c. Fehrenbach, *et al.* 1976.
d. Walborn, 1980, private communication to Chu and Lasker.
e. Conti, 1980, private communication to Chu and Lasker.

considered by Minkowski as a planetary nebula and is now on the list of ring nebulae, and M1-67 which Minkowski also classified as a planetary nebula and is an H II region, according to Pişmiş and Recillas-Cruz (1979).

Formerly it had been found that about 44% of the Wolf-Rayet stars are associated with H II regions (Crampton 1971), these being either the small so-called ring nebulae or large nebulae normally linked with clusters or associations (Smith 1968). Now it appears that the percentage is much large and it may be that we will end up with a percentage as high as 100%. The new situation together with the facts that Wolf-Rayet stars are strongly concentrated to the galactic plane and are considered as spiral arm tracers are elements to be taken into account in any speculation regarding their evolutionary status and evolutionary history.

IV. WOLF-RAYET STARS IN CLUSTERS AND ASSOCIATIONS

Another item that I would like to discuss today relates to the membership of Wolf-Rayet stars in clusters and associations. Roberts (1958) was the first who pointed out that about 20% of the Wolf-Rayet stars are in very young clusters and associations and that the WN's are in higher proportion than the WC's. From such a membership, Reddish (1967) concluded that Wolf-Rayet stars must be very young objects indeed.

An interesting and probably significant fact that has been stressed by Lortet and Gómez (1980) is that a very large percentage of Wolf-Rayet stars in associations are located at a certain distance from the center, and the same appears to be true in clusters. Table 5 lists such distances in clusters, as given by Lundström and Stenholm (1980); to such a list we could add the WN6 star HDE 311884, which is probably a member of Hogg 15 (Moffat 1974), diameter = 3′, age ≤ 8 × 10^6 years, a is located 1′.8 from the center.

In regard to Lortet and Gómez results, it would se‹ that (although it is a case of small numbers statistics) t tendency is for Wolf-Rayet stars not to be centra located in associations, but to be near their edges.

We have mentioned the well known fact that Wc Rayet stars are strongly concentrated to the galac plane, the maximum of their distribution being along t spiral arms (Rublev 1975); they are taken as spiral ar tracers and assigned to *extreme Population I.* In M: Corso (1975) found that Wolf-Rayet stars are a strongly concentrated in the spiral arms and that th "avoid the central portions of large associations of bl stars although they are frequently found on their edge: 54% of them are "on the edge of, or immediately ad cent to, conspicuous dust particles and lanes".

Recently, Gómez *et al.* (1980) have called attenti to the following additional facts, namely:

a) in clusters and associations, some subclasses ‹ often found close to each other: for instance, two W‹ in Cygnus OB2, two WN5 in Cygnus OB1, three WN7 Carina OB1;

b) although young clusters and associations seem show preference for WN7's and WC5's these t‹ subclasses never appear near each other;

c) the Cygnus region is rich in WC' and WN5 a WN6 stars, the Carina arm displays a clustering of WC‹ and Car OB1 of WN7 and WC6 stars;

d) in the Large Magellanic Cloud, there is a clusteri of WN's in the nucleus of 30 Doradus, and a la number of WC5's farther away from the nucleus.

In addition, I should mention that Westerlund a Smith (1964) had remarked that in the Large Magella Cloud, the WN7's are found in the youngest associatio: while WN8, WN6, and WN5's are found in associatic that are not extremely young, and WN3, WC6, WC

TABLE 5

DISTANCES OF WOLF-RAYET STARS FROM CLUSTER CENTERS[a]

Cluster	Diam (′)	Age (10^6 yr)	Star	Sp	Distance from center (′)
Cr 121	50	7	HD 50896=MR 6[b]	WN5	20
Cr 228	15	≤5	HD 93131=MR 28	WN7	7
Tr 16	10	≤5	HD 92740=MR 25	WN7	29
			HD 93162=MR 29	WN7	6
Stock 16	3	5	MR 44	WC6	7
			MR 45	WN4	3
NGC 231	15	≤5	HD 151932=MR 64	WN7	23
			HD 152270=MR 65	WC6-7+O5	2

a. Given by Lundström and Stenholm 1980.
b. HD 50896, most probably, is not a member of Cr 121.

/C8 and WC9's are almost never found in associations Smith 1968).

V. POST RED SUPERGIANT STAGE?

Although I do not think that I should discuss the oint in this report, I will mention, for the sake of ompleteness, that it has been proposed that a large raction of the Wolf-Rayet stars are in the post red upergiant stage in the evolution of stars with masses in he range 60-15 $\mathcal{M}_\odot$ (Maeder *et al.* 1980) and that they /ill become supernovae of type I if the initial mass was irger than 30 $\mathcal{M}_\odot$. The arithmetics is applied to the Iagellanic Clouds taking into account their accepted, ow metal abundances. My comments to the suggestion that perhaps one should remember:

a) The fact that a large percentage of Wolf-Rayet tars are binaries and that the percentage of binaries mong red supergiants is smaller than on the main equence.

b) The fact that the chemical composition of the Iagellanic Clouds, in contrast to that of the Galaxy, oes not seem to be completely certain.

c) The information I have summarized in the preeding sections.

VI. EVOLUTIONARY STATUS

Now, which is actually the evolutionary status of a Volf-Rayet star? Or, even before this question, could /e answer the one Thomas (1968) posed at the Boulder neeting, namely, when we deal with a Wolf-Rayet pectrum, are we dealing with an "object" or with a 'phenomenon"? Earlier, everybody thought we were ealing with "objects" and now some astronomers are eginning to talk in terms of "phenomena". Which of he two positions actually reflect the outcome of a horough consideration of the problem?

To tackle the problem of the evolutionary status of he Wolf-Rayet stars, we should first try to decide as to he chemical composition of the objects. I have given easons of why we should think in terms of normal hemical composition. And, as Underhill (1980*a*) puts it, once it is recognized that Wolf-Rayet stars have nearly ormal composition, there is no need to think that they re at a late stage of evolution". I have mentioned the bservational facts that suggest that we are dealing with ery young objects. Underhill (1980*b*) has shown that he location of the WN7/WN8 stars in the H-R diagram is 1 the core H-burning band, close to the B0 supergiants, /hile most WN's and WC's occupy the region near the 30.5 III stars. If the chemical composition is "normal." nd the scheme that predicts that the WN's result from he evolution of Of stars does not hold, one way out may e to think in terms of objects that are approaching the nain sequence, as Sahade (1958), Underhill (1966, 1980*b*) and Schmidt-Kaler (1970) have independently suggested, as an alternative possibility. Then, the location of the Wolf-Rayet stars in clusters and associations and the stellar types that are found might perhaps be understood in terms of the sequence of star formation in the aggregate and in terms of the parameters that characterize the material out of which the stars were formed. I shall not elaborate on this point any further at this time; work will be done to ascertain whether we have in front of us a door for further progress or whether we should abandon this line of thought.

VII. WN AND WC SEQUENCES

Another question is crucial and should be approached in spite of its difficulties. I am referring to the two sequences in which Wolf-Rayet stars are divided.

There are a number of cases where one finds anomalous line intensities and no peculiar abundances are invoked; in some of them, peculiarities are understood in terms of selective mechanisms at work in the line formation process. Let us enumerate a few examples,

a) a C-N dichotomy is also displayed by the O and early B stars;

b) different relative intensities of emission lines of N and C are displayed by Of stars;

c) the literature records spectra of novae which were strong in O (Nova Aquilae 1918), in H (Nova Geminorum 1912), or in Fe (Nova Pictoris 1925);

d) the spectrum of Nova Aquilae 1918 displayed very strong N III 4634-4642 which gradually changed to C III-IV 4650 (cf. Kuhi 1968*b*);

e) Cecilia Payne-Gaposchkin would classify the first rocket solar spectrum as WC6 (cf. Thomas 1968).

Nobody would talk about abundance differences in the cases just listed.

If we now go back to the Wolf-Rayet stars, we have to admit that we are facing the problem of line formation in a situation that is far removed from the classical one. In the Wolf-Rayet stars we have a very extended envelope with:

a velocity field,
a peculiar law of variation of T_e,
a (peculiar?) density variation law,
opacity: electron scattering,
mechanical energy at work,
no hydrostatic equilibrium,
no radiative equilibrium,
no thermodynamical equilibrium,
regions with non-parallel geometry,
regions where collisional excitation is important;
regions with large turbulence, and
there may be problems of diffusion of radiation and problems of particle perturbation on the atomic energy levels.

It is, naturally, simpler to deal with the problem without paying attention to complications that we do not know how to handle. But, is it reasonable to talk about abundance differences from the outset? And the fundamental problem that remains unanswered is the one related to the mechanism that produces the loss of mass and gives rise to the laws that govern the variations in excitation temperature, in velocity and in density in the extended envelope. In the same context I should mention again my suggestion of the two maxima of T_e; in the case of γ_2 Vel (Sahade and Zorec 1980) it is clear that the second T_e maximum could arise because of the shock wave that is originated when the supersonic flow of matter from the Wolf-Rayet component reaches the companion star. Since this second T_e maximum appears to be present in all Wolf-Rayet stars, then, if they are not all binaries, we have to think in another mechanism, at least, for the single stars. Auger ionization could be one answer but, so far, X-radiation has been detected in only one Wolf-Rayet object.

VIII. CONCLUDING REMARKS

We have only outlined some problems of the Wolf-Rayet stars that, in my view, ought to be thought of from a more ample perspective than it is the case now. I would feel satisfied if this paper would originate efforts in different directions and with different possible views in order to make further progress in our understanding of Wolf-Rayet stars. It would seem as though priority should be placed at the moment on the observational side.

I am greatly indebted to all the colleagues that have sent me published as well as unpublished papers on Wolf-Rayet stars. In particular, to Dr. Virpi Niemela for a number of preprints she very kindly put at my disposal and were of much help in the preparation of this report, and to Dr. Barry M. Lasker for letting me have the results of his joint work with Dr. Chu, before publication, as well as for other related material.

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DISCUSSION

Mendoza, E. ¿Cuál es la confiabilidad de las determinaciones de masas mayores a 40 $M_\odot$?
Sahade: Si la pregunta se refiere a las masas de estrellas Wolf-Rayet, debo mencionar que el problema de la determinación de las masas está vinculado al hecho de que líneas de distintos elementos sugieren curvas de distinta amplitud y a veces con distinta fase. En general, se adopta como curva de velocidad de la WR la que corresponde al elemento más ionizado y, por consiguiente al que se forma más cerca de la estrella, el cual da un K menor. Si la pregunta se refiere a las masas de estrellas O, la determinación está afectada por los fenómenos que perturban las velocidades radiales y obligan a adoptar ciertas suposiciones a fin de interpretarlas.
Pacheco: La no detección de rayos-X en algunos objetos no implica la inexistencia de una atmósfera extendìda, la cual puede ser opaca a rayos-X Además, la emisión continua indica pérdida de masa con valores del orden de 10^{-4} $M_\odot$ año^{-1}.
Sahade: Al primer comentario, respondo que es verdad, pero si la radiación X queda absorbida en la atmósfera extendida entonces no puede pensarse en ionización Auger para explicar el aumento de la temperatura de excitación en las capas exteriores de baja densidad.
Serrano: Usted ha expresado que las estrellas WR no están quemando He en el centro. ¿Quiere decir ésto que podrían estar quemando hidrógeno en la secuencia principal?
Sahade: Creo que la evidencia observacional no está en favor de la creencia de que estamos tratando con estrellas que consumen He en el centro. Eso lleva a algunos astrónomos (Underhill entre ellos) a pensar que se trata de estrellas de composición química normal. Y por consiguiente, que ya no es necesario concluir que son objetos en estado avanzado de evolución. Podría ser que estén llegando a la secuencia principal, y, si bien hay elementos que apoyan esta posibilidad, aún sería necesario analizar algunos datos adicionales.
Peimbert: ¿Se ha obtenido información adicional sobre los procesos físicos que producen las líneas de emisión a partir de observaciones del *IUE?*
Sahade: Los anchos de las líneas de resonancia de los elementos altamente ionizados sugieren que ellos se producen por turbulencia, lo que uno debe esperar si los valores de la temperatura de excitación en las capas exteriores de las envolturas resultan de la dispersión de ondas de choque.

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