NUCLEI OF PLANETARY NEBULAE

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1. Introduction

In 1969 Aller and I collected information about the spectra of emission-line nuclei of planetary nebulae. (See also Aller, 1967, for classification of both emission and absorption spectra.) We classified them and compared them to the spectra of Population I stars. Our idea was to follow this general classification by detailed observation and comparison of stars in each of the classes. Most of the detailed studies are not complete, but already the picture has changed from the way Aller and I saw it.

Let me emphasize first that the spectra of planetary nuclei frequently mimic those of massive Population I stars. This presumably results from the fact that both types of stars are hot. We are considering now only those spectra which show emission lines, and are ignoring those which do not. Note, however, that many of the latter are classified as O type and are rather like the spectra of Population I O stars.

An object is called a planetary nebula if it is in the Perek-Kohoutek *Catalogue*

TABLE I

The numbers of planetary nuclei and population I stars in the various spectral groups

Class[a]	Planetary[a] nuclei	Population I Stars with ring nebulae		Population I Stars in general	
		Definite	Possible	Galaxy	Mag. Clouds
WR	2 WC6	3 WN5		65 WN[f]	44 WN[e]
	1 WC8	2 WN6	2 WN6[b]	56 WC	16 WC
	2 WC9	1 WN8	1 WN7		
	1 WN8				
O VI	10	←?—3—?→		4[c]	
Of	1 O7f[d] (NGC 2392)	1 (NGC 7635)		Many	
Of pec	5			Some[d]	
WR-Of	5 (e.g. NGC 6543)			? (HD 93131)[g]	

[a] According to Smith and Aller (1969).
[b] Crampton (1971) adds one WN7 and one WN6 to the list given by Smith (1966; quoted by Underhill, 1968).
[c] Sanduleak (1971).
[d] Heap (1971).
[e] Smith (1968b).
[f] Smith (1968a).
[g] Walborn (1971).

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(1967, henceforward PKC). That is not very helpful to the present discussion. (See Heap, 1970, for a suggestion of a more specific definition.) For our present purpose I suggest a simple observational distinction between planetary nebulae and the 'ring' nebulae observed around Population I WR stars – the spectrum of a planetary nebula always appears superimposed on the spectrum of the central star, while that of a ring nebula does not. This observational definition is obviously related to the relative brightness of the star and the nebula. Most of the objects considered in this paper which are in the PKC satisfy the above criterion for a planetary nebula; however, there are a few exceptions which will be noted in the section on O VI spectra.

The situation as it was in 1969 is summarized in the first two columns of Table I. I will take each class in turn and try to bring the picture up to data.

2. WR Spectra

There are six planetary nuclei whose spectra are known to be reasonable imitations of the spectra of Population I WR stars; of these, 5 have WC spectra and only one has a WN spectrum. This is in sharp contrast to the distribution of the galactic WR stars, in general, where WN and WC spectra are about equally numerous, and to that

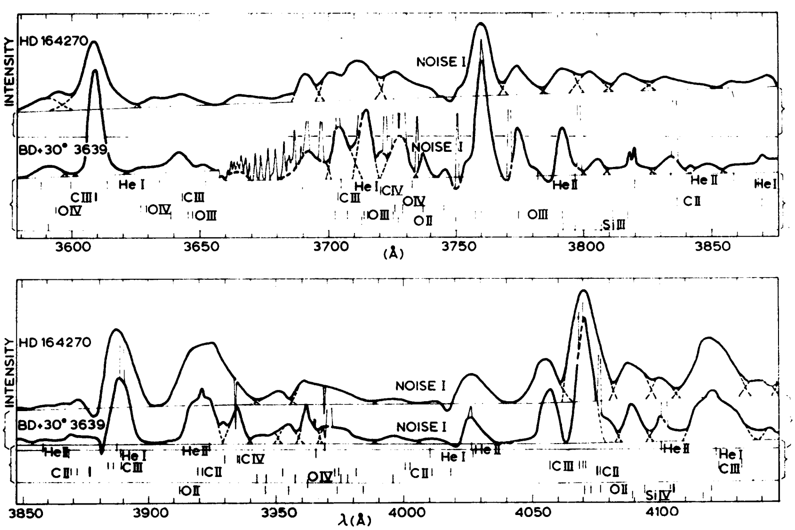

Fig. 1.

of WR stars associated with ring nebulae, in particular, which all have WN spectra. A detailed comparison of the spectrum of one of the WC9 nuclei, BD + 30°3639, with that of the Population I WR star HD 164270, shows (Smith and Aller, 1971) that the two are extremely similar, with the exception that the line widths differ systematically by a factor of 1.6. Figure 1 shows a section of the spectrum of each star.

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Clearly, the spectrum of the Population I star looks like a smeared version of the spectrum of the planetary nucleus (minus the nebular spectrum). The line widths are shown plotted against ionization potential in Figure 2. The equivalent widths of lines in the two spectra are the same with the exception of those of lines of Si III, He I and C II which are 1.4 to 2.4 times larger in the spectrum of the Population I star.

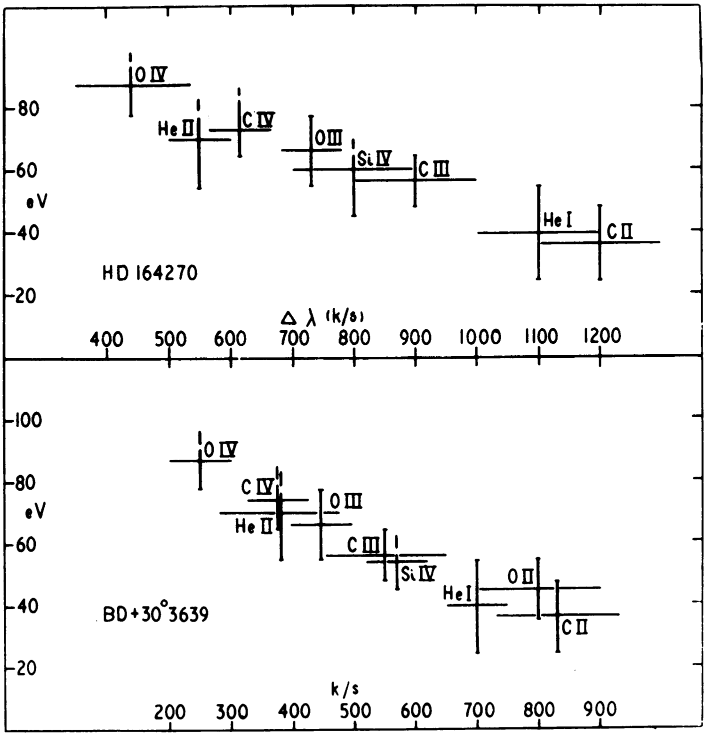

Fig. 2.

A similar situation apparently applies to the WC 9 spectrum of the nucleus of He 2–99, and probably also to the WC8 spectrum of the nucleus of NGC 40. However, comparison of the WC6 spectrum of the nucleus of NC 6751 to those of Population I WC6 stars shows a different situation; the line widths are, in this case, comparable, but the spectrum of NGC 6751 is unusual in the presence of strong N IV λ 3480 emission and possibly other nitrogen lines as well (see Aller, 1967). The spectrum should probably be classified WC6–WN5. There *are* intermediate N–C spectra among the Population I WR stars, but they are uncommon and, when they do occur, are usually of lower excitation class, e.g. WC7–N6.

The WN8 spectrum of the nucleus of M1–67 appears, to visual inspection, to be identical in every way to the WN8 spectra of Population I stars.

3. O VI Spectra

The second group of spectra Aller and I called 'O VI Spectra' because the strongest lines are O VI λ 3834, λ 3811. Some of these have absorption lines and narrow emission lines like Of spectra; others have broad emission lines and no absorption lines like WR spectra. While the O VI lines are present in all the high excitation WC spectra, Aller and I thought that their occurrence as the dominant lines in the spectrum was unique to the planetary nuclei. This is not the case. Sanduleak (1971) has pointed out five objects whose spectra fall in this class that are not in the PKC. One is in the Small Magellanic Cloud (SMC) and one in the Large Magellanic Cloud; their luminosities are comparable to those of the WR stars. Photometry and spectra of the object in the SMC are given by Smith (1968b) (the spectrum is in Plate 1 and is incorrectly labelled SMC 1 instead of SMC 2), and of one of the galactic objects by Blanco *et al.* (1968a, b).

There is a region of confusion between the planetary and non-planetary nebulae at this point. I have chosen to distinguish planetaries from Population I ring nebulae by the high relative brightness of the nebula to the star, so that the spectrum of the nebula always appears superimposed on the stellar spectrum. However, Abell (1966) has identified objects as old planetary nebulae that are characterized by large size and very low surface brightness. Consequently the nebular spectrum does not always appear superimposed on the stellar spectrum, and some of the nebulae are similar in appearance to the ring nebulae. One such object is Abell 78. A similar object is NGC 5189. Both are listed in the PKC; both nuclei show O IV spectra. The object No. 4 in Sanduleak's list is also situated in a large faint ring of nebulosity; this object is not in the PKC. I have indicated in Table I that these three objects are of uncertain population. My guess is that they are closely related to the planetary nebulae, but without some independent way of determining the luminosity of the central stars this cannot be proven.

4. Of Spectra

Among Of spectra, Aller and I considered two types: those that showed only helium and nitrogen in emission – which is the common form among Population I stars – and those that also showed carbon lines in emission with strengths comparable to those of the nitrogen lines. We believed the latter to be unique to the planetary nuclei – in the sense that, while carbon lines do sometimes occur in the spectra of Population I Of stars, they are usually rather fainter than the nitrogen lines. However, Heap (1971) has found that, for many planetary nuclei with Of pec spectra, spiral-arm stars can be found with essentially identical spectra.

In summary, it is probably safe to extend Heap's statement to all of the emission-line nuclei – the spectra of many emission-line planetary nuclei (from all defined classes) have counterparts among the spectra of Population I stars. However the relative numbers of stars showing the various types of spectra are quite different. Whereas Aller and I believed that certain types of spectra were characteristic of planetary nuclei alone, that statement now needs modification to – "certain types of spectra are much more common amongst planetary nuclei than among Population I stars".

This begins to make sense in the light of an observation made by Heap (1971). She notices that the intermediate N–C spectra are found among the *early*-Of spectra. This may imply that there is a correlation between the strength of the carbon lines and the temperature of the star, in the sense that the hotter stars have stronger carbon lines. Thus the predominance of spectra with strong carbon lines among the planetary nuclei may simply reflect the fact that planetary nuclei have higher temperatures, on the average, than do Population I stars.

The same situation may apply to the WR and O VI spectra. If we interpret the O VI spectra as a high excitation extention of the WC sequence, as suggested by Freeman *et al.* (1968), then a greater frequency of O VI spectra among planetary nuclei than among Population I stars may again reflect the greater frequency of high temperatures among planetary nuclei. (I would not invoke the same logic to explain the difference in distribution between WN and WC spectra, since I do not think the difference between WN and WC spectra is due to difference in temperature.)

5. WR-Of Spectra

I have ignored the last group in the table until now, because they are the most confused. Aller and I found there were some spectra which appeared to be intermediate between WR and Of spectra in the sense that they had narrow lines, like Of spectra, but did not appear to have an absorption spectrum. We considered these spectra also to be unique to the planetary nuclei.

The best observed star among those that we placed in this class is the nucleus of NGC 6543. Aller (1967) has found absorption lines in the spectrum and noted that at least some of them were of P Cygni type. Heap (1971) has noted that the spectrum is rather similar to that of HD 93131, a star in the Carina association which is classified WN7. She confirms that the spectrum of the nucleus of NGC 6543 shows narrow emission lines of C, N and O (see also Swings, 1940; Aller, 1943; Aller, 1956) and that the absorption lines are of P Cygni type. The spectrum of HD 93131 (Walborn, 1971) shows, of the three elements of interest, only N in emission, and P Cygni profiles on all of the H and He lines. Underhill (1968), has previously noted the presence of "an absorption dip" at Hγ and suggested that the star was composite. However, absorption edges on the Pickering series are also found in the spectrum of HD 151932, the WN7 star included in the *WR Atlas* (Kuhi and Smith, 1973); in this case the lines cannot be attributed to a companion (see elsewhere in this Symposium), and would seem to be characteristic of the class.

Mostly on the basis that the N III and C IV lines in the region 4630 to 4660 Å are much narrower in the spectrum of NGC 6543 than in WR spectra, and that the absorption lines are of the P Cygni type (rather than undisplaced as in Of stars), I am still inclined to classify this spectrum as intermediate; however, the reality and correct definition of the class are open to question.

Aller and Heap classify the emission spectrum of HD 45166 (which they believe to be a member of the disk population) as WR-Of. This spectrum has narrow emission lines (of greater number and strength than is characteristic of Of spectra) together with broad undisplaced absorption lines. In view of the intermediate H/He ratio, 5/1, that they derive, the assigned classification appears to be physically meaningful. It would be of great interest to know whether the same applies to some of the planetary nuclei that are presently classified WR-Of.

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DISCUSSION

Conti: We all know that, generally speaking, planetary nebulae are Population II objects. Could you review the evidence that shows that the nuclei of planetary nebulae must also be Population II objects? The statement is made that planetary nebulae are of Population II and, therefore, the nuclei are Population II also. Can you be sure that these objects are really Population II by evidence other than that they have planetary nebulae. In other words, is there kinematic evidence for this group or not?

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Smith: I do not know off hand what the velocities of these objects are. You have only a very small sample, by the time you have selected only known emission line nuclei. I should emphasize in all discussions of the distinction between Population I and Population II nebulae, that if you take one nebula and say "prove to me that this is Population II", that is pretty difficult to do.

Conti: What I want to know is, do we have to say these are one solar mass objects because they have planetary nebulae, or could they be massive objects that have formed planetary nebulae which looks like any other planetary nebula?

Smith: There are many planetary nuclei whose spectra mimic those of Population I objects; why should there not be some that mimic WR and Of stars?

Underhill: Is there any information on proper motions and radial velocities of these particular objects? If not, then I think it is essential to get such data because these objects do have apparent nebulae around them. On Tuesday we spent a long time talking about ring nebulae around certain Wolf-Rayet stars, and one can quite easily change that idea into planetary nebula-type extensions. I think that it is very important to tighten the argument up for these objects, because you can have planetary nebulae that are barely detectable. And you can have of course the classical ones which were seen and gave the name to that kind of object. We begin from the ring nebulae in Wolf-Rayet-like stars and possibly some ring nebula O-stars, if there are any, which overlap in concept.

Smith: I do not believe that the ring nebulae form a continuous sequence with the planetary nebulae. Their properties are quite distinct from planetary nebulae: their morphological appearance is different and their electron densities are much lower – a few hundred per cc. There are, incidentally, no 'ring' nebulae around O stars.

Underhill: What do you mean by their 'morphological appearance'? I have seen pictures of planetary nebulae that just almost are not there. And they have condensations and irregularities. It is a little bit difficult to decide what is meant by morphological properties.

Smith: All the ring nebulae have a somewhat filamentary, shell-line structure to the extent that the region in the immediate vicinity of the star is obviously of very low density.

Underhill: You mean you do not see any Hα radiation from it?

Smith: Correct. This is a usual structure for a planetary nebula (although some of Abell's very old nebulae have a similar form). So far as I am aware, the morphology of planetary nebulae with emission line nuclei is not systematically different from that of other planetaries. In particular, they do not show the filamentary, ring-like structure that is characteristic of the Population I nebulae. Planetary nebulae are generally 'filled in', often with extensive structure in the inner regions.

Underhill: I do not understand what you mean by them being filled. I am thinking of the very common picture of the Ring Nebula in Lyra, the center of which in a usual photograph, is not filled.

Smith: That is right. But the nucleus is not an emission line star. My statement stands that the nebulae around emission line nuclei do not differ in any systematic way from all other planetaries.

Morton: Could you describe the difference in the following way? The planetary nebula is fairly uniform over the whole diameter, or at least uniform over finite width, like the classical Ring Nebula, whereas nebulae around WR stars all have a very sharp outer shell but no inner boundary?

Smith: Yes, that is a fair statement. The ratio on the thickness of the shell to the radius is very large in all the Wolf-Rayet nebulae, larger than is characteristic of planetary nebulae.

Morton: You mentioned the problem of differing excitation in the nebulae. Is there a notable difference between the two kinds?

Smith: In part. The nebulae around the Population I WR stars have spectra like ordinary, low excitation, diffuse nebulae. Among the planetary nebulae, the excitation varies; the nebulae with 'O VI' nuclei are of very high excitation, NGC 6751 (WC6 nucleus) is also of high excitation; such high excitation is, I believe, characteristic of planetary nebulae and is not found among diffuse nebulae. However, the planetary nebulae with WC8 and WC9 nuclei show low excitation; I could not say, off hand, whether there are obvious differences from the Population I nebulae or not.

Johnson: I think Anne Underhill has a point about the morphological difficulties, because Minkowski, perhaps the most expert of all recognizers of nebulae, thought the shell around HD 50896 was a planetary nebula and also Pikelner has the classification of NGC 6888 as a supernova remnant. So among these shells around Population I Wolf-Rayet stars there is an ambiguity of morphological classification by the experts.

Smith: I cannot emphasize enough, though, that you take one object, and it is impossible to tell the difference. But, statistically, I think the differences between the two is impressive.

Johnson: I do want to mention one other point, and that is we do not know too much about the

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motions in the nebulae in these Population I shells, but in the case of NGC 6888 at least two people agree that the expansion velocity is around 50–60 km s^{-1}, which would be rather high for a planetary and rather low for a supernova remnant. Whereas in the case of NGC 2359 and 3199 (ring nebulae around Wolf-Rayet Population I stars), the Courtes group find internal velocity dispersions of just a few km s^{-1}, which might be comparable with planetary nebula dispersions of velocity. So there, I think, the velocity criterion does not tell you whether the shells are like planetary nebula shells or not.

Smith: Again stressing the statistical aspect, if you divide the nebulae according to whether it is called a planetary nebula or not you find many statistical differences between the stars in the middle of the nebulae. Including, I might say, the fact that all the stars in the middle of the ring nebulae are WN's whereas most of the ones in the middle of planetaries are WC's.

Walborn: Following along that line, the arguments are statistical, but I am struck by the fact that there are three categories there on the board, each of which has only one object in it, and, therefore, statistical reasoning is very dangerous. In each one of those cases the most distinguishing characteristic is that it is different from the majority and it is most similar to Population I. That is the O7f, the WN8, and the one that looks like HD 93131. Also, there is always the possibility of runaway stars too, even if they are out of the plane, in the case of an individual object.

Kuhi: Coming back to the Ring Nebula in Lyra, if you photograph it in the lines of Ne v, is it not true that it is completely filled in? Has anybody ever looked at any of these nebulae around your WR stars in emission lines from the higher stages of ionization to see if anything similar happens?

Smith: No, there are only ordinary red photographs, to my knowledge.

Kuhi: How many WR stars are you talking about? You say the statistics are very good, but I do not know what the number is.

Smith: Well, there are 6 Wolf-Rayet nuclei and 6 to 9 'ring' nebulae, depending on how many of the 'possible' ones you count.

Van Blerkom: Several years ago, Johnson and Hogg looked at NGC 6888 and calculated how much interstellar material would be swept up. The nebula around that star was pretty massive compared to planetary nebulae, around 4 solar masses.

Morton: Are there very many nebulae with masses less than 0.1 solar mass?

Paczyński: The total number of objects is about 30 or so. You need the electron density to estimate the mass of a planetary nebula without knowing the distance. The estimates of electron density are very uncertain and contribute to the observed scatter of nebular masses. Vauclair (1968, *Ann. Astrophys.* **31**, 199) derived nebular masses from the radioemission observed in about 20 planetary nebulae. He got masses anywhere between 10^{-3} and 10 solar masses. I think there is no observational reason to believe that all planetary nebulae have masses of 0.2 or 0.6 solar masses. This mean value was originally derived to get the distances to a large number of nebulae, and the distance estimate is not very sensitive to the assumed value of the nebular mass.

Smith: It would probably be safe to say that the planetary nebulae are less than 10 solar masses, whereas the nebulae around Population I WR stars have masses as high as 100 $M_\odot$ (see Johnson in this symposium). Many of them are much more massive than planetary nebulae.

Thomas: Is there any reason to speculate now that maybe the upper or the lower limit is the more reasonable value and that everything else is just observational inadequacy? If I take what Lindsey Smith says here, could I say everything should be at the upper limit of the scatter and everything else is the spread. Or everything should be at the lower limit of the scatter and everything else is the spread.

Paczyński: As long as you do not have reliable estimates of the observational errors, you can just say that the true value is somewhere in the middle and that the intrinsic scatter is unknown. I tried to derive the mass of the nebula around BD + 30° 3639. Depending on whose value I choose for the electron density and for the surface brightness of the nebula, I can get anything between a fraction of a solar mass and almost 100 solar masses.

Morton: Do I understand you are saying that the masses of the rings around some Wolf-Rayet stars may not be too different from planetary nebula masses? Do you really want to suggest that a typical planetary nebula could be easily within the range of the masses of these ring nebulae?

Paczyński: I suspect that the definition of a planetary nebula is sufficiently vague to make any definite statement difficult. Depending on the definition, you may either include those objects in a list of planetary nebulae or you may consider them to be different from planetary nebulae.

Morton: Do we agree then, that the ring nebulae around Wolf-Rayet stars are in the upper mass range of all planetary nebulae? They are definitely not typical of the average.

Thomas: Let us come back to pushing the argument farther. Suppose I take what Kuhi, Conti and

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Paczyński have been talking about, that the real index of the Wolf-Rayet kind of spectrum is the mass loss, in some sort of a vague way. Then, if I take the three characteristics of the Wolf-Rayet-type planetary nebula spectrum that Lindsey Smith pointed out and consider the fact that the lines have about the same equivalent widths but with a factor of 1.6 in the actual width between the two cases, that means that the central intensity of the planetary nebula-type Wolf-Rayet star is higher relative to the continuum than is the central intensity of a Population I type Wolf-Rayet star.

Smith: Aller and I attempted to account for the observed similarities and differences between BD + 30° 3639 and HO 164270 by suggesting that they were exact scale models of each other. This works quite nicely. If you believe that you have two stars which differ in mass by a factor of 10, then, in order to obtain similar surface conditions, you have to change the radius by a factor of about 3. So I suggest that the planetary nucleus is 3 times smaller than the Population I star, and, in other respects, they are exactly the same.

Thomas: It must be more active!

Smith: This immediately gives you the difference in the line width, because presumably the acceleration process is the same, and in the bigger star the accelerating force operates over about 3 times as great a distance. You have to pick the dependence of the accelerating force on the radius such that the ratio of observed velocities is the square root of the ratio of the radii, but since a $1/r^2$ accelerating force satisfies the requirement, that would not appear to be a problem. You predict that the equivalent widths of the optically thin lines will be $\sqrt{3}$ times greater in the spectrum of the larger star, in reasonable agreement with the observations. However, you also predict that the equivalent widths of the optically thick resonance lines will be $\sqrt{3}$ greater in the larger star. Resonance lines are not observed, but the optically thick subordinate lines have equal equivalent widths in the two stars. Thus, there may be a disagreement with the model at this point. Van Blerkom did some calculations showing that the properties of the nebula are completely consistent with the properties we required for the nucleus, if it is a scaled version of the Population I star. So, we did not run into any serious conflicts with the assumption that they differed by a factor of 10, except for the central intensity.

Thomas: Then I suggest that you can only reconcile the question of the intensity by increasing the activity, in which case the presence of the nebula measures it.

Smith: That may go in the direction of explaining one thing we could not cope with, so I am very happy. However, greater activity would probably also affect the optically thin lines which appear to behave as predicted.

Morton: Would Lindsey Smith like to comment on the galactic distribution of planetary nuclei?

Smith: The galactic latitudes of the planetary nuclei range up to very high numbers, so that there is obviously a strong galactic distribution difference between these emission line nuclei and the Population I Wolf-Rayet stars. For the Wolf-Rayet nuclei alone, the galactic latitudes go up to 9° and the mean (absolute) value is about 5°, whereas the galactic latitudes of the Population I WR stars rarely exceed 5° and the mean (absolute) value is about 2°. If you include the O VI planetary nuclei in the sample, you include objects up to 20° from the plane.

Morton: What is the latitude dependence of ordinary planetary nebulae?

Smith: They are up to about 20° from the plane; they are 'disk' population.

Alcaino: I understand that one planetary nebula has been found in a globular cluster; does anyone know which cluster is this?

Kuhi: M 15.

Paczyński: What is the galactic latitude of Wolf-Rayet stars with ring nebulae?

Johnson: All ten degrees, or less.

Paczyński: So they are just like those planetary nebulae with WC spectra. Another thing is, we have statistics of about 5 or 7 objects in each class. We may expect random scatter to be large. The main morphological difference between these two classes is such that ring nebulae have very low surface brightness and shell-like structure, while those few planetary nebulae are much smaller and have much larger density.

Smith: Yes, the planetary nebulae have higher surface brightness.

Paczyński: Let us forget about our prejudice that these are two different kinds of objects, and let us assume that this is one kind of object at different evolutionary stages. Perhaps we see the evolution of those nebulae proceeding together with the evolution of the central stars. When a nebula is young, the central star appears like a WC object. Later on the nebula expands and the spectrum of the central star is changed into WN. This would be much more comfortable: at present it is difficult to understand why single WC stars do not produce ring nebulae. I would not like to push this new suggestion too hard, it just came to my mind a few minutes ago – but I think it is not less justified than the subdivision of those objects into two different populations.

Thomas: So you are arguing for all these stars having the same masses, whatever the mass?

Paczyński: Yes.

Johnson: There is the interesting case of the object called GX 3 + 1, longitude 3°, latitude + 1°, which was earlier identified at Cerro Tololo with the X-ray source and later found that the position of the X-ray source is different. However, this is one of those objects which has O VI λλ 3811-34 and so forth strongly in emission, and it also has a ring nebula around it. And the ring nebula is something like 5′ in size; it is not very small. So there you have an ambiguous case which could be a WC planetary nebula with a ring, a weak ring, but nonetheless quite visible. And yet, one cannot be sure that it is a planetary nebula either, at the present time.

Paczyński: Are the expansion velocities derived from the violet displaced absorption edges known for planetary nuclei with the Wolf-Rayet spectra? BD + 30° 3639 was shown here, but are the expansion velocities known for other nuclei too?

Smith: Spectra have been obtained, but have not been measured yet.

Morton: Qualitatively, do all of the Wolf-Rayet nuclei have violet displaced absorption lines?

Smith: Yes.

Morton: And what about the O VI nuclei?

Smith: Not obviously. However, the Of nuclei often show P Cygni profiles. Heap and Aller note P Cygni profiles in NGC 6543. I am not familiar enough with other objects to be able to say.

Morton: So there is a possible problem with the O VI nuclei, that they do not all have evidence of mass loss?

Smith: From Aller's preliminary tracings of the O VI spectra, there do not appear to be strong violet absorption edges.

Underhill: Bappu attempted to see the displaced absorptions and he got results on O VI in a couple of stars. There is great difficulty in detecting those displaced absorptions which occur at O VI in very hot objects. It would indeed take a very careful spectrophotometric study, which has not been done. The nebular spectra fall on top of what you are looking and that is why the detection of expanding shells is spectrophotometrically an unproved thing at the present time.

Van Blerkom: The presence of very broad emission lines indicates that mass outflow takes place. Whether or not violet displaced absorption components appear depends on the structure of the atmosphere.

Paczyński: The violet displaced absorption component is the most clear evidence of mass outflow and it gives directly the velocity of outflow independently of any theoretical model. This should be measured and published every time when the measurement is possible. I had great difficulty in finding those data in the literature.

Sahade: I suppose that one of the conclusions of this Conference is that from now on, we will not say any more that all central stars of planetary nebulae have one solar mass. Very often in the literature we find some very definite statement which people repeat over and over again and later when we look more thoroughly into the problem we find that the statement is not true. I am afraid that the question of the mass of planetary nuclei will be one such case.

Smith: Obviously, if you are going to assert that WR nuclei are more massive than one solar mass you are saying that those nuclei are a great deal more luminous than we have assumed. Somebody must check what that means in terms of their distances and masses, etc., and see if you come up with any contradictions. It seems to me that you have no good reason for separating the Wolf-Rayet nuclei from the rest and declaring that they have the same luminosity and mass as the Population I stars. Why not assert the same for the O VI and the Of and the O absorption spectra and all the others? Because these spectra also mimic all of the Population I types.

Underhill: We come back to my original statement, that to settle this we do need the kinematic information about these stars because the population type is basically defined on kinematics. This is a very difficult observational program, but I think we can here underwrite it.

Paczyński: I believe that the radial velocities were measured by Minkowski for all the possible planetary nebulae some ten or twenty years ago. Unfortunately, those measurements were never published. Is it possible to do anything about it?

Morton: In fairness, whether or not we cross out one solar mass for planetary nuclei, we have not really had any evidence against that for the traditional planetary nebulae in this discussion. It raises just the question of the Wolf-Rayet planetary nebulae, which is, I understand, a very small sample of the total number of planetary nebulae, 1% or something like that.

Sahade: We have quite a variety of objects, and to assign to all of them the same mass does not seem very reasonable.

Westerlund: There are more than a 1000 planetary nebulae known. It would be about 10 or 20 here, which means that we are talking of about 2% of them.

Smith: Unfortunately we have not been able to observe the nuclei of most of the planetaries, so we have some nasty selection effects on this.

Thomas: How many nuclei have you observed you can be sure of?

Westerlund: Would emission lines from the nuclei not show up fairly well also in spectra taken of the nebulae only and not aimed particularly for the nuclei?

Mendez: There are more or less 50 or perhaps 60 nuclei of which spectra with some details have been taken.

Thomas: So, the percentage we are concerned with might be 30%.

Conti: Lindsey Smith has spoken of the differences in line widths of the WR nuclei with respect to normal WR; what about the Of stars? If you just look at the spectrum and did not know about the nebula, would there be any difference?

Smith: I think the line widths are similar but I have not studied the problem. I suspect you can find a Population I Of star which has the same line width as any given planetary nucleus Of star.

Conti: And the only reason for thinking these might be different, in addition to having the nebula around them, is, in fact, the galactic latitude.

Smith: Yes, and the fact that they tend to have a slightly different spectral appearance.

Bappu: I have one question to ask on the widths of the lines in a planetary nucleus as compared to the normal Wolf-Rayet star. It is just a matter of making such a comparison with a typical type star, but amongst the Wolf-Rayets of that particular spectral class, what would be the range in widths?

Smith: Much less than the difference between the two groups; there are two WC9 stars that have nebulae associated with them, and both have lines which are obviously much narrower (even with casual inspection) than lines in the spectra of seven of the other WC9 stars.

Johnson: I recall that in the papers by the Russian and French groups who did the NGC 6888 velocities getting the expansion of about 60 km s^{-1}, that when they took the mean of the expansion to and from in the line of sight, the mean of the nebular velocities came out comparable in absolute size with the expansion velocity. This nebula happens to be in the direction of Cygnus, of course, so you do not expect much differential galactic rotation and, therefore, it seems that, if you take the straight means, the nebula is moving with a Population II velocity although it is surrounding HD 192163, which is certainly a Population I Wolf-Rayet star. I do not mean to draw any conclusion from this, but I think it is an interesting point.

Morton: Do you have a measurement also of the radial velocity of the particular star?

Johnson: No. Unfortunately not, because it has such wide lines. I suppose most Wolf-Rayet stars do not have a radial velocity measurement in the usual sense.

Morton: Can you not even estimate the velocity to 60 km s^{-1}.

Smith: You get velocities differing by a hundred km from different lines.

Bappu: I think that it could be pinned down to about 10 or 15 km.

Smith: In the Wolf-Rayet spectrum, we do not know which lines to measure. The γ-velocities of binary systems derived from different lines can differ by a hundred kilometers per second from one another. So, how do you know which emission line is giving you the right velocity?

Underhill: Bappu, from his high dispersion work, is now in a position to do this job.

Morton: I presume that there are no known binaries in any of these.

Smith: In the ring nebulae, no. In the planetary nuclei, no. The O VI Wolf-Rayet star, which does not have a nebula appears to be a composite spectrum. But apart from that no other object on the board has a composite spectrum (unless you consider the peculiar Of Wolf-Rayet spectra to be composite). All the others show just emission, no absorptions.

Seggewiss: May I come back for a moment to the distribution in the galactic latitude? If these nuclei are much fainter than the Wolf-Rayet stars, as supposed by Lindsey Smith, then the distribution in latitude must be higher than that of the more luminous Wolf-Rayet stars.

Smith: That is correct; both types have galactic latitudes as high as $+10°$. However, the planetary nuclei are 10–15th magnitude objects and the WR stars are 7–12th magnitude objects. So that if you assume that they are the same luminosity, the distances of the 'planetary nuclei' from the Sun and from the galactic plane are much greater than those of the Population I stars. Temperature does not

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enter. I am just determining the distance from the apparent visual magnitude and the assumed absolute visual magnitude.

Paczyński: Visual magnitude depends on the temperature, and even if these objects have the same bolometric luminosity...

Smith: You are trying to tell me that these are ordinary Population I objects. Do not change your hypothesis.

Paczyński: I do not know. I just cannot see the population difference between the two kinds of objects.

Smith: It is suggested that the 'planetary nuclei' are Population I Wolf-Rayet stars. So I may assert that, therefore, I know their luminosities, etc., and may determine their distances, the same way that I have determined the distances for other Population I WR. And the result is the one I have mentioned a moment ago.

Paczyński: Let me make one suggestion. Let us forget about all the planetary nebulae and all about the Wolf-Rayet stars. Let us forget about Population I and Population II objects. Let us concentrate on those 12 or so objects which do show Wolf-Rayet type spectra and some nebulosities around them. You get about five or so objects which are classified as planetary nebulae and seven objects which are classified as ring nebulae. Now, let us forget about any absolute magnitude estimates for either classical Wolf-Rayet type stars or classical planetary nebulae, as we are not sure that there are no systematic differences between our ten objects of either classes. Let us just try to consider those twelve objects divided into two sub-classes, and see in which way these objects differ, and without referring to any knowledge of genuine Population I objects and genuine planetary nebulae. This will save us a lot of confusion, I believe.

Morton: And, what do we conclude if we do make this?

Paczyński: Let us see; is there any difference, any population difference? And is there any reason from the status of these objects, that they belong to a different population or that they have different luminosities?

Morton: Do you think we have enough information to draw any conclusions?

Paczyński: No, I believe we do not. I think that there is no reason to believe that these two subclasses are really different, if we do not refer to other Wolf-Rayet stars which do not show nebulosities, and those planetary nebulae which do not show Wolf-Rayet-type spectra. And up to now, the procedure was the following: we assume that we know two distinct classes of objects, Population I, Wolf-Rayet type stars, which are frequently binaries, and planetary nebulae which belong to the disc population. Now, it happens that some objects were classified originally as Population I Wolf-Rayet stars, and some others were classified originally as planetary nebulae, and we had a large bias because of this original classification. So, let us forget about this. Let us just concentrate on those twelve objects that you have here, and do not assume that some of them have luminosities or masses like planetary nebulae or like Population I Wolf-Rayet stars. I have no idea what is the population assignment of those objects; that is a thing to be done. But we cannot assign those objects to Population I or II, just because there are similar objects known among Population I or Population II stars.

Morton: Can we not derive at least one conclusion from the totally alternative hypothesis that they are all at roughly the same distance? Then we conclude that the absolute visual magnitudes of the two groups must be quite a bit different, because the apparent magnitudes are different.

Paczyński: The absolute bolometric magnitudes, not necessarily.

Morton: We do not know about that, of course. But then, there is at least one natural separation by apparent magnitude.

Underhill: I have a question to throw out. It concerns the definition of population type. Do you have to assume that all Population I objects are younger than 10^7 yrs, and, therefore, that the objects appearing to have high effective temperatures must be in an early stage of evolution? Some of the Wolf-Rayet stars with nebulae may have been formed 10^7 yrs ago, yet they have raced through to a rather advanced stage of evolution where they are in a stage of producing a planetary nebula, but the development of that nebula and of the central star itself has not yet been completed. The character of these seven or eight stars that Lindsey Smith mentioned may be like the planetary nebula class.

Paczyński: I believe there is nothing wrong with this conclusion as far as stellar interior theory is concerned.

Thomas: What is the problem with the distances?

Smith: I suspect that if you assume that the nuclei of the planetary nebulae have absolute magnitudes equal to those of Population I WR stars, their distances from the Sun will be unreasonably large and their distances from the plane of the Galaxy will be too great for Population I objects.

Underhill: My question was whether there is anything against supposing that some of the hot objects are not −4.4, recognized only from the spectra, but that they have reached the stage where they are considerably fainter. Then the nebula star is not at 6–8 kiloparsecs, because, you could not see the nebula at 6 to 8 kiloparsecs. A star within a ring nebula has, then, to be reasonably close. The only way to make these apparently faint stars close is to assume that their intrinsic luminosities are low. Consider the stars in question which are attributed to Population I. You have no kinematical knowledge of their absolute magnitude. The assumed absolute magnitude is based upon the correlation, a unique correlation it is presumed, between spectral type and visual magnitude. I question the uniqueness of that correlation.

Morton: Has any one looked at any of these planetary nebulae with a radio telescope, as it has been done with ring nebulae?

Johnson: Many planetary nebulae have been observed but I do not know specifically the answer to these things of interest.

Bappu: As far as kinematical aspects that concern the first WN8 object, let me point out that what prompted its first publication by Merrill was that the WN8 object had a real high velocity. That was the principal theme of his paper. And then it turned out to be a planetary and the high velocity corroborated this nature.

Paczyński: Do you expect to discover ring nebulae at large distances?

Smith: Ring nebulae might be difficult to detect at large distances in the galactic plane because of high absorption and their low surface brightness.

Morton: If ring nebulae have the same distribution as the planetaries, you would want to see some at high galactic latitude.

Underhill: It is a very attractive point of view to consider that by taking planetaries of different appearance, you take objects at different evolutionary stages. Then you could say that the only stars you see high up are indeed very old ones. If they have a nebula, they have got one for a very special purpose.

Smith: We have tabulated, for the ring nebulae, the Morton Roberts number of the central star, its spectral class, apparent visual magnitude and galactic latitude. The distances are derived from the absolute magnitudes tabulated in my review and the intrinsic colours derived by me in 1968. For the planetary nebulae are tabulated an identifying name, the spectral type of the central star, its visual apparent magnitude and galactic latitude (see Table Ia and Ib). The absolute magnitudes are assumed equal to those of Population I WR stars of the same sub-class, the distance modulus is derived assuming an absorption of one magnitude (on the basis that the galactic latitudes are all greater than 3°, so after about 1 kpc the line of sight is out of the galactic plane).

The derived distances of the planetary nuclei are absurdly large, 5 to 44 kpc, the derived distances from the galactic plane are correspondingly absurd. Obviously the assumption of high luminosity is incorrect.

I expect that any other set of specific assumptions along the lines being discussed here can similarly be shown to be inconsistent with the observations.

Paczyński: Is the spectrum of NGC 6543 different from that of a Population I object, as far as absorption lines are concerned?

Smith: I do not know.

Underhill: The absorption spectrum is practically identical with the blended absorption and emission line spectrum of HD 93 131.

Paczyński: Then that Population I object can also show an absorption spectrum?

Underhill: Yes, it does.

Paczyński: In addition to the violet-displaced absorption edges?

Underhill: Yes. Can you show the spectrum of HD 93131? It has beautiful O-type spectral lines.

Paczyński: This Population I object is interpreted as a binary, but the nucleus of a planetary nebula is believed to be single?

Smith: WN7 spectra do show violet-shifted absorption components to the Pickering lines. However, if HD 93131 shows undisplaced absorption and is not a binary, then it is not a WR star under the current definition of the class.

Underhill: We have no adequate radial velocity study.

Smith: There are some very big question marks in this area of the classification, and these objects deserve very careful attention.

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TABLE Ia

Ring Nebulae

MR	Sp. Type	v	b	D (kpc)	z (pc)
6	WN5	6.9	−10.1	1.6	284
7	WN5	11.7	− 0.1	6.9	12
21	WN5	11.2	− 1.0	3.6	63
34	WN8	7.8	− 4.8	4.0	336
49:	WN6–C	10.9	+ 0.2	4.8	17
60	WN6	11.4	− 1.5	4.0	105
97[a]	WN7	12.3	+ 1.7	1.0	1.0
100[a]	WN6	8.3	+ 1.6	1.9	53
102	WN6	7.7	+ 2.4	1.4	59

[a] Crampton, D.: 1971, *Monthly Notices Roy. Astron. Soc.* **153**, 303.

TABLE Ib

Planetary Nebulae

Name	Sp. Type	v	b	M_v	$v - M_v - 1$	D (kpc)	z (pc)
NGC-40	WC8	11.0	+9	−4.8	14.8	9	1400
He2-99	WC9	–	−4	−4.4	–	–	–
NGC-5315	WC6	14.8	−4	−4.4	18.2	44	3100
NGC-6751	WC6	13.3	−5	−4.4	16.7	22	1900
MI-67	WN8	10.2	+3	−6.2	15.4	12	630
BD + 30° 3639	WC9	10.1	+5	−4.4	13.5	5	440

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