THE POSITION OF THE CENTRAL STARS OF PN ON THE HR DIAGRAM

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1. INTRODUCTION

Central stars can be placed on the HR diagram if their effective temperature (T_{eff}) and radii are known. Knowledge of the radius can sometimes be replaced by another indication of the luminosity. The distance, which always plays an important, really critical role, is not well known. This is the essential reason that there is so much uncertainty about the position on the HR diagram.

The situation as it was several years ago is the following. Kaler (1983) studied the central stars of an extensive group of large, presumably evolved nebulae. He assumed the distance could be obtained from the Shklovskii method. His resultant diagram, which is shown as Fig. 5c, covers mainly the region after the nuclear burning has stopped. The central star positions are consistent with theoretical evolution calculations for core masses between 0.5 and 0.8 $M_\odot$.

I have approached the problem in a somewhat different way (Pottasch, 1983). The statistical methods of determining distance were discarded. Only those central stars were used whose distance could be determined in an independent way. The fact that they are independent of the statistical methods does not mean they are correct, because determining accurate distances is difficult. The general conclusions indicated: (1) the existence of less luminous central stars than predicted by the Schönberner (1981) 0.55 $M_\odot$ evolutionary track, and (2) the existence of very high temperature central stars.

A third approach to the problem is given in the work of Mendez et al. (1981, 1985). Here the profiles of the stellar H and He lines are measured at high resolution. With the help of model atmospheres, the profiles are fitted to derive T_{eff} and the gravity g. Using theoretical evolution tracks, g may be separated into the central star mass M_{cs}, and the stellar radius R. This leads directly to the luminosity. The distance is a by-product. The method can only work if the model atmospheres is approximately correct. The atmospheres used at present can only reproduce stars with an absorption line spectrum which limits the applicability of the method.

A related method of obtaining information from the evolutionary

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tracks makes use of a comparison between the predicted nebular ages and those observed. This has especially been applied by Schönberner (1981) who plots the predicted absolute magnitude M_V as a function of predicted age, and compares these with the observed values. He has obtained the result that most central stars have core masses between 0.55 $M_\odot$ and 0.6 $M_\odot$. In the comparison knowledge of the distance is necessary and these have been obtained from the Shklovskii method. Another important assumption which goes into this method is a knowledge of at what time in the theoretical evolution the nebulae is ejected. Schönberner (1981) assumes that this occurs when the star has a temperature of 5000 K, but this is apparently an arbitrary choice.

We shall report here on the most recent developments in these approaches, hopefully in a critical way.

2. DISTANCES TO PLANETARY NEBULAE

As mentioned above, the distance determination is critical for placing the central star on the HR diagram. The use of statistical distance scales is becoming more and more suspect, not only by myself (e.g. Pottasch, 1984; 1987; Gathier, 1983) but by others as well (e.g. Wood et al., 1986; Kinman et al., 1987). I feel that it is very dangerous to use for an arbitrary sample of nebulae because of the evidence that young nebulae are much more affected than older ones. This immediately biases the evolution. Kalers results using Shklovskii distances will be discussed below.

It is necessary to separate the groups of nebulae according to how the distance has been determined. This is not only because there may be inherent systematic errors which refer only to that particular group, but also because there are important selection effects present which should be known when intercomparing the results.

The four groups are:

(1) that diccussed by Gathier (1984) and Gathier and Pottasch (1987). They have used distances determined in various ways, but two methods dominated the sample. These are the extinction distance diagrams discussed in detail by Gathier et al. (1986a) and the 21 cm absorption method (Gathier et al., 1986b). The sample of the above authors has been modified to remove the expansion distances determined using photographic plates, for reasons which will become clear presently.

(2) that discussed by Mendez et al. (1987), which uses the analysis of the central star line profiles as discussed above. Only the latest results have been used, since these authors consider them more reliable. They are clearly selected as the brightest known central stars having an absorption line spectrum.

(3) that discussed by Kaler (1983). This group represents distance determination using the Shklovskii method and was chosen as a comparison with the group having independent distance. This particular study was chosen above others using the same distance method for two reasons. First, it has been widely cited and appears to be representative. Secondly, only large evolved nebulae are included in the sample, for wich the errors in the mass are probably limited to an order of magnitude and the distance is probably correct to about a factor of 2.

(4) a sample of galactic center nebulae selected for their faintness. Many are recently reported by Kinman et al. (1987). Some have been discussed by Webster (1975). Radio continuum flux densities have recently become available for all (Gathier et al., 1983; Zijlstra, unpublished).

These samples will now be compared assuming the distance given by the above authors is correct. Fig. 1 is a histogram of the intrinsic 6 cm continuum flux density which the nebulae would have if placed at the galactic center, for the four samples. The results of Jacoby (1980) in a survey of nebulae in the Magellanic Clouds is included for comparison. For many of the nebulae studied by Kaler (1983) and the Magellanic Cloud nebulae radio measurements are not available. In that case Hβ fluxes were used and converted to radio continuum assuming $T_e = 10^4$ K and $He^+/H = 0.1$. The extinction given by the authors was used.

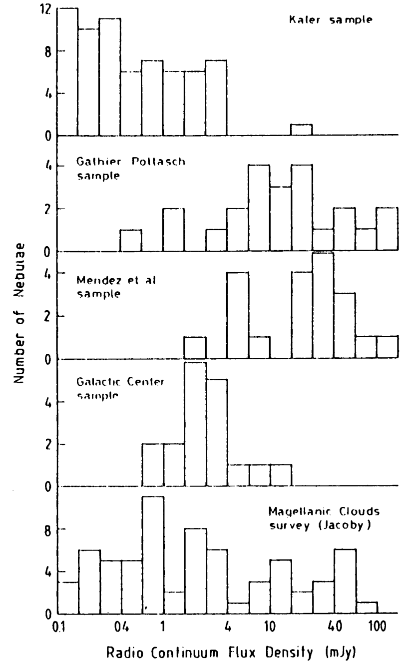

Fig. 1 - Histogram showing the intrinsic 6 cm radio continuum flux density which the nebula would have if placed at the galactic center, for the four samples of nebulae discussed in the text.

From the figure it is clear that the nebulae in both the Mendez et al. sample and (to a slightly lesser extent) the Gathier-Pottasch sample are intrinsically equally bright and are an order of magnitude brighter that the average nebula as defined by the Magellanic Cloud objects. By contrast the nebulae in Kaler's sample are generally very faint objects indeed. Some of them are fainter than the best survey's of the Magellanic Clouds could detect. By comparison, the galactic center sample of faint nebulae seem to be bright.

If the nebular brightness of the Gathier-Pottasch (GP) and the Mendez et al. (M) samples appear similar, in most other ways they are substantially different. First of all most of the GP nebulae are at low galactic latitude, because the method of distance determination is applicable only for low latitudes. The M nebulae in contrast are usually higher latitude objects. In that respect they are similar to the Kaler sample. Another important difference between the GP and M samples is the brightness of the central star. A histogram of the absolute visual magnitude of the central star for the GP and M samples is shown as Fig. 2. As can be seen from the figure there is a difference of at least 5 magnitudes (a factor 100) on the average between the samples.

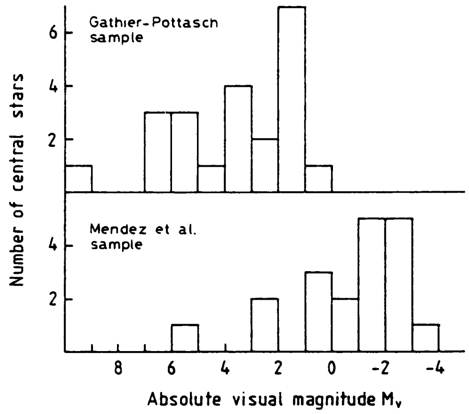

Fig. 2 - Histogram giving the absolute visual magnitude of the central star for two of the samples discussed in the text.

Thirdly there is a difference in morphology between the two samples. The M sample contains mostly symmetric nebulae which are designated as Type II in the classification of Peimbert. The GP sample contains a substantial number of Type I nebulae as well. This is also reflected in the abundances of helium and nitrogen. For example, the histogram in Fig. 3 shows the nitrogen-oxygen ratio for those nebulae in the two samples where it has been well determined (references in the two papers cited). A comparison with all galactic planetaries (e.g. Pottasch, 1984) is given in the bottom part of the diagram. It can be

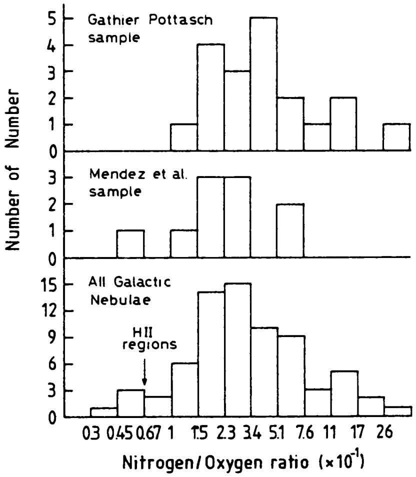

Fig. 3 - Histogram comparing the nitrogen-oxygen ratio of two of the samples with all known galactic planetary nebulae. An arrow in the lower diagram indicates the N/O ratio in HII regions.

seen that the higher N/O values are well represented in the GP sample but are hardly represented in the M sample. The Kaler sample is not plotted but high values of N/O are also present (Kaler, 1983). The consequences of this will be discusses presently.

3. TEMPERATURE OF THE CENTRAL STAR

Before presenting the HR diagrams a few words can be said about the stellar temperatures T_{eff}. Much recent work has been done. The energy balance method has been improved and applied to a large number of nebulae (Preite-Martinez and Pottasch, 1983). New magnitudes have become available for improved Zanstra temperatures (Reay et al., 1984; Shaw and Kaler, 1985; Walton et al., 1986; Gathier and Pottasch, 1987). Finally Mendez et al. (1987) have determined T_{eff} from the (absorption) line profiles. Only in the last case have model atmospheres been used in interpreting flux ratios as temperatures. In the other cases blackbody radiation has been assumed. While this may not be correct, model atmospheres only represent an improvement if they are the correct model for the particular star under consideration.

One of the problems in the temperature determination has been the interpretation of the difference between the hydrogen Zanstra temperature, $T_z(H)$ and the ionized helium Zanstra temperature $T_z(HeII)$. It has long been known that the latter is often higher than the former. Two interpretations have been given: (1) the nebula is optically thin in hydrogen ionizing radiation, while it is optically thicker in radiation which will doubly ionize helium, (2) the actual atmosphere departs from a blackbody in the sense that there is excess radiation shortward of λ 228 Å. While the first explanation probably plays a role in a few of the very large nebulae, evidence is now accumulating that departure from blackbody radiation are the important effect in most cases. Two arguments may be cited.

The first argument is the following. If a plot is made of the ratio $T_z(HeII)$ to $T_z(H)$ against $T_z(H)$, the ratio is much larger for small values of $T_z(H)$ and approaches unity at temperatures above 10^5 K. Such a plot is shown in Fig. 4. Since electron scattering becomes relatively

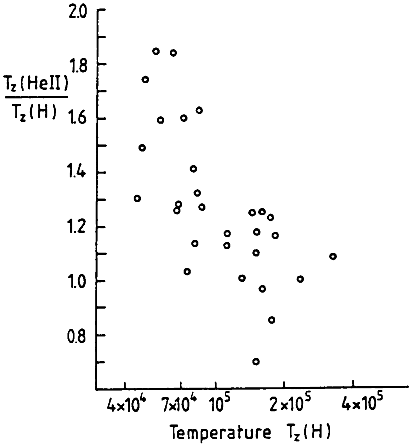

Fig. 4 - The ratio of the HeII Zanstra temperature to the H Zanstra temperature is plotted against the latter quantity (from Gathier and Pottasch, 1987).

a more important source of opacity with increasing temperature, it may be expected that the higher temperature stars emit more like blackbodies than the low temperature objects. Hence the ratio will decrease with increasing temperature as observed. The scatter in the points in the diagram is large and probably real. It may reflect different atmospheric structure at any given temperature.

The second argument derives from a comparison of the various temperature determinations for individual objects, such as shown in Table 1. Here all the stars are listed whose temperature is determined both from a study of the line profiles ($T_{PROFILE}$, Mendez et al., 1987) and from the energy balance method (T_{EB}, Preite-Martinez and Pottasch, 1983). As can be seen from the Table, $T_{PROFILE}$ always lies between T_z(H) and T_z(HeII), usually closer to T_z(H). This is not expected if the difference in the two Zanstra temperatures is due to optical depth effects in which case $T_{PROFILE}$ should be the same as T_z(HeII). It may be concluded that, except for the large, low surface brightness nebulae, a value in between T_z(H) and T_z(HeII) should be used when only Zanstra temperatures are available.

TABLE 1 - STELLAR TEMPERATURES OBTAINED BY VARIOUS METHODS

NEBULA	T_z(H)	T_z(HeII)	$T_{PROFILE}$	T_{EB}
NGC 1535	37	70	58	67
NGC 2392	27	66	47	78
NGC 3242	59	91	68	60
NGC 6891	34	<50	50	40
NGC 7009	68	90	75	60
IC 418	36	-	36	30
IC 2448	49	86	55	70

References: Preite-Martinez and Pottasch, 1983; Mendez et al., 1987; Shaw and Kaler, 1985; Gathier and Pottasch, 1987.

The values of T_{EB} given in the Table are computed assuming the star radiates as a blackbody. They would be reduced, especially for the higher temperatures if the model atmospheres given by Mendez et al. (1987) were used. This would sometimes make the agreement with $T_{PROFILE}$ better, but sometimes it would be worse. In conclusion, it appears that the combination of the different methods yields an effective temperature which is probably reliable to 20%. Obtaining more accurate values of T_{eff} is now very difficult because of present uncertainties in the atmospheric structure. If T_z(H) and T_z(HeII) are equal, the temperature may be more accurate.

4. RESULTANT HR DIAGRAMS

The HR diagrams for each of the samples are shown as Fig. 5a, b and c. On Fig. 5a the GP sample is plotted. The filled circles indicate those nebulae which have high helium/nitrogen abundance and which are known as

Type I nebulae. About half of the sample have T_{eff} greater than 10^5 K while two of the stars (NGC 2440 and 7027) have temperatures of between 3 and 4 × 10^5 K. There is a tendency for the stars falling near the high core mass tracks to also have high nitrogen abundance but there is one exception (NGC 6369) which should be better studied. The stars whose position falls near the low mass tracks all appear to have normal He and N abundances.

Two stars distinguish themselves in Fig. 5a. The star at log T_{eff} = 4.42, log $L/L_{\odot}$ = 2.2 is from the nebula He 2-131. It's distance has been measured by the extinction method both by Maciel (1985) and by Gathier

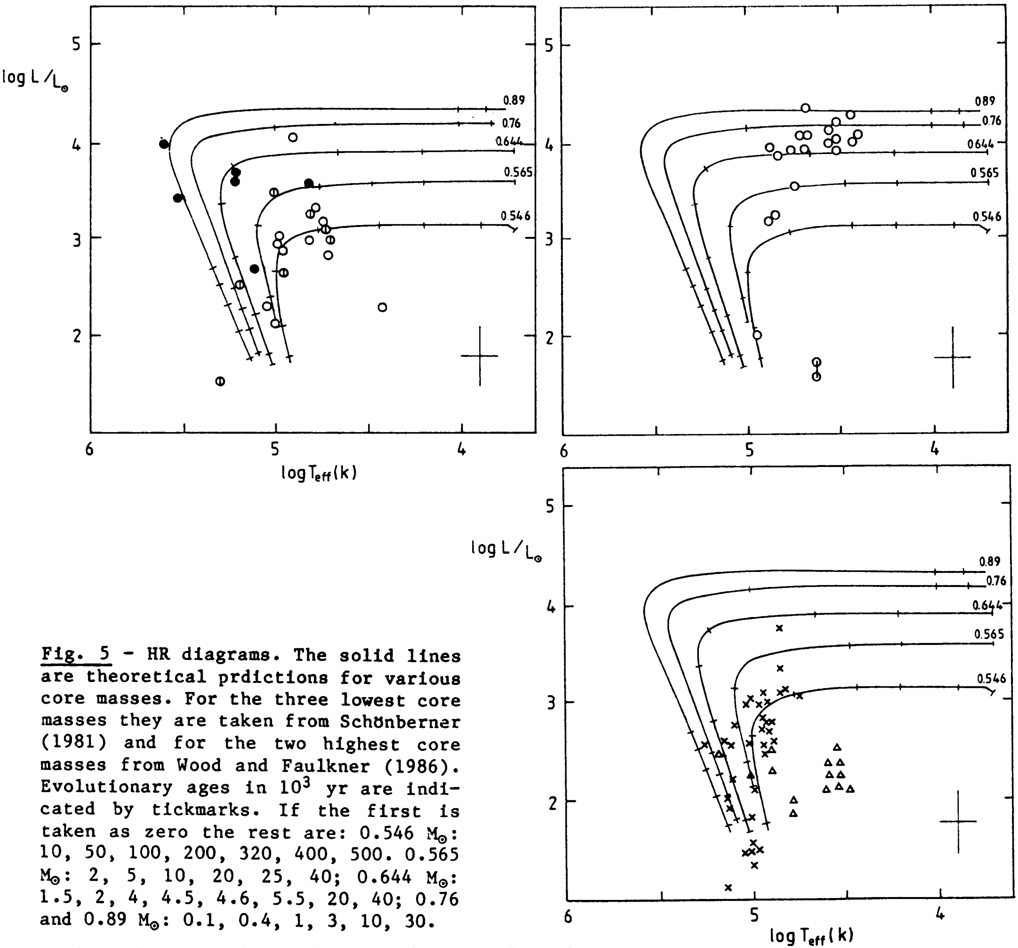

Fig. 5 - HR diagrams. The solid lines are theoretical prdictions for various core masses. For the three lowest core masses they are taken from Schönberner (1981) and for the two highest core masses from Wood and Faulkner (1986). Evolutionary ages in 10^3 yr are indicated by tickmarks. If the first is taken as zero the rest are: 0.546 $M_{\odot}$: 10, 50, 100, 200, 320, 400, 500. 0.565 $M_{\odot}$: 2, 5, 10, 20, 25, 40; 0.644 $M_{\odot}$: 1.5, 2, 4, 4.5, 4.6, 5.5, 20, 40; 0.76 and 0.89 $M_{\odot}$: 0.1, 0.4, 1, 3, 10, 30.

On these diagrams the various samples are plotted:

a. The Gathier-Pottasch sample. The filled circles are those stars whose nebula shows high nitrogen and/or helium abundance. The open circles indicate normal abundance, while for the other nebulae not enough abundance information is available.

b. The Mendez et al. sample. The two circles connected by a line indicate the same star with two different assumptions going into the distance determination.

c. Two samples are given. The crosses are the Kaler sample while the triangles are galactic center sample.

et al. (1986a). It is in a part of the diagram where central stars are not expected according to the evolution caculations. As Maciel points out, the star is somewhat below the galactic plane (b = -13°) which could make the extinction method less reliable. Mendez et al. (1987) also indicate that the distance may be greater. This point is therefore less certain than the others. On the other hand it should be considered as evidence that central stars may indeed populate that part of the diagram.

The other star which is worthy of special note is that in the lower left (log T_{eff} = 5.3, log $L/L_\odot$ = 1.4). This is the central star of the little studied nebula NGC 6565. The distance seems to be well determined. It is a small nebula and therefore quite young. One might therefore expect that the central star is intrinsically bright. Instead it is very faint (Reay et al., 1984; Gathier and Pottasch, 1987) and the Zanstra temperature is much lower; this lower temperature is confirmed by the rather low nebular excitation class (5). This strange behaviour may be caused by an extremely rapid evolution of the central star, so that the nebulae has not yet reached equilibrium with the radiation from the central star. Further study of this nebula is desireable.

Fig. 5b shows the Mendez et al. sample. The majority of these stars have a high luminosity (log $L/L_\odot \simeq 10^4$) and temperatures in the range 25 to 75000 K. There are almost no stars in this range in the GP sample. The theory predicts that very few stars should be found in this range because the evolution proceeds very rapidly. We shall return to the question of the time scale presently. It is also remarkable the none of these high luminosity stars shows a clearly higher nebular nitrogen and/or helium abundance, whereas most of the high luminosity objects in the GP sample clearly do.

A further point to note on Fig. 5b is the presence of a central star at low luminosity and low temperature. The recently discovered nebula, EGB 5, is faint and not well studied. However it falls clearly in the same region of the diagram excluded by the evolution calculations.

The last two samples are shown in Fig. 5c. The crosses are the Kaler sample. As can be seen, there is only one high luminosity central star in the sample. The stars fall mainly in that part of the HR diagram predicted by evolutionary calculations for stars which have stopped nuclear burning and are slowly cooling. The evolution is predicted to be much slower in this region and it would be expected that most central star fall there. This is all the more true since the nebulae were selected as large, low surface brightness and thus presumably old objects. The character of this sample will remain the same even if the individual distances used are in error by a factor of 2.

The sample of faint galactic central stars is shown by the triangle in Fig. 5c. For these stars the distance is better known than for any of the objects discussed so far. All the other properties are not so well known. The temperature has been taken from the excitation class of the nebulae (Kinman et al., 1987) using the calibration given in Pottasch (1987b). The luminosity has been taken as 150 times the Hβ luminosity which is approximately what is expected theoretically for an optically thick nebula and also what has been found in practice in the GP sample.

As can be seen from the figure, many of these faint nebulae fall in the same region of the HR diagram as EGB 5 and He 2-131, and which is excluded by the evolution calculations. It seems that at least some of them are real. This poses a problem for the theory.

In calculating the luminosity of the galactic center nebulae it was assumed that the nebulae are optically thick for radiation which can ionize hydrogen. The evidence for this is presented in Fig. 6, which is a plot of the nebular mass against its radius. The galactic center nebulae form a sequence in which the mass varies as the radius over the entire range of mass observed (0.01 $M_\odot$ to 0.4 $M_\odot$). The only reasonable interpretation of this is that the nebula is optically thick at every stage. The mass then increases with radius because as the density decreases the same number of ionizing photons can ionize an increasingly greater mass. Kinman et al. (1987) have reached the same conclusion for these nebulae.

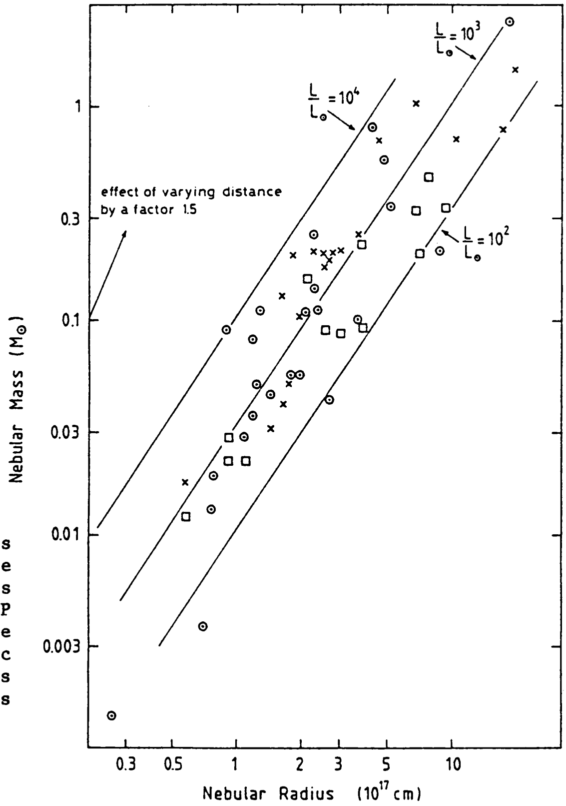

Fig. 6 - A plot of the nebular mass against the nebular radius for the nebulae studied in the various samples. The circles are from the GP sample, the crosses are the M sample while the squares are the galactic center sample. The Kaler sample falls on a line at M = 0.18 $M_\odot$ with radius between 5 and 20 × 10^{17} cm.

The other samples have also been plotted on Fig. 6. Both the GP and M samples show the same kind of mass increase as the radius increases, indicating that most must be optically thick (ionization bounded). In contrast the Kaler sample would fall on a horizontal line at M = 0.18 $M_\odot$ between a radius of 5 × 10^{17} cm and 20 × 10^{17} cm, only partly overlapping with any of the individually determined values.

5. EVOLUTIONARY TIME

On the theoretical evolution tracks in Fig. 5, the time it takes for the evolution is indicated by tik marks which are given values in the figure caption. In general the evolution becomes very rapid for high masses because the nuclear burning occurs more rapidly. The zero point is arbitrary however, if it is defined as the time since nebular ejection. The ejection time is not known in the evolution calculations as it could occur on the AGB or at any time after the star leaves the AGB. This time is known observationally however assuming that the nebular expansion velocity has been constant. The time, or nebular age, is then the ratio of the nebular radius to the expansion velocity.

Schönberner (1981) and others since have tried to make use of a comparison of the predicted time with the nebular age to derive the mass of the central star. Plots have been made of the absolute magnitude of the star against the nebular age. An example of such a plot is shown in Fig. 7. The theoretical curves make use of the assumption that the nebular ejection occurs when the star has a temperature of 5000 K. On the diagram we have plotted the individual stars from the sample of M and GP. The sample falls in the mass range lower than 0.64 $M_{\odot}$, with the majority less than 0.57 $M_{\odot}$. This is completely inconsistent with the mass found for this sample of stars from the HR diagram. If the M luminosities and distances are correct, either the theoretical times are not correct or the zero point (assumed time when ejection occurs) is not correct. Mendez et al. favor the latter conclusion. It has the consequence that all masses derived using this diagram are incorrect, because the abscissa (for the theoretical curves) must be shifted by an unknown amount, which may have a different value for each nebula.

But one of the other possibilities could also be wrong. For example, Mendez et al. give a luminosity for NCG 2392 which places it slightly above the M = 0.89 $M_{\odot}$ track. On this track the times for evolution from a star of 15000 K to its present 47000 K is calculated to be

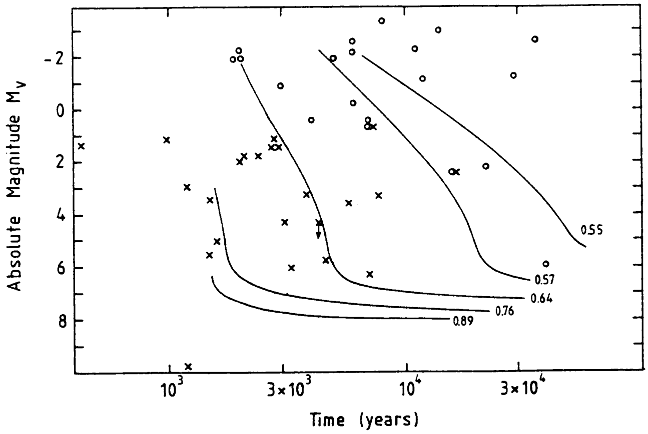

Fig. 7 – Absolute visual magnitude of the central star is plotted against nebular age. The theoretical curves assume that the nebula was ejected when the star reached a surface temperature of 5000 K. The circles from the M sample while the crosses are from the GP sample.

less than 100 years. The picture of the nebulae made by Curtis (1918) more than 70 years ago does not noticeably differ from its present morphology, suggesting that 70 years ago the amount of ionizing radiation was the same or at least very similar. Thus either the luminosity given is too high or the theoretical times are not correct.

There are also indications from the GP sample that the theoretical times are wrong. For example, NGC 2440 and 7027 are predicted to have evolved from a star of T = 10000 K in 100 to 200 years, yet they have observed ages of 8000 and 1000 years respectively. One must again conclude that the ejection must have taken place before the star reached 5000 to 7000 K, thus invalidating the use of diagrams such as Fig. 7 to determine the core mass. But again Curtis' pictures of these nebulae show that they are essentially the same 70 years ago as they are today. There was no trace of a central star 70 years ago in either of the nebulae indicating thta they had a high tepmerature even then. They do not appear to evolve as quickly as predicted.

The opposite effect is also present, especially in the GP sample. The stars clustering near the $M = 0.55\ M_\odot$ track have predicted ages of the order of 10^5 years or older yet the observed nebular age is usually younger than 10^4 years. This problem may be related to that of the stars which fall in the lower righthand part of the HR diagram and which, according to theory, evolve too slowly to be seen as planetary nebula, yet which apparently are real nebulae.

6. SUMMARY

While new observations have become available in the past 5 years, they confirm only the rough outline of the theoretical evolution and leave many problems for future consideration. For example, there is a direct conflict between the distances found by Mendez et al. (1987) and those determined earlier by Liller et al. (1968) for the same nebulae from nebular expansion. It is easy to say that nebular expansion is a very difficult technique, but whether the results are wrong should be carefully investigated. The model atmosphere technique, also contains assumptions which are doubtful. While it has been tested with success on some hot stars, PN central stars may be different enough to cause important errors.

Taken at face value we must take the tentative conclusion that there are two distinct groups of central stars with core masses greater than $0.65\ M_\odot$. The one, represented in the GP sample, are those faint stars associated with Type I nebulae, having very high temperature and whose nebulae have high nitrogen and helium abundance. The other high core mass stars, found in the M sample, have more symmetric nebulae at high galactic latitudes. They have nebulae with average N and He abundances. The stars are intrinsically much brighter and evolve more slowly.

It appears from both samples that a conflict between observed and predicted nebular ages exists. Part of it can be removed by assuming that the nebula was ejected at a very early stage in the evolution from the AGB. Since this ejection time cannot be predicted, the comparison of observed and predicted ages which have appeared in the literature are very questionable. The core masses derived from this comparison and the conclusion that most PN have core masses close to 0.58 $M_{\odot}$ is therefore doubtful.

Further progress involves the determination of more accurate distances. It also involves the more detailed study of nebulae in the galactic bulge, whose distance is quite reliably known.

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