VII RELATED OBJECTS

HELIUM RICH SUBDWARF O STARS AND CENTRAL STARS OF PLANETARY NEBULAE*

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1. INTRODUCTION

In this review we will discuss the hottest subluminous H-deficient stars, namely those with T_{eff} > 30000 K. In the absence of reliable distance determinations for hot subluminous stars, the best way to discuss their properties and evolutionary status is to find their positions on the log g - log T_{eff} diagram. In the last few years, after extensive computational work, first in Kiel and more recently also in Munich, it has become possible to obtain log g and T_{eff}, together with the surface He abundance, directly by fitting the observed H and He absorption line profiles with theoretical profiles obtained from non-LTE model atmospheres and associated line formation codes. The non-LTE models are plane-parallel, in hydrostatic and radiative equilibrium, and the atmosphere is assumed to consist of H and He only. A recent paper by Groth et al. (1985) gives most of the references on the application of this non-LTE model atmosphere approach to the study of all kinds of hot subluminous stars.

Let us call $y = N(He) / (N(He)+N(H))$. Figure 1 shows the positions in the log g - log T_{eff} diagram of 51 subluminous stars. They have widely different values of y. Objects known to be members of close binary systems have been omitted. In Section 2 we will discuss the He-rich sdO stars, $0.1 < y < 0.8$, and the extreme He-rich sdO stars, defined as showing no trace of H absorption lines in their spectra ($y \simeq 1$). Section 3 will be devoted to H-deficient central stars of planetary nebulae (CSPN). Let us remark that, up to now, only one such CSPN

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has been positioned on the log g - log T_{eff} diagram: K1-27 (Méndez et al. 1985). All the other CSPN represented in Figure 1 are H-rich ($0.01 < y < 0.13$).

2. HE-RICH AND EXTREME HE-RICH sdO STARS

Before considering the He-rich sdO's, it is convenient to mention some recent work on the He-poor sdB's and sdOB's (Heber et al. 1984, Heber 1985). These stars appear now to be convincingly explained as evolving away from the extended horizontal branch (EHB) and towards the white dwarf configuration (an EHB star is defined to have a ratio q (core mass/total mass) so high that H-burning becomes negligible). Their low He abundances are attributed to gravitational settling. Their heavier-element abundances are not yet well understood.

The He-rich sdO stars (filled circles in Figure 1) pose two problems: how to produce a high photospheric He abundance, and how to keep it high against gravitational settling, since some H is left in their photospheres. Let us consider first the second problem. Groth et al. (1985) have studied the role of convection at photospheric and subphotospheric levels. They conclude that photospheric convection helps to explain the persistence of He in the photospheres of the observed He-rich sdO stars only if they had a high initial photospheric He abundance. This has an important evolutionary implication: these stars cannot have reached their present positions in the log g - log T_{eff} diagram following evolutionary tracks similar to those of EHB stars; because once a star becomes He-poor, the photospheric convection zone cannot develop, and the star is bound to remain He-poor (indeed, the hottest He-poor sdOB's in Figure 1 are well within the "convective" region).

Therefore, now it seems possible to predict what horizontal branch stars should become He-rich sdO's. First, they must have q so high that they either cannot reach the top of the asymptotic giant branch (AGB), or, if they do, and eject a planetary nebula, their subsequent evolution is so slow that the nebula is dispersed before the star becomes hot enough to ionize it (according to Schönberner (1983), this would be the case if the stellar mass after nebula ejection is smaller than 0.55 solar masses). Second, they must have q not so high as to become an EHB star, with an inert H-rich envelope. It would be necessary to specify more precisely, from the interplay between diffusion and mass loss, in which regions of the log g - log T_{eff} diagram is gravitational settling expected to dominate, and to confirm, by means of more detailed evolutionary calculations, if it is really possible to obtain evolutionary tracks leading to the filled circles in Figure 1 while avoiding the "He-sinking" regions.

Of course, a complete picture should also explain how does the high initial photospheric He abundance originate. At the present time the problem is not solved, and we can only make guesses.

Consider a star, initially somewhat more massive than the Sun, on the red giant branch, and assume (Hunger and Kudritzki 1981) that it suffers a severe mass loss, before and/or as a consequence of the core

He flash. We do not want it to lose all its H-rich envelope, because a star starting from the He main sequence would not explain most of the points in Figure 1. If a small, inert H-rich envelope remains, then we have an EHB star, whose subsequent evolution we expect to produce sdB's and sdOB's, all He-poor. It would seem that the only alternative is to start with a more normal horizontal branch star, burning He in the core and H in a shell. In this case we expect a normal initial photospheric He abundance, and the only hope seems to be additional mass loss and/or mixing during the subsequent double-shell-burning phase. Groth et al. (1985), following Paczynski (1971), favor the idea of mixing, apparently the less unlikely choice, speculating that it could arise as a consequence of the He shell flashes known to occur in double shell configurations.

The properties of extreme He-rich sdO's (plus signs in Figure 1) add some confusion to the picture. They are spread all over the log g - log T_{eff} diagram; in particular, some of them are placed among the CSPN

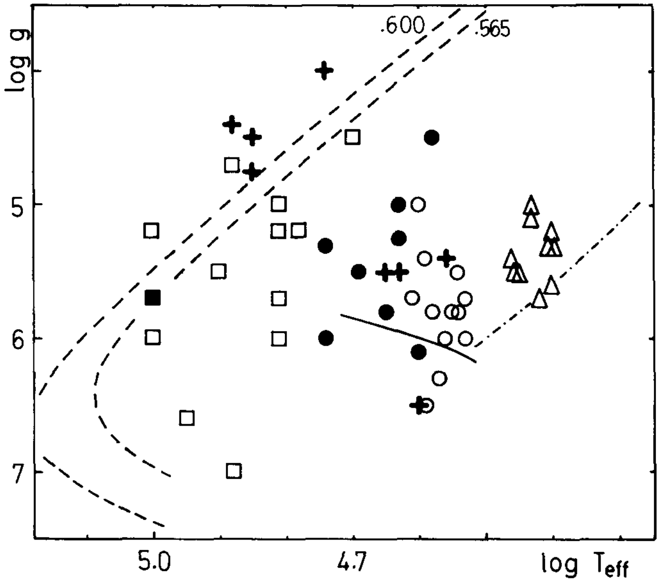

Figure 1. The positions of 51 subluminous stars in the log g - log T_{eff} diagram. The triangles are the extremely He-poor sdB stars, y<0.015, all with temperatures below 30000 K. The open circles are He-poor sdOB stars, y<0.09. Filled circles indicate the He-rich sdO stars, 0.1<y<0.8. The plus signs are extreme He-rich sdO stars, showing no trace of H absorption lines in their spectra. The open squares are H-rich CSPN, 0.01<y<0.13. The filled square is the H-deficient central star of K1-27. The full line is the He main sequence (Paczynski 1971). The dashed - dotted line is an EHB, extrapolated from Caloi et al. (1978). The dashed lines are theoretical evolutionary tracks for stars of 0.6 and 0.565 solar masses, descending from the asymptotic giant branch (Schönberner 1981, 1983).

(see Husfeld, Heber and Drilling, these Proceedings), but no nebula has been detected around them. One can speculate that these objects are really following post-AGB evolutionary tracks but somehow, in spite of their comparatively large masses, manage to evolve so slowly that the nebulae have disappeared long ago, or that it may be possible for evolutionary tracks corresponding to high q values to intersect the post-AGB tracks, or that it may be possible for a star to reach the top of the AGB without ejecting a planetary nebula.

3. H-DEFICIENT CSPN

3.1. Introductory notes on the spectral classification of CSPN

Some parts of the current scheme of spectral classification for CSPN (see e.g. Smith and Aller 1969, Lutz 1978) need revision. Objects having very different spectra are grouped together under the "O VI" label (Méndez and Niemela 1982, Heap 1982). The "continuous" objects are not continuous (Kudritzki et al. 1981a, b) and will have to be given other spectral types when better spectrograms become available. All this produces a certain amount of unnecessary confusion. The easiest way to overcome these problems is to redefine the main groups so that they become as homogeneous as possible.

Table I gives a preliminary revised spectral classification scheme (Méndez, in preparation). There are four main factors affecting the spectral characteristics of a CSPN: surface abundances, mass loss rate, T_{eff} and log g. The spectral types in Table I have been arranged in such a way that (as far as we can tell) the photospheric H-abundance decreases towards the left, the mass loss rate decreases towards the bottom, and surface gravity increases towards the bottom ("hg" stands for high gravity). The parentheses are used to indicate the chemical element whose lines predominate in the visual and photographic spectrum. For example, the central star of K1-27 shows only He II absorptions, and is therefore called O(He) (or perhaps hgO(He); the use of the label hg in this case is not yet clearly defined), while the central star of Longmore 4 shows very strong C IV absorptions, and is therefore called O(C). Parentheses are also used to describe peculiarities (e.g. " N strong ", see Table II).

We strongly emphasize that the arrangement of spectral types in Table I is schematic, particularly concerning the photospheric H abundance. Suitable model atmospheres for many of these stars are lacking, and therefore a precise determination of T_{eff}, log g and surface abundances is not yet possible. However, from what we know about very hot stars, it seems reasonable to call a CSPN "extremely H-deficient" if its spectrum does not show H lines.

3.2. A list of extreme H-deficient CSPN

To produce a list of extreme H-deficient CSPN is a delicate task. Most CSPN are faint, and many are embedded in nebulae of very high surface brightness. An efficient sky-light-suppressor, a spectral resolution of

TABLE I

REVISED SPECTRAL CLASSIFICATION SCHEME FOR CSPN (PRELIMINARY)

H-deficient			H-rich
WC	WN		
		WR-Of	
A30-78			
			Ofp, Of
O(C), O(He)			O(H)
hgO(C), hgO(He)			hgO(H)

about 0.5 Å and a good signal-to-noise ratio are sometimes necessary to detect stellar H or He lines masked by strong nebular emissions. Therefore, in many cases, the available spectral descriptions are not good enough to be sure about the absence of stellar H lines. We have listed in Table II only those objects about which we are sure, and we have added a supplement with slightly less certain objects, for which we are not able to provide a more precise classification. In Table II we have also added references on nebular abundances, which will be discussed later.

We remark that in Table II we have included the star Sanduleak 3, following the suggestion by Barlow and Hummer (1982) that it is the remnant central star of a planetary nebula which is no longer visible. This suggestion has been confirmed by van der Hucht et al. (1985), who discovered IR emission from a circumstellar dust shell, with a temperature within the range of dust temperatures found to be common in planetary nebulae.

We would like to comment on three objects we have not included in Table II: He 2-99 (309-4°1), He 2-113 (321+3°1) and M1-67 (50+3°1).

We start with the central star of He 2-99, classified WC9 by Smith and Aller (1969). On calibrated image-tube spectrograms obtained with the 4-m telescope at the Cerro Tololo Inter-American Observatory (CTIO), we have found that the spectrum of this star, from 3700 to 6600 Å, is very similar to that of the Population I WC9 star HD157451. The full widths of emission lines are similar (with one outstanding exception: the C III emission at 5696 Å is narrower in He 2-99), and also the equivalent widths are similar, several lines being slightly stronger in the spectrum of He 2-99. In a recent paper on WC9 stars by Torres and Conti (1984) we find that most of the emission lines of HD157451 are stronger than those of HD164270. Finally, Smith and Aller (1971) have shown that the lines of HD164270 are stronger and wider than the lines of the WC9 CSPN BD+30°3639. Clearly, if we do not want to question the

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TABLE II. A LIST OF EXTREME H-DEFICIENT CSPN

Object	PK designation	Spectral type	Refs. on spectral type	Refs. on nebular abunds.
K1-27	286 -29°1	O(He)	1	
K1-16	94 +27°1	hgO(C)	2	
Longmore 3	258 -15°1	O(C)	1	
Longmore 4	274 +9°1	O(C)	1	
NGC 246	118 -74°1	O(C)	3,4	3
Abell 30	208 +33°1	A30-78 (N strong)	4	13
Abell 78	81 -14°1	A30-78 (N strong)	4	13
NGC 5189	307 -3°1	WC 2	5	
NGC 2452	243 -1°1	WC 3	5,6	15
NGC 2867	278 -5°1	WC 3	5	16
NGC 6905	61 -9°1	WC 3	5,6	15
NGC 7026	89 +0°1	WC 3	5,6	15
Sanduleak 3		WC 3	7	
NGC 5315	309 -4°2	WC 4	5	14
NGC 6751	29 -5°1	WC 4 (N strong)	8	15
IC 1747	130 +1°1	WC 4	5,6	15
NGC 40	120 +9°1	WC 8	6,9	15
BD+30°3639	64 +5°1	WC 9	6,9	14
SwSt 1	1 -6°2	WC 9	5,6	17
M4-18	146 +7°1	WC10	10	18
CPD-56°8032	332 -9°1	WC10	10	
V348 Sgr	11 -7°1	WC10	10	
Supplement: slightly less certain objects				
NGC 1501	144 +6°1	WC early	4	
NGC 2371-2	189 +19°1	WC early	4	15
NGC 6578	10 -1°1	WC early	11	11
IC 2003	161 -14°1	WC early	4	14,15
M3-30	17 -4°1	WC early	12	12

References:

1 Méndez et al. 1985
2 Grauer and Bond 1984
3 Heap 1975
4 Heap 1982
5 Méndez and Niemela 1982
6 Aller 1977
7 Barlow et al. 1980
8 This paper
9 Smith and Aller 1969
10 Webster and Glass 1974
11 Kaler 1985
12 Kaler and Shaw 1984
13 Jacoby and Ford 1983
14 Torres-Peimbert and Peimbert 1977
15 Aller and Czyzak 1983
16 Aller et al. 1981
17 Flower et al. 1984
18 Goodrich and Dahari 1985

TABLE III

A LIST OF CSPN IN WHOSE SPECTRA H LINES HAVE BEEN CLEARLY SEEN

*Longmore 1	*LSS 1362	*Longmore 13	*NGC 6629
*NGC 1360	*NGC 3242	*He 2-151	Abell 46
*NGC 1535	*NGC 4361	*He 2-162	*NGC 6720
*Abell 7	IC 3568	Abell 39	*Abell 51
*IC 418	*Longmore 8	NGC 6210	NGC 6804
IC 2149	*MyCn 18	*He 2-182	NGC 6826
*Abell 15	*Abell 36	*H 2-1	NGC 6853
*NGC 2392	*He 2-108	*IC 4637	*NGC 6891
*He 2-5	*NGC 5882	Sa 4-1	NGC 7008
*EGB 5	*LSE 125	*Tc 1	*NGC 7009
*Abell 31	*Sp 1	*M1-26	NGC 7094
*IC 2448	NGC 6058	Abell 43	*NGC 7293
*Abell 33			

Note: we have suitable spectrograms of all those objects marked with an asterisk. The others are taken from the following references: Aller 1968, Greenstein and Minkowski 1964, Heap 1977, Lutz 1977, Sanduleak 1983.

widely accepted statement that subluminous WC9 stars have weaker and narrower lines, we have to consider the central star of He 2-99 as a massive, Population I star. Until the situation is clarified, it seems prudent to stop counting He 2-99 among the planetary nebulae.

The central star of He 2-113 has been classified WC10 by Webster and Glass (1974). We have not included it in Table II because they say there may be some H at or near the surface of the star.

For a similar reason we have not included the WN8 central star of M1-67 (now accepted again as a planetary nebula, see van der Hucht et al 1985): although very probably H-deficient, it appears to show some H in its spectrum (Aller 1977).

In conclusion, Table II lists 27 extreme H-deficient CSPN. It may be interesting to compare this number to the amount of H-rich CSPN, defined as those showing in their spectra clear evidence of H lines. From spectrograms at our disposal, and the information available in the literature, we have counted 49 confirmed H-rich CSPN, which are listed in Table III. Of course, it would be wrong to conclude that 35% of all CSPN are extremely H-deficient, because there is a huge selection effect favoring the detection of CSPN with WC spectra. Therefore, 35% appears to be a quite solid upper limit.

3.3. WC early CSPN

The spectral types we have adopted for these stars are based on the classification criteria defined by Méndez and Niemela (1982). These

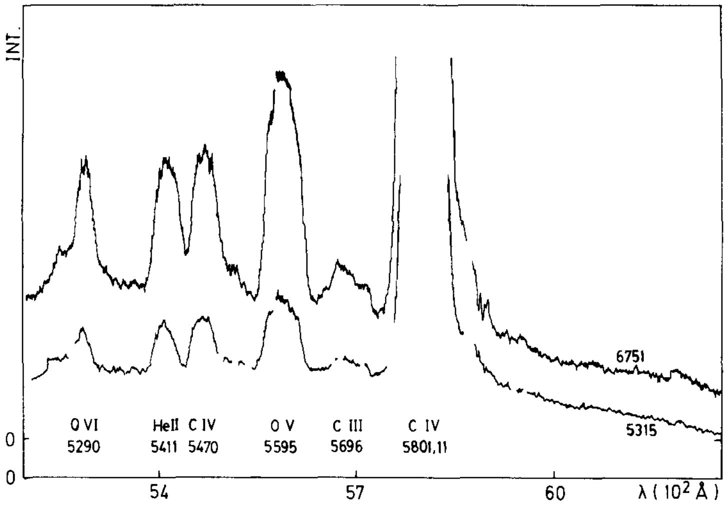

Figure 2. Intensity tracings of the WC4 central stars of NGC 6751 and NGC 5315. The nebular emission lines have been omitted. The levels of zero intensity are indicated for each object.

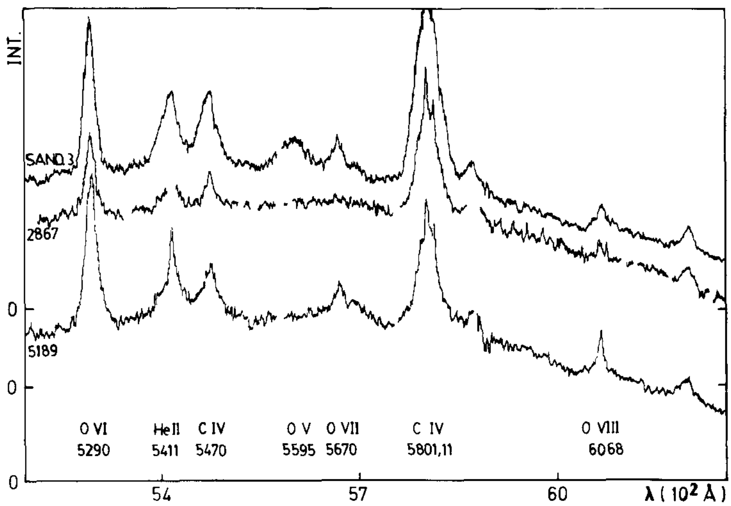

Figure 3. The same as Figure 2, for Sanduleak 3 (WC3) and the central stars of NGC 2867 (WC3) and NGC 5189 (WC2).

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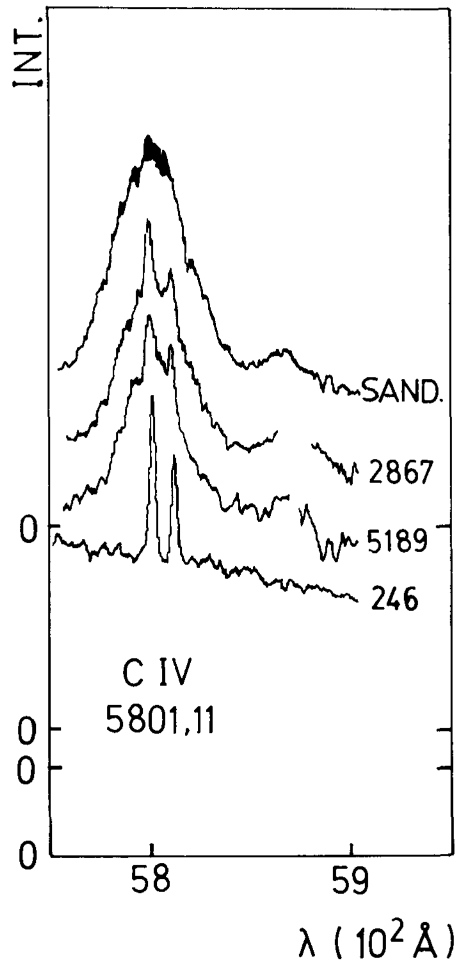

Figure 4. The C IV doublet in the spectra of Sanduleak 3 and the central stars of NGC 2867, 5189 and 246. The levels of zero intensity are indicated for each object.

criteria provide a smooth connection with the classification system used in the Sixth Catalogue of galactic WR stars (van der Hucht et al. 1981).

Figures 2,3 and 4 show intensity tracings obtained from calibrated image-tube spectrograms taken with the CTIO 4-m telescope. Figure 2 shows that the central stars of NGC 5315 and NGC 6751 are WC4, not WC6 as repeatedly misclassified in the literature; notice the weakness of the C III feature at 5695 Å compared to O V 5595 and O VI 5290. It is important to remark that we have not found any example of spectral types WC5, 6 or 7 among CSPN. Méndez and Niemela (1982) show in their Figure 3 the very different distributions of WC subtypes for CSPN and for Population I WC stars. Since no selection effect is expected to be working against the discovery of WC5, 6 or 7 CSPN, we have to conclude that this striking deficiency is real.

Figure 3 shows the spectrum of the earliest known WC CSPN (NGC

5189). Notice the weakness of the O V feature at 5595 Å and the strength of O VIII 6068. Another interesting detail is the complex profile of C IV 5801-11, also visible in the spectrum of NGC 2867. Figure 4 shows these C IV doublet profiles in more detail, compared to the C IV profile in the spectrum of the O(C) central star of NGC 246. Apparently, in the cases of NGC 2867 and 5189 the wind is becoming optically thin, and we are beginning to see "photospheric" components shining through it. We can reasonably expect that, when the stellar wind dissipates further, the central stars of NGC 2867 and 5189 will become objects very similar to the central star of NGC 246.

3.4. O(C) and O(He) CSPN

Figure 5 shows intensity tracings of the central star of NGC 246, again obtained from calibrated image-tube spectrograms taken with the CTIO 4-m telescope. Notice the O VI absorption at 5278 Å. It is interesting

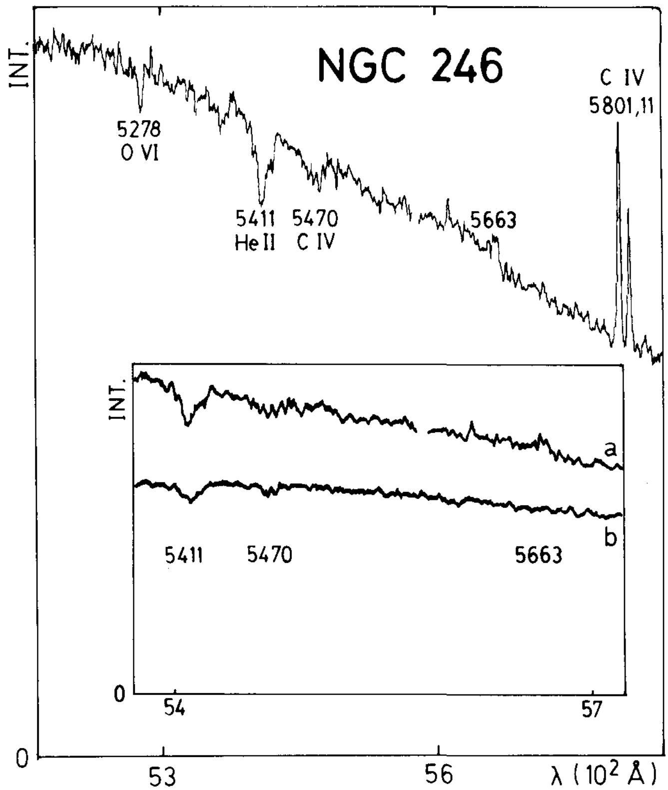

Figure 5. Intensity tracings of the O(C) central star of NGC 246. The insert shows the region from 5400 to 5700 Å in more detail. The levels of zero intensity are indicated in each case. The spectrogram labeled "a", which is reproduced twice, was taken on January 8, 1979. The spectrogram labeled "b" was taken with the same spectrograph and emulsion on June 30, 1982.

to note that in the spectrum of this star, from 3700 to 6600 Å, there is no evidence of O VII or O VIII lines, with the possible exception of a weak emission at 5663 Å, which in spite of its somewhat discrepant wavelength might be attributed to O VII. If one believes in the close connection between NGC 5189 and NGC 246, then the conclusion is that the very high ionization features are lost with the wind. We further note that the emission feature at 5663 Å, undoubtedly present in 1979, was no longer there in 1982 (see the insert in Figure 5).

Now we turn our attention to the hgO(C) and O(C) central stars of K1-16 (Grauer and Bond 1984), Longmore 3 and Longmore 4 (Méndez et al. 1985). Their spectra are dominated by C IV and He II absorptions. The central star of K1-16 does not show O VI emissions at 3811, 3834 Å; we tentatively use the absence of these emissions as the criterion to apply the label "hg" to an O(C) CSPN. In the case of Longmore 3 and 4 we do not have the necessary information; they might also be hgO(C). A reliable determination of T_{eff}, log g and surface abundances for O(C) objects appears to be within reach in the very near future (Husfeld 1986).

Grauer and Bond (1984) have discovered that the central star of K1-16 sometimes pulsates, and have stressed the spectroscopic and photometric similarities with the previously known hot pulsator PG1159-035. Subsequently, Bond et al. (1984) reported the discovery of two additional hot pulsators, again with similar spectroscopic and photometric characteristics. These four objects appear to define a new pulsational instability strip at the hot edge of the HR diagram, the cause of the pulsation being very probably the cyclical ionization of C and O (Starrfield et al. 1984). The obvious inference is that other O(C) CSPN may also be pulsating, for example Longmore 3 or 4. As far as we know, this possibility has not been checked yet.

Sion et al. (1985) have reported the discovery of strong O VI absorptions in the spectra of several members of the "PG1159" class, confirming the plausibility of the proposed pulsation mechanism, and have suggested an evolutionary link connecting the WC early CSPN with the PG1159 stars, the central star of K1-16 being considered a transition object, because of its still visible nebula and of its longer period and presumably lower surface gravity than the PG1159 pulsators.

The existence of these hot pulsators opens the possibility of detecting period changes produced by stellar evolution in very short times (a few years). There is no doubt that these stars will receive a lot of attention in the near future.

A final comment in this section concerns the O(He) central star of K1-27 (Méndez et al. 1985), whose existence demonstrates that not all the H-deficient CSPN show strong carbon lines. What is the reason for the difference? At the present time we can offer no answer.

3.5. Do all H-deficient CSPN belong to a single evolutionary sequence?

Whatever their surface abundances, CSPN are expected to follow post-AGB evolutionary tracks leading from low to high surface temperatures and from low to high surface gravities. The mass loss rate should decrease sooner or later along any of these tracks. Based on these expectations,

TABLE IV. H-DEFICIENT CSPN: COMPLEMENTARY DATA

Object	Spectral type	Neb. exc. class	Stellar temp. (10^3 K)	V_∞ (Km/s)	Neb. exp. vel. (Km/s)	References
K1-27	O(He)		100			0
K1-16	hgO(C)		>80	8500		1
NGC 246	O(C)	10	>85	>3200	39	2,1,3,4
Abell 30	A30-78 (N st)		>72	4900	40	5,6,4
Abell 78	A30-78 (N st)		>69	5000		1,6
NGC 5189	WC 2	7		3800	37	7,6,4
NGC 2452	WC 3	7	97			8,9
NGC 2867	WC 3	7	91			10,9
NGC 6905	WC 3	7	62		44	8,9,4
NGC 7026	WC 3	6	58		37	8,9,4
NGC 5315	WC 4	6	50			11,9
NGC 6751	WC 4 (N st)	4	61		40	8,9,4
IC 1747	WC 4	6			28	8,4
NGC 40	WC 8	2	35	2600	29	8,9,6,4
BD+30°3639	WC 9	1	32	2000	23	10,9,12,4
SwSt 1	WC 9	3	33	2000	13	13,14,6,15
M4-18	WC10	1	22		<15	16,4
CPD-56°8032	WC10	1				17
V348 Sgr	WC10	1	23			17,16

References:

0 Méndez et al. 1985
1 Kaler and Feibelman 1985
2 Heap 1975
3 Heap 1982
4 Sabbadin 1984
5 Kaler 1983
6 Cerruti-Sola and Perinotto 1985
7 Johnson 1976
8 Aller and Czyzak 1979
9 Preite-Martinez and Pottasch 1983
10 Aller 1965
11 Martin 1981
12 Kaler et al. 1985
13 Acker 1975
14 Flower et al. 1984
15 Acker 1976
16 Goodrich and Dahari 1985
17 Webster and Glass 1974

it is natural to propose an evolutionary sequence for H-deficient CSPN, starting with the WC late objects, then WC early, A30-78, O and hgO.

Now we ask if the observational evidence supports this picture. For the discussion of this subject we have tried to use only the most reliable information, and to keep the interpretation of the observations to a minimum. For that reason we have avoided the color temperatures of hot CSPN estimated from IUE data, which we consider too unreliable, and we have not used any of the distance determinations found in the literature. We have selected the following observational characteristics: the nebular excitation class (expected to have some relation to the stellar effective temperature), the stellar T_{eff} itself, or in its defect a temperature derived from careful studies of nebular spectra, the terminal velocity of the stellar wind (expected to increase along the evolutionary tracks, see Heap 1982), and the nebular expansion velocity. The relevant information is collected in Table IV. In Figures 6 to 9 we have plotted these nebular and stellar characteristics as functions of the spectral type.

In all four cases we find a satisfactory correlation; the observational evidence is consistent with the proposed evolutionary sequence. Besides, in Sections 3.3 and 3.4 we have seen additional reasons to suggest that WC early CSPN will become O(C) objects like NGC 246, then hgO(C) objects like K1-16, then PG1159 stars, presumably ending as non-DA white dwarfs.

However, a few problems remain. Can we really incorporate A30 and A78 into the sequence? They have unique properties. First, their central stars show moderately strong nitrogen lines in the photographic and visual regions of the spectrum (a characteristic they share with NGC 6751). Second, their central stars have managed to eject H-deficient material, which is now seen in the inner regions of these two planetary nebulae. In contrast, all the other H-deficient CSPN appear to be surrounded by essentially normal H-rich nebulae (including NGC 6751). The references are listed in Table II. At this point it is necessary to remark that in many cases there might be H-deficient inner regions around H-deficient CSPN; very careful observations would be necessary to reject this possibility. The very high angular resolution to be obtained with the Space Telescope would be very useful for such studies. However, at the present time we do not have observational evidence of the existence of more such H-deficient inner regions, and A30 and A78 remain unique among the well known H-deficient CSPN. Therefore, their connection with the other objects is not clear.

Another problem is posed by the absence of carbon lines in the spectrum of the central star of K1-27, as mentioned at the end of Section 3.4.

Finally, if the WC late and WC early objects belong to the same sequence, why are there no WC5,6 and 7 CSPN? Looking at the stellar temperatures listed in Table IV, it would seem that there is a deficit of H-deficient CSPN between 35000 and 50000 K. This is not expected from evolutionary considerations.

On the other hand, the alternative of different sequences appears somewhat artificial. We would need non-WC predecessors for the WC early, and non-WC followers for the WC late. In connection with this, it would be very important to check if there are O(He) or O(C) CSPN with surface temperatures below 60000 K. No such objects are currently known to exist.

In summary, there may be more than one way to produce a H-deficient CSPN, and/or there are many details of post-AGB evolution that we do not understand.

3.6. On the masses of H-deficient CSPN

In this section we want to discuss the available evidence on possible

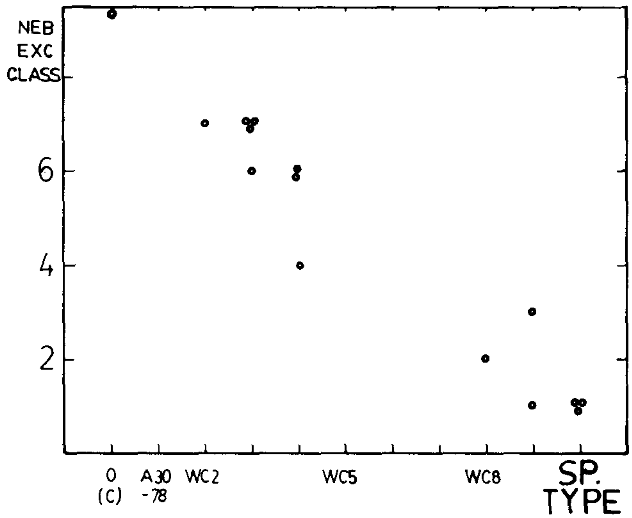

Figure 6. Nebular excitation class plotted as a function of spectral type.

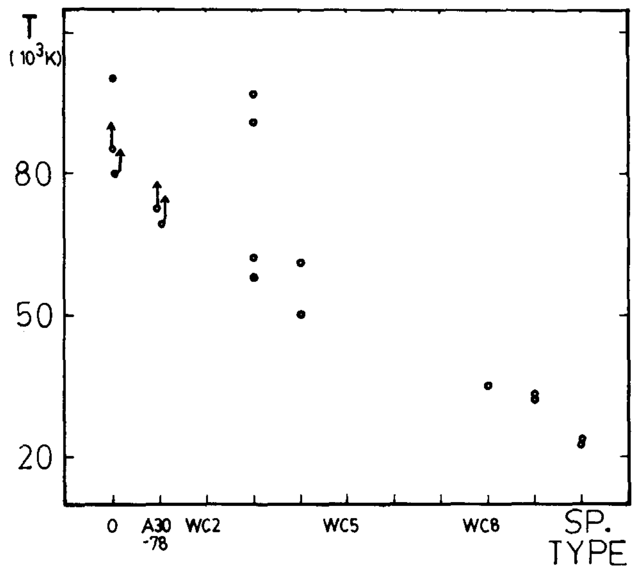

Figure 7. Stellar surface temperature plotted as a function of spectral type.

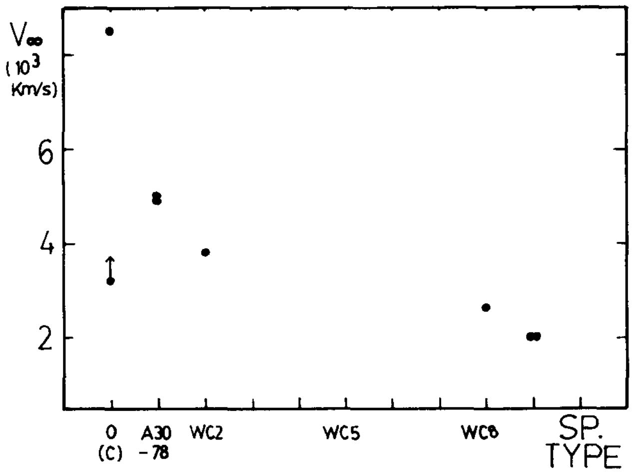

Figure 8, Terminal velocity of stellar wind plotted as a function of spectral type.

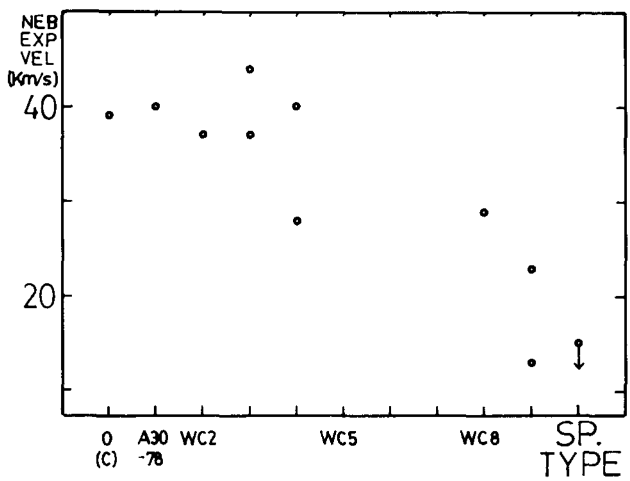

Figure 9. Nebular expansion velocity plotted as a function of spectral type. The trend is similar to that found by Phillips (1984).

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differences between the masses of H-deficient and H-rich CSPN or of their ancestors.

Greig (1971,1972) states that WC objects are associated with what he calls "B" nebulae, which would appear to belong to an intermediate Population I having more massive ancestors than "non-B" nebulae. Peimbert and Torres-Peimbert (1983) state that "Type I" planetary nebulae, defined as having nebular abundances N(He) / N(H) > 0.125 and/or log (N/O) > -0.3, frequently belong to the "B" class defined by Greig, and give additional arguments to suggest that Type I PN are associated with the most massive ancestors. Heap (1982, 1983), based on plots of absolute visual and ultraviolet magnitudes as functions of the nebular radius, suggests that WC CSPN may be more massive than O-type CSPN (meaning by "O-type" the stars we have called O(H) and hgO(H) in Table I).

On the other hand, Phillips (1984), on diagrams very similar to those used by Heap, finds no clear difference between the masses of WC, Of, O and sdO CSPN, and finds them less massive than CSPN classified as WR-Of. Perhaps this helps to understand why we are not inclined to give much weight to available distance determinations.

Let us study more carefully the relation between surface abundances of CSPN and nebular classes defined on the basis of morphological or nebular abundance determinations. We divide CSPN in two groups: the 27 H-deficient CSPN listed in Table II, and the 49 H-rich CSPN listed in Table III. Looking now for those objects that have been assigned a morphological class (see, e.g., Sabbadin 1984), we find among H-deficient CSPN 9 B and 4 non-B objects, and, among the H-rich CSPN, 6 B and 16 non-B objects. There would seem to exist a tendency for H-deficient CSPN to be associated with B nebulae and for H-rich CSPN to be associated with non-B nebulae.

In view of this, we should expect to find most of the H-deficient CSPN associated with Type I nebulae, as defined by Peimbert and Torres-Peimbert (1983). We have what seem to be reliable determinations of the required nebular abundances for 12 of the H-deficient CSPN listed in Table II. We find 4 of them associated to Type I nebulae (NGC 2371, 2452, 5315 and 6751), while 8 are definitely not (NGC 40, 2867, 6578, 6905, 7026; IC 1747, 2003; BD+30°3639). The prediction has failed.

From the evidence we have discussed, we conclude that there is no strong reason to associate the surface H-deficiency of CSPN with more massive CSPN or more massive progenitors.

We further note that the available evidence does not support the suggestion that WC early CSPN might be more massive than WC late CSPN (Peimbert 1985).

Unfortunately, the log g - log T_{eff} diagram is still of very limited usefulness in the present discussion. Only one H-deficient CSPN (K1-27) is plotted in Figure 1, where it appears among the H-rich CSPN, again speaking against a significant difference in mass. However, we prefer to end this section by saying that, at the present time, it is not possible to make any solid statement on the subject.

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3.7. Observational constraints

In its present state, the theory of stellar structure and evolution is not able to explain in detail the variety of characteristics observed in stars approaching the white dwarf configuration. A completely satisfactory description will probably have to wait until better theories for mass loss and convective mixing are developed. Normally, the best way for making progress is a semi-empirical approach, in which observational constraints play an essential role. With this in mind, we summarize those few observational constraints which appear to be well established from what has been discussed about CSPN:

(a) The lack of separation in Figure 1 between CSPN and extreme sdO stars not known to be surrounded by planetary nebulae. A careful search for faint nebulosities or dust shells around these sdO stars might yield positive results, as it did in the case of Sanduleak 3 (van der Hucht et al. 1985), perhaps leading to the elimination or modification of this constraint.
(b) Less than 35% of all CSPN are H-deficient.
(c) The absence of WC5, 6 and 7 CSPN.
(d) The existence of an evolutionary link connecting WC early, O(C), hgO(C) and PG1159 objects.
(e) The variety of surface abundances which is beginning to become apparent among H-deficient CSPN.
(f) Surface H-deficiency appears to be much more common than ejection of H-deficient material. However, as mentioned in Section 3.5, studies on the possible existence of nebular He abundance gradients or discontinuities near the H-deficient CSPN are lacking, and future work might change this conclusion.

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REFERENCES

Acker, A. 1975, Astron.Astrophys., 40, 415.
Acker, A. 1976, Ph.D.Thesis, Univ.L.Pasteur.
Aller, L.H. 1965, in Landolt-Bornstein, Group VI, Vol. 1, ed. H.H.Voigt (New York: Springer), p. 566.
Aller, L.H. 1968, IAU Symp. 34, p. 339.
Aller, L.H. 1977, R.A.S.C.Journal, 71, 67.
Aller, L.H. and Czyzak, S.J. 1979, Astrophys.Sp.Sci., 62, 397.
Aller, L.H. and Czyzak, S.J. 1983, Astrophys.J.Suppl., 51, 211.
Aller, L.H., Keyes, C.D., Ross, J.E. and O'Mara, B.J. 1981, M.N.R.A.S., 197, 647.

Barlow, M.J., Blades, J.C. and Hummer, D.G. 1980, Astrophys.J., 241, L27.
Barlow, M.J. and Hummer, D.G. 1982, IAU Symp. 99, p. 387.
Bond, H.E., Grauer, A.D., Green, R.F. and Liebert, J.W. 1984, Astrophys. J., 279, 751.
Caloi, V., Castellani, V. and Tornambe, A. 1978, Astron.Astrophys. Suppl., 33, 169.
Cerruti-Sola, M. and Perinotto, M. 1985, Astrophys.J., 291, 237.
Flower, D.R., Goharji, A. and Cohen, M. 1984, M.N.R.A.S., 206, 293.
Goodrich, R.W. and Dahari, O. 1985, Astrophys.J., 289, 342.
Grauer, A.D. and Bond, H.E. 1984, Astrophys.J., 277, 211.
Greenstein, J.L. and Minkowski, R. 1964, Astrophys.J., 140, 1601.
Greig, W.E. 1971, Astron.Astrophys., 10, 161.
Greig, W.E. 1972, Astron.Astrophys., 18, 70.
Groth, H.G., Kudritzki, R.P. and Heber, U. 1985, Astron.Astrophys., 152, 107.
Heap, S.R. 1975, Astrophys.J., 196, 195.
Heap, S.R. 1977, Astrophys.J., 215, 609.
Heap, S.R. 1982, IAU Symp. 99, p. 423.
Heap, S.R. 1983, IAU Symp. 103, p. 375.
Heber, U. 1985, 'The atmospheres of subluminous B stars II', Astron. Astrophys., in press.
Heber, U., Hunger, K., Jonas, G. and Kudritzki, R.P. 1984, Astron. Astrophys., 130, 119.
van der Hucht, K.A., Conti, P.S., Lundstrom, I. and Stenholm, B. 1981, Sp.Sci.Reviews, 28, 227.
van der Hucht, K.A., Jurriens, T.A., Olnon, F.M., The, P.S., Wesselius, P.R. and Williams, P.M. 1985, Astron.Astrophys., 145, L13.
Hunger, K. and Kudritzki, R.P. 1981, The ESO Messenger, No. 24, p.7.
Husfeld, D. 1986, Ph.D.Thesis, Munich Univ., Institut f. Astron. und Astrophysik.
Jacoby, G.H. and Ford, H.C. 1983, Astrophys.J., 266, 298.
Johnson, H.M. 1976, Astrophys.J., 208, 127.
Kaler, J.B. 1983, Astrophys.J., 271, 188.
Kaler, J.B. 1985, Astrophys.J., 290, 531.
Kaler, J.B. and Feibelman, W.A. 1985, Astrophys.J., 297, 724.
Kaler, J.B., Jing-Er, M. and Pottasch, S.R. 1985, Astrophys.J., 288, 305.
Kaler, J.B. and Shaw, R.A. 1984, Astrophys.J., 278, 195.
Kudritzki, R.P., Méndez, R.H. and Simon, K.P. 1981a, Astron.Astrophys., 99, L15.
Kudritzki, R.P., Simon, K.P. and Méndez, R.H. 1981b, The ESO Messenger, No. 26, p. 7.
Lutz, J.H. 1977, Astrophys.J., 211, 469.
Lutz, J.H. 1978, IAU Symp. 76, p. 185.
Martin, W. 1981, Astron.Astrophys., 98, 328.
Méndez, R.H., Kudritzki, R.P. and Simon, K.P. 1985, Astron.Astrophys., 142, 289.
Méndez, R.H. and Niemela, V.S. 1982, IAU Symp. 99, p. 457.
Paczynski, B. 1971, Acta Astron., 21, 1.
Peimbert, M. 1985, Rev.Mex.Astron.Astrof., 10, 125, see also p. 133.
Peimbert, M. and Torres-Peimbert, S. 1983, IAU Symp. 103, p. 233.
Phillips, J.P. 1984, Astron.Astrophys., 137, 92.

https://doi.org/10.1017/S0252921100090928 Published online by Cambridge University Press

Preite-Martinez, A. and Pottasch, S.R. 1983, Astron.Astrophys., 126, 31.
Sabbadin, F. 1984, Astron.Astrophys.Suppl., 58, 273.
Sanduleak, N. 1983, Pub.A.S.P., 95, 619.
Schönberner, D. 1981, Astron.Astrophys., 103, 119.
Schönberner, D. 1983, Astrophys.J., 272, 708.
Sion, E.M., Liebert, J. and Starrfield, S.G. 1985, Astrophys.J., 292, 471.
Smith, L.F. and Aller, L.H. 1969, Astrophys.J., 157, 1245.
Smith, L.F. and Aller, L.H. 1971, Astrophys.J., 164, 275.
Starrfield, S., Cox, A.N., Kidman, R.B. and Pesnell, W.D. 1984, Astrophys.J., 281, 800.
Torres, A.V. and Conti, P.S. 1984, Astrophys.J., 280, 181.
Torres-Peimbert, S. and Peimbert, M. 1977, Rev.Mex.Astron.Astrof., 2, 181.
Webster, B.L. and Glass, I.S. 1974, M.N.R.A.S., 166, 491.

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DISCUSSION

FEAST: Is it known whether or not there are PN in the Magellanic clouds which fit the correlations you have shown?

MENDEZ: No. I don't think so.

LYNAS-GRAY: What is the helium abundance of the hydrogen deficient central star of K 1-27.

MENDEZ: The helium abundance (by number) is 0.6 $\pm$ 0.3 (Mendez et al. 1985, Astron. Astrophys. 142, 289). This result is to be regarded as preliminary, since hotter models and pure He models are not yet available.

SCHÖNBERNER: Is the nebular abundance known for K 1-27?

MENDEZ: We don't know it for this object. We know the nebular abundance for several WC central stars. In several cases the nebular abundance is normal. Nobody has checked whether there is a change in He abundance as you go near to the star. For that we need much better angular resolution. I would suggest space telescope should study this problem.

LIEBERT: Could you compare the likely atmospheric parameter for K 1-16 with K 1-27? I would have expected based on our models for PG 1159-035 that $T_e \approx 100000$ K and log g $\geqslant$ 6. K 1-16 should fall very close to K 1-27. But the spectra have some rather interesting differences in the absorption lines. In particular, you see He II 4540 of the Pickering series, which is strong and easily defined. In K 1-16, you don't see that. Normally this would be interpreted as a gravity effect. I just wondered if you had given any thought to fitting the absorption lines in K 1-16 with just helium models.

MENDEZ: I would not dare to, because you see all He II lines are severely contaminated with C IV lines. You would not know what you are doing. We need non-LTE model atmospheres for mixtures of He and C, which are not yet available.

DRILLING: I wanted to mention that I have looked for photometric variability in the LS objects and found none to show pulsations.

MENDEZ: Perhaps they are cooler, you would expect pulsation at about 100000 K more or less.