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# INITIAL MASSES

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## 1. INTRODUCTION

Planetary nebulae represent a transitory stage in the life of the majority of stars as they proceed towards the end of their nuclear evolution and descend to the domain of white dwarfs. The immediate precursors of the central stars are probably red giants which populate a part of the HR diagram far removed from the region inhabited by the central stars of well recognised nebulae. The problem of determining the initial masses is complicated by the widespread occurrence of massloss on the red giant branch. The total amount of mass lost by a star must depend upon a number of stellar parameters including the initial mass, but the exact nature of this dependence remains to be discovered and a unique relation between the final masses and initial main sequence masses is not yet available. Thus even though the mass distribution of the nuclei of planetary nebulae (NPN) has been derived in the last few years, it has not been possible to deduce from this an unambiguous initial mass distribution of the progenitors. Further, an observed sample always suffers from selection effects and, in the particular case of NPN mass distribution, this has led to irretrievable loss of information.

Planetary nebulae are observed to have a great diversity of chemical and kinematical properties. This must, in some way, relate to the diversity of stars that they descend from. They are fairly numerous in the Galaxy and considering that their lifetimes are very short on astronomical timescales, it is obvious that their production rates are quite high, which, in turn, implies that they must originate from stars at the lower end of the mass spectrum. Since it is also firmly established that the nuclei are incipient white dwarfs, we must seek a common origin for both. The theory of stellar evolution puts rather severe constraints on the masses of stars evolving to white dwarfs and these limits should also apply to stars evolving to planetary nebulae.

*S. Torres-Peimbert (ed.), Planetary Nebulae, 493–503.*

## 2. CLASSIFICATION INTO POPULATION TYPES - BROAD HINTS ON THE INITIAL MASSES

The diversity of morphology, kinematical properties and chemical composition of the nebulae as well as their galactic distribution has led various authors to the classification of these objects into different groups indicating their Population types. Since the lifetime of the nebulae is very short, the galactic distribution and kinematics closely reflect the properties of the progenitor stars and hence carry information on the initial masses. In Table I we summarise these various schemes with emphasis on the information relevant to initial masses. For Classes B and C nebulae as well as Heap and Augensen's Population types Schmidt's (1963) calibration of the mean distance from the plane versus the main sequence mass has been used to derive the mean initial mass. Although widely used, this procedure of comparing the mean height of planetary nebulae with the mean height of main sequence stars to deduce a mean intial mass is not correct, since the mean height of stars in Schmidt's calibration samples stars of all ages for any particular mass, while by its very nature the planetary nebula population selects a particular age sample (the oldest) for each mass.

**TABLE I. CLASSIFICATION SCHEMES OF PLANETARY NEBULAE**

| Class | Criterion | Kinematics | Mean Height above plane (pc) | Initial Mass ($M_0$) | Source |
|---|---|---|---|---|---|
| B | Large ansae or tubular or filamentary structure | Circular motion $\sigma_z = 15$ kms$^{-1}$ | 160 | 1.5 | 1,2 |
| C | Centric increase in surface brightness | noncircular motion $\sigma_z = 26$ kms$^{-1}$ | 320 | $< 1.0$ | |
| Pop I | P[5] $< 1.5$ | Circular motion | 144 | 1.5 | 3 |
| Pop I$^+$ | $1.5 < P < 2.0$ | | 340 | | |
| Pop II | $P > 2.0$ | $\Delta V_r > 60$ kms$^{-1}$ | 774 | $< 1.0$ | |
| Type I | He/H $> 0.125$, N/O $> 0.50$ | | | 3-5 | 4 |
| Type II | He/H $= 0.11$ | $\Delta V_r < 60$ kms$^{-1}$ | $< 1000$ | 1.5-3 | |
| Type III | He/H $= 0.11$ | $\Delta V_r > 60$ kms$^{-1}$ | $> 1000$ | 1.0-1.5 | |
| Type IV | | Halo | | $<1.0$ | |

**Notes to Table I:** 1. Grieg (1971, 1972), 2. Cudworth (1974), 3. Heap and Augensen (1987), 4. Peimbert (1985), 5. Population index $P = 1 + \surd[z^2 + (\Delta V_r/60)^2]$

A better discriminant of the initial masses is the more elaborate classification scheme proposed originally by Peimbert (1978) and rediscussed by Peimbert and Serrano (1980) and Peimbert and Torres-Peimbert (1983, hereafter PTP 83). Since the chemical composition is a sensitive function of the evolutionary history and hence the initial main sequence mass of the progenitor star, this scheme provides a better idea of the range of initial masses producing the different types of nebulae. In assigning the limits in this case use has been made of evolutionary calculations and theories of dredge-up. We should remember that the existing theories of dredge-up are not fully in agreement with observational data.

A comparison of these various classification schemes shows a general one-to-one correspondence between Types I and I-II nebulae of Peimbert and Class B nebulae studied by Cudworth and the Population I nebulae of Heap but there are some ambiguities. For example, NGC 6629, 6894 and 7008 are all classified as Type I in PTP 83 while they belong to the list of Class C nebulae according to Cudworth. Some of the Population I objects in Heap and Augensen also belong to Class C nebulae. NGC 6058 belongs to Population II category according to Heap but to Class B according to Cudworth.

## 3. PLANETARY NEBULAE AND WHITE DWARFS IN CLUSTERS

Perhaps the most direct of the indirect ways to determine the initial masses is to look for planetary nebulae in clusters with well defined turn-offs. Unfortunately only one globular cluster (M15) and one open cluster (NGC 2818) contain a planetary nebula each. Based on the cluster data the progenitor of K648 in M15 is deemed to be a 0.8 $M_\odot$ star and that of NGC 2818 a 2.1 ± 0.3 $M_\odot$ star (Peimbert 1981).

Much more extensive data are available on white dwarfs in open clusters. Their presence in young clusters like the Pleiades and NGC 2516 is the best evidence we have for the high initial masses of the progenitors. The upper limit on the progenitor mass is an important number predicted by the stellar evolution theory. However, the number depends upon metallicity, massloss rate and the treatment of convection during the core burning phases and a range of values (5 $M_\odot$ to 11 $M_\odot$) is obtained (Becker and Iben 1979, Iben and Renzini 1983, Castellani et al. 1985). For a set of chosen parameters, theory predicts a well defined relation between the masses of degenerate remnants and the initial masses. In general, the more massive a progenitor, the more massive is its stellar remnant. Therefore, if massive NPN's or white dwarfs are found, one would infer large initial masses for their progenitors. Observationally, such massive nuclei would be difficult to discover, since the fading time for the massive degenerate cores is very short.

The cluster white dwarf data have been used by Weidemann and Koester (1983, hereafter WK) and Weidemann (1984) to derive an empirical relationship between the white dwarf masses and the initial masses. This empirical initial-final mass relation is much flatter than the ones predicted by theory. The flatness of the relation implies that although stars over a wide range of initial masses may evolve to the PN/WD stage, the final mass distribution of these objects should be rather narrow. The theoretical curves, on the other hand, would result in a broader final mass distribution for the same range of initial masses. Alternatively, a narrow final mass distribution coupled with the theoretical relation would suggest that the observed sample descends from a restricted range of initial masses. The white dwarf mass distribution of Koester, Schulz and Weidemann (1979) is rather narrow with two thirds of all DA white dwarfs confined to about 0.58 ± 0.10 $M_\odot$. The NPN mass distribution has been studied by Schonberner (1981), Kaler (1983), Pottasch (1983) and Heap and Augensen (1987). These span a range from the very narrow Schonberner distribution to the broader Kaler distribution. In Table II the ranges of initial masses inferred from the theoretical and the empirical initial-final mass relations are given.

**TABLE II. INITIAL MASSES FROM STUDIES OF MASS DISTRIBUTIONS**

| Authors | Range of Final Masses | Range of Initial Masses | | |
|---|---|---|---|---|
| | | $\eta = 1/3$ | $\eta = 1$ | Empirical WK |
| Schonberner | 0.55-0.8 | 0.86-2.0 | 1.1-2.8 | 2.3-5.3 |
| Kaler<br>Heap and Augensen | 0.55-1.0 | 0.86-2.9 | 1.1-4.0 | 2.3-6.5 |
| Koester et al | 0.45-1.0 | | 0.47-4.0 | 1.0-6.5 |

For a low massloss rate ( $\eta$ = 1/3) theory predicts that essentially all low mass stars down to the Galactic turn-off ($M_{to} = 0.95\ M_\odot$ for a $T_G = 12\text{x}10^9$ y) evolve through a pn phase, while for $\eta = 1$ stars upward of 1.1 $M_\odot$ do the same. The empirical relation suggests a drastically different range and according to it stars more massive than 2.3 $M_\odot$ evolve through the pn phase. To choose among these various alternatives it is necessary to consider other discriminating data. The birthrate of planetary nebulae and their mean height from the galactic plane are two important criteria in this context.

A significant result emerging from a study of these mass distributions is the difference in the observed lower limits between the WD masses and the NPN masses. The WD distribution extends to 0.45 $M_\odot$ on the lower side while in none of the studies quoted above does the NPN sequence extend below 0.55 $M_\odot$ . This implies that the low mass stars do not pass through a visible pn phase. Several other lines of evidence have also indicated that the lower mass limit of observable pn formation is higher than the one that applies to WD formation. In Table II we get limits consistent with this idea if $\eta > 1$ or if the WK relation were used.

## 4. BIRTHRATE OF PLANETARY NEBULAE

Ever since the recognition of the one-way nature of the evolution of the central stars of pn to white dwarfs, it has been common to compare the birthrate of white dwarfs to the deathrate of planetary nebulae. Also since the planetary nebula/white dwarf formation seems to be the common end for all single stars in a specified mass range limited by the lifetime of the Galaxy on one end and the lower limit of nondegenerate carbon ignition on the other, the birthrate of planetary nebulae/white dwarfs has been compared with the deathrate of main sequence stars. Of the observational uncertainties in the determination of the planetary nebula birthrate, the distance to these objects is the most crucial factor. Since the distance determination to individual nebulae is restricted to a handful of objects, for a study of the birthrate statistical distance scales have always been favored. Over the years several such distance scales have been advocated and they differ from each other by scale factors as large as 2. The birthrate depends on the fourth power of the scale factor and hence the various birthrates differ by as much as one order of magnitude. The observed nonuniform expansion of nebulae (Reay 1983) and the assumption of a uniform lifetime for all nebulae in the sample add further complications. The first problem may be solved if the particular form of V(r) were used, while the narrowness of the observed mass distribution of the nuclei implies that for the observed sample, the dispersion in lifetimes may not be as large as to make a significant difference. Since it is more or less established now that the star formation rate in the disk of our Galaxy has not varied greatly during its lifetime, the deathrate of main sequence stars can be calculated from the birthrate function discussed by Miller and Scalo (1979). The result is shown in Figure 1.

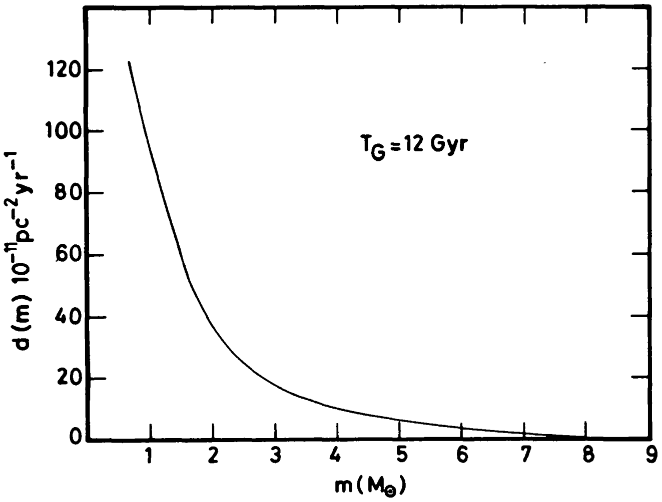

Figure 1. Integrated deathrate of main sequence stars as a function of m, the lower mass limit.

The deathrate is a rather steep function of the lower mass limit of formation of planetary nebulae and therefore, a comparison with the observed birthrate may once again yield a lower limit on the progenitor mass.

The variety of birthrates based on the different distance scales yields a variety of lower mass limits - from less than 1.0 $M_\odot$ for the Cahn and Wyatt (1976) and Daub (1982) scales to 2.5 $M_\odot$ for the Cudworth scale (see Mallik 1985). If we compare these limits with the limits in Table II, it is obvious that for consistency each one would require a different value of the parameter $\eta$. The situation is rather unsatisfactory unless the choice of $\eta$ could be restricted by other means. However, if the empirical WK relation were used instead, only the Cudworth scale is seen to yield a consistent lower limit. Weidemann (1984) has argued in favor of the flat WK relation. If this relation proves to be the correct one in further analysis, two important results would follow: (1) among the different distance scales, the Cudworth scale is to be preferred, (2) the lower limit on the initial mass of a planetary nebula progenitor is 2.5 $M_\odot$, significantly above 1.0 $M_\odot$.

Recently, the observed birthrate of planetary nebulae has been revised upward by a factor of 2 with respect to Daub's and a factor 9 with respect to Cudworth's (Ishida and Weinberger 1987). This value is higher than the white dwarf birthrate. It is obvious that this birthrate cannot be accomodated at all with theoretical deathrate estimates given above.

## 5. HEIGHT DISTRIBUTION

Planetary nebulae show a fairly strong concentration to the galactic plane. The mean height is low, typically between 100 pc and 200 pc. Since they originate from stars of different lifetimes, the current population contains nebulae formed from old low mass stars and from the more recent heavier ones. The diffusion of stellar orbits increases the velocity dispersion perpendicular to the plane with age. Thus the less massive planetary nebula progenitors will be on an average farther from the plane than the more massive ones. It is possible to relate the age to the velocity dispersion and the latter to the scale height of the distribution (Wielen and Fuchs 1983). The distribution itself is of the form $n(z) = n(z=0)\ \mathrm{sech}^2\ z/H$ where the scale height $H = \sigma_W^2/\pi G \mu$, where $\sigma_W$ is the velocity dispersion and $\mu$ the surface density of stars. These relations have been used to obtain the height distribution displayed in Figure 2.

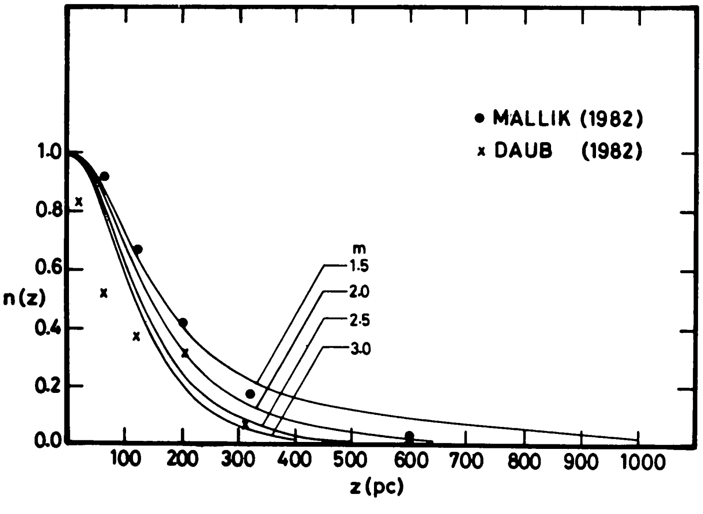

Figure 2. Normalised height distribution for different values of m.

The different curves correspond to the different lower limits on the initial mass since $n(z) = \int_{m}^{\infty} n_m(z)\,dm$. It is clear that for low values of m a larger fraction of old less massive stars is present in the sample and n( z ) decreases less rapidly with increasing z. The observational points from two different samples are also plotted in the Figure. The observed height distribution shows a rapid drop which, in turn, suggests the absence of light progenitors in the observed samples. While it is not worth attempting an exact fit, we see from Figure 2 that with an m ~2.0 $M_\odot$ the observed height distribution is rather well reproduced.

## 6. CHEMICAL COMPOSITION OF NEBULAE AS INDICATOR OF THE INITIAL MASS

A significant fraction of planetary nebulae show definite signs of enrichment as a result of nuclear processing in the parent stars. The stellar evolution theory has been able to identify the processes leading to such enrichment and to predict the amount of enrichment as a function of the main sequence mass. Certain trends are very clear: (i) the He/H ratio increases monotonically with the initial mass, (ii) the He and N abundances show proportionate increases with initial mass during the second dredge-up phase, (iii) the C and He abundances increase monotonically with mass due to the third dredge-up. The functional relationships depend upon a host of parameters - the massloss rate, initial metallicity, the assumed dredge-up law, treatment of convection etc. These factors introduce uncertainties in any initial mass that may be inferred by matching the observed nebular abundances with model predictions. The theoretical predictions from the models of Becker and Iben (1979, 1980) and Renzini and Voli (1981) have been compared with the observed abundances of planetary nebulae with conflicting inferences (PTP 83, Kaler 1983, Pottasch 1984). Several authors have used these comparisons to arrive at the initial masses. It appears that the Type I planetary nebulae originate from stars in the mass range 3-5 $M_\odot$ and that their C/O and N/O ratios require moderately efficient envelope burning (Torres-Peimbert 1984).

The main problem in comparing the dredge-up theories with observations is the conflict with the core masses. The models show that the core masses for effective dredge-up are rather large, in the neighbourhood of 1.0 $M_\odot$ while the observed mass distribution of NPN shows very few nuclei, if any, of this mass. More specifically, Heap and Augensen (1987) have derived masses for several Type I central stars and found them to be low ($\sim$ 0.65 $M_\odot$). The dredge-up theories predict hardly any enrichment for such small core masses. Convective overshooting so far neglected in the dredge-up models will produce larger cores and enhancement at smaller initial masses and will not solve the problem of dredge-up at small core masses. PTP 83 suggests that NGC 6302 is the most massive well-documented object. However, its He and N abundances are beyond the range produced in the models. A He/H $>$ 0.18 cannot be satisfactorily produced in the dredge-up models. Even as one requires an initial mass > 6 $M_\odot$, an inconsistency creeps in because, according to the same dredge-up models, stars more massive than 5 $M_\odot$ do not evolve to planetary nebulae but explode as supernovae. The latter event will surely modify the envelope abundances, nor shall we see a pn. Similarly, the observed N/O ratio in NGC 2440 is much too high to match any of the models.

Type II and Type III nebulae show very similar abundance trends. Comparison with dredge-up models indicates initial masses in the range 1.0-2.5 $M_\odot$ for them. However, their initial CNO values are rather diverse and this introduces an extraneous scatter whose effects are difficult to disentangle. Considering that the vast majority of planetary nebulae belong to Types I, II and III, we conclude from chemical composition alone that they originate from stars with main sequence masses 1.0-5.0 $M_\odot$ although individually some of the nebulae (e.g. NGC 6302) do not fit into the scheme at all.

## 7. PLANETARY NEBULAE IN BINARY SYSTEMS

Approximately 25% of the known planetary nebula population is expected to be in binary systems; the number actually discovered is somewhat less. Besides those which are members of visual binary systems and the ones which are spectroscopic and/or eclipsing binaries with well observed periods, there are many which are inferred to be binaries since optically only cool stars are seen associated with the nebulae. In some cases IUE observations have clearly revealed the presence of the hot star.

Peimbert and Serrano (1980) considered the binary nature of NGC 3132 and NGC 2346 and based on the evolutionary lifetime considerations inferred the initial masses of the central stars to be above 2.0 $M_\odot$. Recently Whitelock and Menzies (1986) have discussed the binary nature of the nuclues of the new nebula IRAS 1912 + 172 P09 where the optically visible companion is a B9V star of mass 2.9 $M_\odot$. This is by far the earliest companion discovered amongst the binary central stars. Again based on pure evolutionary timescale considerations they infer an initial mass of 3.0 $M_\odot$ for the progenitor. While NGC 3132 is a wide binary system, it is not clear if NGC 2346 and IRAS 1912 + 172 could be assumed to be so. If the central stars of these objects were members of interacting binary systems, the intial mass could be significantly higher.

The interacting binary scenario for the origin of the planetary nebulae is radically different since Roche lobe overflow and common envelope evolution introduce new aspects to the evolutionary problem. A recent review on the subject is due to Paczyński (1985). Several systems which are definitely the result of a common envelope evolution leading to pn formation are known and generally classed as precataclysmic binaries (Bond 1985, Ritter 1986). In Table III, I summarise the relevant information on them. The secondaries are all low mass stars presumably unevolved. The primaries are hot subdwarfs and exciting the nebulae. The fact that is crucial to our discussion is the shortness of the periods. During the common envelope (CE)

TABLE III. CLOSE BINARY CENTRAL STARS

| Name | Spectra | $M_2(M_\odot)$ | q | P(d) | Source |
|---|---|---|---|---|---|
| | a) Short period systems - precataclysmic binaries | | | | |
| A 63 | sdO+K-MV | 0.6 | 0.57 | 0.465 | 1 |
| A 46 | | 0.2-0.3 | 0.43 | 0.472 | 1 |
| A 41 | sdO+MV | 0.1-0.3 | 0.2-0.5 | 0.113 | 2 |
| DS1 | sdO+MV | 0.3 | 0.43 | 0.357 | 1 |
| K1-2 | | | | 0.671 | 1 |
| LoTr5 | sdO+G5III-V | | | 0.35 | 3 |
| | b) Systems with P > 1.0 | | | | |
| NGC 2346 | ?+A2V | | | 16. | 4a |
| | c) Systems with unknown P | | | | |
| NGC 1514 | sdO+AOIII | | | | 2 |
| A 35 | ?+G8III-IV | | | | 2 |
| He 2-36 | sdO+A2III(?) | | | | 4b |
| Cn 1-1 | sdO+F5III-IV | | | | 5 |
| IRAS1912<br>+172P09 | ?+B9V | | | | 6 |

**Notes to Table III.** 1. Ritter (1986) 2. Bond (1985) 3. Acker (1985) 4a. Mendez and Niemela (1981) 4b. Mendez (1978) 5. Lutz (1984) 6. Whitelock and Menzies (1986).

phase large orbital contraction is possible due to the loss of mass and orbital angular momentum. It is possible to make reasonable guesses about the initial mass ratios of these systems from the currently observed periods and mass ratios. Some idea of the initial period of the system is necessary. This determines, in turn, the stage at which mass exchange takes place preceding the CE formation. For Roche lobe overflow during the AGB evolution of the primary, the periods are respectively in the range 55d to 3y and 25d to 16y for a $5M_\odot$ and a $3M_\odot$ star. Conservatively one may assume a value of about a year for the initial period. Since a CE formation followed by orbital contraction needs a large mass ratio it is unlikely that the initial mass of the primary be less than $3M_\odot$. From the formula due to Tutukov and Yungelson (1979) the initial mass ratios could be obtained. For a period $11^h$ as in A 63 and a current mass ratio of 0.5 this yields an initial mass ratio of about 17 and hence an initial mass of about $5M_\odot$ for the primary. For the short period systems the initial mass of the pn progenitors is thus $5M_\odot$ or more. According to Iben and Tutukov (1985) stars initially more massive than $5M_\odot$ are able to shed their He-rich envelope during a second phase of Roche-lobe overflow. Thus many of these nebulae may have He-rich inner zones.

Two nebulae in Table III are associated with binary central stars having periods much longer than a day indicating that binaries can emerge from a CE phase with fairly long periods. For the rest periods are not definitely known. A remarkable fact about these systems is that the companions are all within a narrow Spectral

Type range lying close to or slightly off the main sequence suggesting that they have masses between 2.0 and 3.0 $M_\odot$. If these systems evolved out of a CE phase we may immediately conclude that the initial masses of the primaries are < 5 $M_\odot$. According to Iben and Tutukov (1985) stars more massive than 5 $M_\odot$ go through two episodes of Roche-lobe overflow and it is highly unlikely that we see a planetary nebula emerging out of a CE phase following the second such episode, since most of the donor mass would already have been extracted earlier. For primaries less massive than 5 $M_\odot$ only one episode of Roche-lobe overflow takes place following which these stars burn He for a very long time and achieve surface temperatures compatible with those found in central stars of planetary nebulae. Then, primordial mass ratios are in the neighbourhood of 2, and it seems plausible that large orbital contraction has not taken place in these systems. The periods may have been marginally shortened through CE evolution and one should search for long periods in these systems.

## 8. CONCLUSION

Wisdom gained from stellar evolution theory had led to the belief that planetary nebulae originate from all stars in the mass range 1-8 $M_\odot$. Recent calculations with convective overshoot have brought down the upper mass limit to the neighbourhood of 6 $M_\odot$. However, observational considerations based on birthrate, height distribution and the empirical $m_f / m_i$ relation suggest that the lower mass limit of pn formation is near 2.0 $M_\odot$. This will also explain the paucity of planetary nebulae in globular clusters and the galactic halo. Chemical composition of the Type I nebulae suggests that they come from rather massive progenitors (3-5 M). Planetary nebulae in binary systems classed as precataclysmic variables probably evolve from massive progenitors ($M \gtrsim 5\ M_\odot$). The others with cool companions and unknown periods have evolved from progenitors in the range 4-5 $M_\odot$. Further observations are needed to establish these limits firmly. Abundance analyses of nebulae with binary nuclei may provide important clues.

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