

On the Consequences of a New Initial-Final Mass Relation for Low and Intermediate Mass Stars and the Birthrate of Planetary Nebulae

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(Received January 25, 1984; in final form April 30, 1984)

Recent work on the initial-final mass relation for low- and intermediate-mass stars and the mass distribution of the nuclei of planetary nebulae sets a lower limit on the initial mass of progenitors of PN which is substantially higher than $1 M_{\odot}$. With such a lower limit the theoretical estimates of the deathrate of main-sequence stars would be consistent with the observed PN birthrate only if the distance scale due to Cudworth (1974) were used. A raised lower limit on the progenitor mass also helps explain the low mean distances of planetary nebulae from the galactic plane and the paucity of PN in Population II systems.

INTRODUCTION

In a recent paper Weidemann and Koester (1983) have proposed a new initial-final mass relation for stars in the mass range $1-8 M_{\odot}$ which is considerably flatter than the earlier versions of the same relation (Fusi-Pecci and Renzini, 1977; Wood and Cahn, 1977). Although, a complete theory of nonconservative stellar evolution of low- and intermediate-mass stars should be able to uniquely predict this relation, no such comprehensive theory exists at the moment. Hence, the attempts at deriving the initial-final mass relations (hereafter m_f/m_i -relation) have largely been empirical. Weidemann and Koester have used new results on white dwarfs in open clusters, especially the rich and distant cluster NGC 2516, to derive their semi-empirical m_f/m_i -relation. This relation extends the upper mass limit for white dwarf progenitors, m_{WD} , to 8 or $9 M_{\odot}$ which is coincident with the lower limit for nondegenerate carbon ignition. At the lower end the new relation accommodates the observed low mass of 40 Eri B.

It is also generally believed that planetary nebulae represent a transitory stage in the evolution of low- and intermediate-mass stars following their double-shell-source phase and preceding their demise as white dwarfs. The birthrate of planetary nebulae has thus always been compared with the deathrate of these stars, and the deathrate of PN with the birthrate of white dwarfs (Weidemann, 1968; Salpeter, 1971; Cahn and Wyatt, 1976). However, there is evidence now that all low-mass stars may not evolve through a planetary nebula phase before reaching the domain of white dwarfs. The mass distributions of white dwarfs and of nuclei of planetary nebulae (NPN) have been the subject of several recent investigations. The mass distribution of white dwarfs derived by Koester *et al.* (1979) and Koester and Weidemann (1980) is found to be rather narrow and sharply peaked at $0.58 M_{\odot}$. The lowest masses in the derived distribution lie in the neighbourhood of $0.45 M_{\odot}$. The NPN mass distribution has been independently derived by Schönberner (1981), Schönberner and Weidemann (1983), Heap (1983) and Kaler (1983). Although similar to the white dwarf mass distribution, the NPN mass distribution shows a lower limit cut-off at $0.55 M_{\odot}$. Initially the narrowness of the distribution obtained by Schönberner had been the

subject of some controversy, although the more recent work by Heap using uv magnitudes and a different distance scale essentially confirms Schönberner's results (see also Pottasch, 1983). However, there is a high-mass extension to the NPN mass distribution obtained in the work of Heap and also Kaler which was absent in the Schönberner distribution. Independent determination of masses of at least three NPN in LMC by Stecher *et al.* (1982) shows that high mass nuclei do exist. This is more in conformity with the mass distribution obtained by Kaler (*op. cit.*) which extends from $0.55 M_{\odot}$ to approximately $1 M_{\odot}$ at the higher end. The existence of a lower mass cutoff first found in the Schönberner distribution has been confirmed by all the subsequent authors. There are no NPN with masses below $0.55 M_{\odot}$ in any of the samples. This implies that a fraction of the present white dwarf population has not evolved through a visible planetary nebula phase. One should expect, therefore, the white dwarf birthrate to be actually higher than the PN birthrate. Since observational uncertainties in the determination of birthrates are fairly large, no such clear conclusion can be reached. Yet the fact that, the NPN mass distribution is seen to cut off at a value that is significantly higher than the mass of the lowest mass white dwarfs, has several interesting implications. Such a cut-off coupled with the proposed m_f/m_i -relation indicates the existence of a lower limit on the initial main-sequence mass of progenitors of planetary nebulae which is much above $1 M_{\odot}$. The hitherto widely accepted idea that all stars with main-sequence masses between the galactic turn-off mass ($\sim 1 M_{\odot}$) and m_{WD} pass through a planetary nebula phase, does no longer appear to be true. It is the purpose of this letter to point out some of the consequences of having such a lower limit on the initial mass of PN progenitors. If planetary nebulae evolve from stars with main-sequence masses in the range m_i to m_{WD} , where m_i is the lower mass limit referred to above, a comparison of the deathrate of stars in this interval with the observed birthrate of planetary nebulae shows that the Cudworth (1974) distance scale should be preferred over the Cahn and Kaler (1971) scale. Also, with $m_i > 1.0 M_{\odot}$ the observed low scale height of the PN distribution may be easily explained.

Finally, the absence or near-absence of planetary nebulae in Population II systems or in the galactic halo can also be understood in this context since the present turnoff mass of these systems would be below m_i .

THE PRESENT DEATHRATE OF MAIN-SEQUENCE STARS AND THE OBSERVED PN BIRTHRATE

The current deathrate of stars in a mass interval $(m, m + dm)$ is, by definition, equal to the birthrate of stars in the same interval at a time $t_1 - \tau_m$ where t_1 is the age of the Galaxy and τ_m the lifetime of stars of mass m . Following Tinsley (1980), we write for the number of stars born in the mass interval $(m, m + dm)$ and in the time interval $(t, t + dt)$

$$b(m, t) dm dt = \psi(t)\phi(m) dm dt$$

where $\psi(t)$ is the star formation rate (SFR) and $\phi(m)$ the initial mass function (IMF), assumed time-independent and normalised so that

$$\int_{\text{all masses}} m\phi(m) dm = 1.$$

Therefore, the current deathrate of stars in the interval $(m, m + dm)$ equals

$$b(m, t_1 - \tau_m) dm = \psi(t_1 - \tau_m) \phi(m) dm$$

and the integrated current deathrate of stars between any two mass limits m_1 and m_2 ($m_1 < m_2$)

$$d(m_1, m_2) = \int_{m_1}^{m_2} \phi(m) \psi(t_1 - \tau_m) dm. \quad (1)$$

To compare the current deathrate of low- and intermediate-mass stars with the birthrate of planetary nebulae, m_2 is set equal to m_{WD} and the deathrate of all stars from m_{WD} to any m ($m < m_{WD}$) is expressed as

$$d(m) = \int_m^{m_{WD}} \phi(m') \psi(t_1 - \tau_{m'}) dm'. \quad (2)$$

To evaluate the integral it is necessary to know the SFR. This is especially important in the present context since τ_m 's for the less massive of the stars under consideration are on the order of t_1 . Miller and Scalo (1979) have put forth compelling arguments to show that the SFR has not varied significantly over the lifetime of the Galaxy and the assumption of a constant SFR does not grossly violate any of the known observational facts. Twarog (1980) has confirmed this conclusion from a study of the age-metallicity relation of a large sample of F dwarfs. The assumption of a constant SFR simplifies considerably the evaluation of $d(m)$ and we may write

$$d(m) = \psi_1 \int_m^{m_{WD}} \phi(m') dm'. \quad (3)$$

The choice of ψ_1 and $\phi(m)$ has to be such that they are compatible with each other and that they reproduce correctly the present day mass function which is an observed quantity. In the present case we have used the IMF due to Miller and Scalo (1979) for three different values of t_1 and the corresponding ψ_1 's given by them, to derive $d(m)$. Figure 1 shows $d(m)$ as a function of m , where m_{WD} in Eq. (3) has been set equal to $8 M_\odot$. The curve labelled LS in the figure is based on an alternate IMF proposed by Lequeux (1979) and Serrano and Peimbert (1981) and a constant SFR with $\psi_1 = 2.4 \times 10^{-9} M_\odot \text{ pc}^{-1} \text{ yr}^{-1}$. The steep rise in IMF towards the lower masses in both cases makes $d(m)$ very sensitive to m . It is, therefore, possible to obtain a lower limit on the main-sequence mass of the PN progenitors from a comparison of Figure 1 with the observed PN birthrates which are summarised in Table I. Keeping in mind the fact that a lower limit on the progenitor mass has already been set independently by the new m_f/m_i -relation and the NPN mass distribution, we find that compatible values are obtained only in a few cases. Many of the observed birthrates are too high to match the integrated deathrate of main-sequence stars for any mass larger than $1 M_\odot$. For example, the observed PN birthrate due to Cahn and Wyatt equals $d(m)$ at $m = 1$ only for $t_1 = 9$ Gyr while for $t_1 = 12$ and 15 Gyr, $m < 1$. Similarly, the birthrates determined by Acker (1978), and by Cahn and Kaler (1971) match the integrated deathrate when $m = 1.15^{+0.30}_{-0.15} M_\odot$ which implies in turn a very much lower mass of the stellar remnant, and is thus incompatible with the low-mass cut-off of the NPN mass distribution.

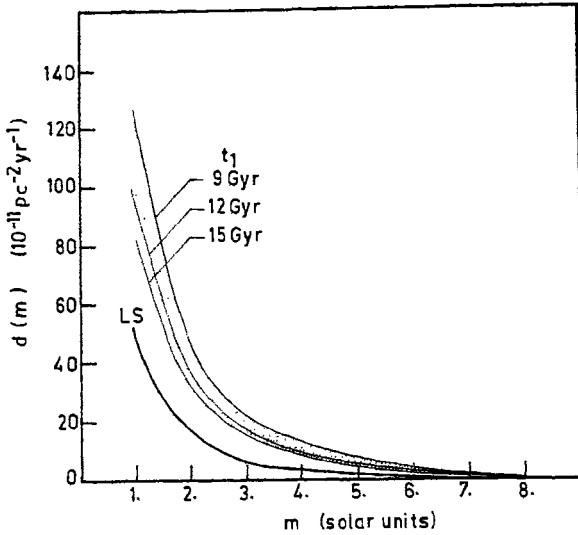


FIGURE 1 The integrated current deathrate of main-sequence stars from $8 M_{\odot}$ to $m(m < 8)$ as a function of m . See text for details.

While the theoretical evaluation of the deathrate is relatively free from assumptions, the observational PN birthrates are crucially dependent on the assumed distances of the nebulae in the local sample. Very few distances are directly measurable; they are generally determined by the indirect Shklovsky method which has to be calibrated using planetaries of known distances (see Osterbrock, 1973). The various calibrations to date differ from each other by as much as 50% and thus introduce differences in the linear sizes of the nebulae and their derived local space densities. Thus, if K were the scale-factor between two different calibrations, the birthrate should differ by a factor K^4 . The catalog of Cahn and Kaler (1971) is based on the calibration of the distance scale by Seaton (1968); the birthrate derived by Cahn and Wyatt is based on a revised version of this catalog. Weidemann (1977) has argued strongly for an upward revision of the Cahn and Kaler distances by a factor 1.3. Cudworth (1974) has given a new calibration based on statistical parallaxes which differs from the Cahn and Kaler scale by a factor 1.5. The consequences of this new distance scale have been discussed at length by Alloin *et al.* (1976). It modifies various quantities related to PN statistics and brings down the birthrate as well as the total number of nebulae in the Galaxy considerably. In the last few years several other methods have been devised to determine distances to planetary nebulae (Acker, 1978; Maciel and Pottasch, 1980; Daub, 1982). Each of these leads to an independent estimate of the local density of planetary nebulae and a local formation rate or birthrate. Results from some of these are included in Table I. From the point of view of yielding consistent results on the lower mass limit of PN progenitors none of these seem to be particularly successful.

The estimates of the birthrate based on the Cudworth scale appear in the last row of Table I. The two separate entries—Class B and Class C, refer to the two distinct kinematical—morphological types of planetary nebulae first discovered by Greig (1971, 1972). Cudworth (1974) treated the two classes separately. The calibrations obtained for the two classes based on observations of statistical parallaxes showed no

TABLE I
Statistics of planetary nebulae

Author	Local Surface Density (kpc^{-2})	Lifetime (yr)	Birthrate ($10^{-11} \text{ pc}^{-2} \text{ yr}^{-1}$)	Scale Height $Z_0(\text{pc})$	Mean Distance from the Plane $\langle z \rangle (\text{pc})$
Cahn and Kaler (CK)	13 ^a	16,000	81.	90	144 ^a
Cahn and Wyatt (CW)	19	16,000	119.	115	171
Weidemann	11	20,000	55.	150	
Acker	13	16,000	81.	200	
Maciéi	12	20,000	60.	144	
Daub	13		116.	125	
Alloin <i>et al.</i> ^b	5.8	24,000	24.2	Cudworth (1974)	B:160 C:320

^a These numbers are due to Osterbrock (1973).

^b Based on the Cudworth scale where a scale factor of 1.5 has been used to revise the distances from Cahn and Kaler.

differences and the final distance scale was derived by combining the data on both these classes. However, Cudworth confirmed their different kinematic character and derived different mean distances from the plane for the two classes. Coming back to the birthrate, it is immediately obvious that this birthrate indicates a rather high m for a match with the integrated deathrate depicted in Figure 1. In particular, a comparison with the $d(m)$ based on the IMF due to Miller and Scalo yields a limit of $2.5_{-0.15}^{+0.35} M_{\odot}$. A lower limit of $2.5 M_{\odot}$ for the progenitor mass agrees remarkably well with the limit obtained from the m_f/m_i -relation and the NPN mass distribution. With the LS IMF the corresponding lower limit is $1.65 M_{\odot}$. This would imply a lower limit cut-off to the NPN masses at $0.50 M_{\odot}$ rather than at $0.55 M_{\odot}$. The NPN mass distribution obtained by various authors (Schönberner, 1981; Heap, 1983; Kaler, 1983) show very clearly the existence of a minimum NPN mass at approximately $0.55 M_{\odot}$. It is unlikely that this determination is off by more than a few hundredths of a solar mass. It is also important to note that this particular result is insensitive to the distance scale used to derive the mass distribution as the Schönberner distribution based on the Cahn-Kaler scale as well as the distribution derived by Heap based on the Cudworth scale obtain the same result. It may be added here that the controversies regarding the NPN mass distribution are centred around the question of the width of the distribution and the high-mass end and are not relevant to the present discussion. On the other hand, the observed PN birthrate is very sensitive to the choice of the distance scale and the foregoing analysis shows that a majority of the distance scales in vogue yield birthrates which match the best theoretical estimates of the integrated deathrate of main-sequence stars only if the minimum progenitor mass is lower than or equal to $1.5 M_{\odot}$. This is incompatible with the new m_f/m_i -relation since the implied final core mass is then very much lower than what is observed. The only observed birthrate which produces consistent results with respect to the minimum progenitor mass is the one based on the Cudworth distance scale. We, therefore, conclude that the evolutionary considerations detailed above indicate a preference for the Cudworth scale over other distance scales.

THE MEAN DISTANCE OF PLANETARY NEBULAE FROM THE GALACTIC PLANE

Planetary nebulae show a fairly strong concentration to the galactic plane. The mean distance from the galactic plane of the local sample is generally found to be small and varies somewhat depending on the different distance estimates that are used. Although an exponential height distribution gives a reasonable fit to the observed data, strictly speaking the distribution cannot be a true exponential as it implies a discontinuity in the density gradient at $z = 0$ (Wyatt, 1978; Mihalas and Binney, 1982). A more general parameter describing the concentration of the nebulae to the plane, independent of the form of the height distribution, is the mean distance from the plane. As the data become incomplete at large distances due to the effect of interstellar extinction, which is especially severe close to the galactic plane, the observations can only tell us about the local height distribution and not its variation with the galactocentric radius. The scale heights as well as mean distances from the plane obtained in the different surveys are

summarised in columns (5) and (6) respectively of Table I. These values are higher than the scale heights ascribed to the distribution of interstellar matter and to the young stellar population but substantially lower than the values quoted for stars with masses close to that of the sun.

Since planetary nebulae originate from stars of different initial masses and different lifetimes, they comprise a mixed sample as far as the population characteristics are concerned. The larger fraction of them comes from the low mass stars with relatively long lifetimes and should, therefore, belong to an older population. However, the fraction coming from the more massive precursors, although contributing less by number, tends to dilute the effects of age on the total population. The irregular gravitational field in the galactic disk is responsible for a rapid diffusion of stellar orbits in velocity as well as positional space resulting in the observed increased of the velocity dispersion of disk stars with increasing age (Wielen, 1977; Wielen and Fuchs, 1983). Stars of different initial masses giving birth to planetary nebulae at the present time would, therefore, have diffused out to different distances from the galactic plane and have different velocity dispersions perpendicular to the plane.

The scale height of the distribution is related to the velocity dispersion and is thus an increasing function of time. The height distribution of the precursors at the present time would be characterised by different scale heights depending on the mass which determines the time elapsed since formation and hence the extent to which the precursor stars have suffered the effects of diffusion. The height distribution of planetaries at the present time is then an integral over the mass of the height distributions of the precursors. The derived height distribution is thus dependent on the mass distribution of precursor stars. From the analysis in the previous section it is clear that the current deathrate function of stars producing planetaries is very sensitive to the lower mass limit of progenitor stars since this limit restricts the relative contribution of the low-mass stars to the current population of planetary nebulae. The precursor mass distribution is already built into this deathrate function. Therefore, the height distribution as well as the mean distance of the nebulae from the plane will also be a function of the lower mass limit of the progenitors.

I have used the theory of diffusion of stellar orbits as formulated by Wielen and Fuchs (1983) to obtain a theoretical height distribution of the current population of planetary nebulae. Accordingly it is assumed that stars are born continuously and uniformly in a thin disk and that their orbits diffuse during the evolution with a constant diffusion coefficient. The theory gives the velocity dispersion perpendicular to the plane as a function of time. This is used to derive the velocity dispersions and scale heights of the precursors of the present generation of planetaries as a function of the initial mass. Thus, if $n_m(|z|) dm$ were the number density of the precursors with initial masses in the interval $(m, m + dm)$ at a height $|z|$ above the plane, the expected number density of planetaries at $|z|$ is given by

$$n(|z|) = \int_{m_i}^{8.0} n_m(|z|) dm \quad (4)$$

where m_i is the lower mass limit of the progenitors. For the numerical calculations it is assumed that the scale height of interstellar matter and of the extreme Population I stars is 90 pc (see Miller and Scalo, 1979). The expected mean distance of planetary

nebulae from the galactic plane is then

$$\langle |z| \rangle = \frac{\int_0^{\infty} |z| n(|z|) d|z|}{\int_0^{\infty} n(|z|) d|z|} \quad (5)$$

In Figure 2, we plot the mean distance $\langle |z| \rangle$ as a function of m_i . As expected, for $m_i \gtrsim 1.0$ the derived mean distance is much larger than the values quoted in Table I. As m_i is raised, the contribution from the lower mass stars is progressively reduced and since the more massive the precursors the closer they remain to the plane on an average, $\langle |z| \rangle$ also decreases. The observed scale heights or mean distances would thus be consistent with a value of m_i between $1.75 M_{\odot}$ and $2.5 M_{\odot}$. If a fraction of the present population of planetaries originated from stars with initial masses as low as $1.0 M_{\odot}$, the mean distance from the plane would have been very much higher based on the theory of diffusion of stellar orbits. The observed low $\langle |z| \rangle$ of the current population of planetaries is thus seen as a consequence of their origin in stars with main-sequence masses in the interval $2.0^{+0.5}_{-0.25} M_{\odot} - 8 M_{\odot}$.

CONCLUSION

The new m_f/m_i -relation of Weidemann and Koester (1983) and the observed lower mass cut-off to the NPN mass distribution imply the existence of a minimum initial mass for the progenitors of planetary nebulae which is substantially higher than $1 M_{\odot}$. The limit obtained from this consideration is consistent with that implied by the current deathrate of main-sequence stars and the observed birthrate of PN if the Cudworth distances are adopted. The observed low mean distances of PN from the galactic plane is also consistent with the above limit. There has been some indication in the past that low mass stars may not evolve through a planetary nebula phase. Thus van den Bergh (1973) had estimated the total number of planetary nebulae

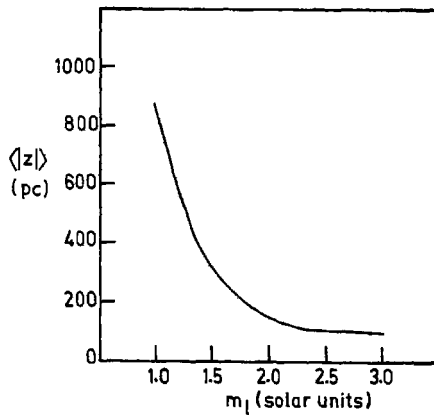


FIGURE 2 The theoretically computed mean distance of the current population of planetary nebulae from the galactic plane vs m_i , the lower mass limit of their progenitors.

in the galactic halo to be only 37. The specific number of planetaries defined as the total number of nebulae per unit mass is thus one order of magnitude lower in the halo than in the disk even with the most conservative estimates of the halo mass. The halo mass is likely to be much higher (Ostriker and Thuan, 1975). Cahn and Wyatt (1976) also arrived at a low specific number of planetaries in the halo from a more elaborate calculation. All this goes to show that Population II systems, e.g., globular clusters and the galactic halo, are notably deficient in planetary nebulae. We have seen that at least for the solar neighbourhood consistent results are obtained if we assume that planetary nebulae originate from stars with initial masses in an interval $m_i - 8 M_\odot$ where m_i is in the neighbourhood of $2 M_\odot$. An extension of this premise to Population II systems with their low turnoff masses will naturally explain the near absence of planetary nebulae in them.

The new m_f/m_i -relation has many other implications particularly for the chemical evolution of galaxies. Much of this is unclear at the moment and will depend upon improvements in the theory of dredge-up processes in low- and intermediate-mass stars. However, certain gross effects are easy to see. On the one hand, the new relation enhances the mass fraction returned to the interstellar medium per stellar generation. On the other hand, by allowing for the possibility of having condensed remnants from stars all the way up to $8 M_\odot$, it precludes the occurrence of total explosion of stars in this mass range (the carbon detonation supernovae) and this may actually imply a decrease in the returned mass fraction on the whole. In either case, the chemical yields from low- and intermediate-mass stars are greatly affected and the total effect on the chemical enrichment of the interstellar medium remains to be worked out.

ACKNOWLEDGEMENT

I would like to thank Dr. M. H. Gokhale for useful discussions.

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