PLANETARY NEBULAE WITH MASSIVE CENTRAL STARS

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ABSTRACT. The paper discusses the problem of planetary nebulae with massive nuclei from the point of view of their theoretical evolution and observational appearances. The available data suggest that NGC 2440, 6302, and 7027 have central stars with masses greater than 0.8 $M_\odot$.

1. INTRODUCTION

It is now commonly accepted that most of planetary nebula nuclei (PNNi) have masses close to 0.6 $M_\odot$. The main controversy concerns the high mass tail of the distribution (cf. Schonberner, 1981; Kaler, 1983; Renzini, 1983; Heap & Augensen, 1986). At present this problem cannot be solved definitively because of observational and theoretical uncertainities. In this review we present the main points concerning massive PNNi and their planetary nebulae (PNe). The principal evolutionary aspects of massive PNNi are outlined in the next section. Section 3 is devoted to the evolution of PNe surrounding massive PNNi. Finally, in Section 4 we discuss the methods for observational determination of masses and the results for individual PNNi. We conclude that at present we know three PNe, i.e. NGC 2440, 6302, and 7027, whose PNNi have masses above 0.8 $M_\odot$.

2. EVOLUTIONARY CHARACTERISTICS OF MASSIVE CENTRAL STARS

The luminosity of a PNN, L, with active shell sources depends only on its mass, M, and can be determined from a widely known formula (e.g. Paczyński, 1971):

$$L/L_\odot = 5.9 \times 10^4 \; (M/M_\odot - 0.52). \qquad (1)$$

The effective temperature varies greatly during the PNN evolution. It is determined by the mass of the H-rich envelope and the nuclear burning activity. However, the maximum value of the effective temperature, T_M, that can be achieved by a PNN is again a function of its mass only. This can be estimated from the formula:

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$$\log T_M = 5.72 + 2.41 \log (M/M_\odot) \tag{2}$$

which is a least square fit to the results of Paczyński (1971), Schonberner (1981, 1983), Iben (1982, 1984), and Wood & Faulkner (1986).

The most spectacular aspect of massive PNNi is that they evolve very quickly, especially in the horizontal portion of their H-R diagram tracks. Let us define, following Paczyński (1971), the nuclear evolutionary time scale as the H-rich envelope mass corresponding to the effective temperature log T = 4.5, M_{EN}, devided by the nuclear burning rate. As an estimate of M_{EN} we can use the formula of Iben (1982 - his Eq. 22):

$$\log M_{EN} = - 5.10 - 4.96 \, (M/M_\odot - 1.0). \tag{3}$$

This relation results from a theoretical study of accretion rejuvenated white dwarfs. However, it fits very well to the results from model PNNi calculated by Paczyński (1971), Schonberner (1983), Iben (1984), and Wood & Faulkner (1986). Combining Eq.(3) with the nuclear burning rate resulting from Eq.(1) (adopting the H abundance, $X_H = 0.7$) one gets the following formula for the nuclear time scale expressed in years:

$$\log \tau_n = 1.0 - 4.96 \cdot (M/M_\odot - 1.0) - \log (M/M_\odot - 0.52). \tag{4}$$

For $M > 0.7 \, M_\odot$ Eq.(4) can be approximated by a simpler formula, i.e.

$$\log \tau_n \simeq 7.3 - 5.9 \, M/M_\odot. \tag{4a}$$

It should be noted that Eq.(4) has been derived from the H-burning models. Some authors argue that the most favourable conditions for a PN formation occur during a He-shell flash. In this case the resultant PNN is powered by the He-burning and generally evolves slower than the H-burning counterpart. It appears, however, that Eq.(4) gives a right estimate of the time span necessary for the He-burning PNNi of Wood & Faulkner (1986) to evolve from log T = 4.5 to 5.0.

The last point we want to discuss in this section concerns the time span that elapses between the PN formation and the moment when the PNN becomes sufficiently hot to ionize the nebular gas, i.e. when log T ≃ 4.5. It is often argued that the PN formation stops when the star departs from the AGB which takes place at log T ≃ 3.7 (Schonberner, 1981, 1983; Renzini, 1983). At this moment the mass of the H-rich envelope is of order .001 $M_\odot$ almost independently of the core mass (Paczyński, 1971). If the subsequent evolution is determined by the nuclear burning alone then even a 1.2 $M_\odot$ star would require a few thousand years in order to increase its temperature from log T = 3.7 to 4.5 (see also Schonberner, 1987). An ordinary stellar wind can somewhat reduce the discussed time span (by a factor of a few at most). The conclusion that arises from the above discussion is that even for the most massive PNNi the time interval between the formation of a PN and its ionization is of order 1000 yrs. The nebular gas is thus expected to drop in density to log N < 5 before it stars being ionized. And this immediately implies that the photoionization of a PN by a massive PNN should lead to strong non-equilibrium effects in the ionization and thermal staructure of the PN. Indeed, the evolutionary time scale of a massive PNN (Eq. 4) can be comparable to or even shorter than the recombination time scale of the nebular gas which is

$$\log \tau_r = 5.1 - \log n \qquad (5)$$

where τ_r is in years if the electron density, n, is expressed in cm^{-3}. The following section is devoted to the discussion of the time-dependent ionization effects within the above scenario.

Recently Wood & Faulkner (1986) have argued that an AGB star capable of producing a core mass greater than 0.86 $M_\odot$ produces a PN with a hydrogen-free PNN. A PNN of this sort would evolve on a very short time scale towards high effective temperatures. This would result in appearance of a very dense, compact, high-excitation PN surrounded by a massive, neutral, dusty envelope. There has been no investigation of the PN evolution along these lines as yet and therefore we cannot discuss this possibility in more detail.

3. TIME-DEPENDENT IONIZATION OF PLANETARY NEBULAE WITH MASSIVE NUCLEI

A detailed discussion of this problem is given in Tylenda (1983) who has calculated time-dependent models of PNe with a 1.2 $M_\odot$ PNN. The study considers the non-equilibrium photoionization in great detail although it neglects dynamical effects. It seems, however, that the influence of the ionizing radiation on the dynamics of a PN with a massive PNN is not important. The radiation momentum integrated over the high luminosity phase of a PNN quickly decreases with the increasing PNN mass (since τ_n rapidly decreases with M - see Eq. 4). For a 1.2 $M_\odot$ PNN the integrated radiation momentum is 3 orders of magnitude smaller than the momentum of a typical PN.

One can distinguish two different phases in the evolution of a PN surrounding a massive PNN (Tylenda, 1983). Initially, when the PNN is luminous and becomes hotter and hotter, a fast (weak R-type) ionization front is moving outwards in the PN. We have then the photoionization phase. The physical state of the nebular gas, especially just behind the ionization front, is far from the equilibrium conditions. If one tries to apply the Zanstra method to the spectrum observed during this phase then the derived values appear to be underestimates, sometimes very severe, of the effective temperature and, especially, of the PNN luminosity. An analysis of the model PNe during the photoionization phase leads to the conclusion that there is an upper limit to the luminosity that can be derived from the Zanstra method, i.e. (Tylenda, 1984)

$$L_Z/(10^4\ L_\odot) \lesssim 1.7\ (1.0 + 0.6\ (\log n - 3.0)) \pm 0.3 \qquad (6)$$

where n is the nebular electron density in cm^{-3}. Condition (6) can be used as a self-consistency test when applying the Zanstra method to PNe with luminous PNNi.

After the nuclear fuel has been exhausted the PNN is decreasing in luminosity. Initially the fading is fast and down to $\log L/L_\odot \simeq 3$ it proceeds on a time scale not much longer than τ_n (Eq. 4). The reduced flux of ionizing photons can maintain the ionization only in the innermost layers of the PN. The outer regions are now recombining and cooling off. The nebula is in the recombination phase. The most spectacular aspect of this phase is the appearance of a double-envelope structure in the image of the PN, i.e. an inner, bright, high-excitation ring is surrounded by a faint, low-excitation halo (Tylenda, 1983). The halo is fading with time. However, the time scale of this process increases because of the decreasing electron density (cf. Eq. 5). Consequently, even after several thousands of years a tenuous, very low-excitation halo showing $n \simeq 10 - 100\ cm^{-3}$ can still be visible.

Finally, it is worth of noting that the appearance of a double-envelope structure, similar to that discussed above, is predicted for PNe with less massive PNNi ($M > 0.6\ M_\odot$) as well, provided that the PNNi burn hydrogen quiescently (Tylenda, 1986; see also Schmidt-Voigt and Koppen, 1987). This is because the PNNi of this sort have a fast decline in luminosity after the cessation of the nuclear burning (Schonberner, 1981).

4. OBSERVED CASES OF PLANETARY NEBULAE WITH MASSIVE CENTRAL STARS

The most classical method for observational testing of the PNN evolution theory is the H-R diagram (see e.g. reviews by R.A. Shaw and by S.R. Pottasch in this volume). After having determined luminosities for PNNi lying in the horizontal part of the H-R diagram one may hope to derive their masses from Eq.(1). Unfortunately, this method cannot give reliable results for individual cases because of the well known problem of the distances to the galactic PNe. However, it can be applied to PNNi in the Magellanic Clouds. A first attempt to determine luminosities of PNNi of three bright PNe in the Magellanic Clouds made by Stecher et al. (1982) gave very high values implying masses close to 1.2 $M_\odot$. It appeared, however, soon that the Zanstra luminosities derived by Stecher et al. violated condition (6) (Tylenda, 1984). In other words, the observed PNNi evolved much slower than a 1.2 $M_\odot$ PNN should have done. Subsequent reanalyses of the observational data suggested much smaller masses, i.e. 0.6 - 0.7 $M_\odot$ (Tylenda, 1984; Heap & Augensen, 1987). Recently Aller et al. (1987) have derived masses for 12 PNNi in the Magellanic Clouds from the observed luminosities. The values range from 0.58 to 0.71 $M_\odot$ including the three controversial PNNi. In all cases condition (6) is satisfied. In conclusion, we do not see massive PNNi within the brightest PNe in the Magellanic Clouds. This is not surprising since massive PNNi evolve very quickly while being luminous. We, therefore, expect to find them rather among hot, low-luminosity PNNi.

Schonberner (1981) has elaborated a method which compares theoretical models with observations on the Abell's (1966) diagram: stellar M_v versus nebular radius. Since the evolutionary time scale is very sensitive to the stellar mass (Eq. 4) the theoretical tracks are well separated in this diagram even for small differences in mass. Hence its potential usefulness for empirical mass determination. However, with the present uncertainities both in the observations (distances) and in the theory (mechanism and time of the PN formation, subsequent dynamics of the PN, importance of residual stellar winds) conclusions drawn from the M_v-R_n diagram alone can be, sometimes, very misleading. Recently Heap & Augensen (1987) have derived individual PNN masses using the discussed method. For about 30% of the objects they have obtained values in excess of 0.65 $M_\odot$. Most of this comes from compact PNe having R_n < 0.1 pc. A closer analysis shows that precisely these stars have in majority log $L/L_\odot$ < 3.5 and log T < 4.85. Consequently they lie below the horizontal part of the 0.6 $M_\odot$ track in the H-R diagram (e.g. Pottasch, 1983). And this suggests that these are very low mass PNNi. The situation is, therefore, not clear and requires thorough study.

Very recently Mendez et al. (1987) have derived PNN masses for 21 PNe from a model atmosphere analysis of the observed stellar H and He absorption profiles. For a half of the sample they have derived masses above 0.7 $M_\odot$ - a result really surprising in view of other studies in our Galaxy (Schonberner, 1981; Kaler, 1983) and in the Magellanic Clouds (Aller et al. 1987). Let us concentrate on two PNNi, i.e. NGC 2392 and He 2-138, for which Mendez et al. have found masses close to 0.9 $M_\odot$. It appears that with the distances proposed by Mendez et al. the Zanstra lminosities for these two PNe do not satisfy condition (6). In the case of NGC 2392 the HeII Zanstra luminosity is log $L_z/L_\odot$ = 4.69 (HeII λ 4686 line intensity taken from Aller & Czyzak, 1979; other data from Mendez et al. 1987) whereas the HI Zanstra luminosity for He 2-138 is log $L_z/L_\odot$ = 4.41. The upper limits from Eq.(6) are 4.34 ± .06 (log n = 3.5 - Aller & Czyzak, 1979; Shaw & Kaler, 1985) and 4.42 ± .05 (log n = 3.9 - Torres-Peimbert & Peimbert, 1977), respectively. Even the case of He 2-138 cannot be regarded as mariginally consistent since Eq.(6) has been obtained using Eq.(4a) which gives the time scale for the overall nuclear evolution. The two PNNi, according to Mendez et al., have log T < 4.7 and for these temperatures the stellar evolution is much faster than τ_n. The model PNNi of Schonberner (1981) evolve from log T = 4.4 to 4.7 during a time span 10 times shorter than τ_n. Thus an 0.9 $M_\odot$ PNN requires only some 10 years in order to pass this temperature interval. NGC 2392 has been seen for more than 100 years (it was discovered in 1853 - Perek & Kohoutek, 1967). The discrepancy is important and we conclude that Mendez et al. (1987) have overestimated the PNN masses, at least for NGC 2392 and He 2-138.

A lower limit to the mass of a PN can be obtained from Eq.(2) if we know its effective temperature. This method has the advantage of being independent of the distance. The main problem is, of course, the temperature determination the more so as we expect log T > 5.3 for massive PNNi. The existing methods for effective temperature determination have recently been analysed by Stasińska & Tylenda (1986) from the point of view of their usefulness in the case of very hot stars. They conclude that only the Zanstra method can give a reliable estimate of the effective temperature of a hot PNN. Other methods underestimates, sometimes seriously, the temperature in this case.

Table 1
Planetary nebulae with massive central stars

Name	log T_Z	log T_S	$M/M_{\odot}$
NGC 2440	5.50	5.26	>0.81
NGC 6302		5.48	>0.80
NGC 6445	5.27	5.18	>0.65
NGC 6537	5.29		>0.66
NGC 6741		5.37	>0.72
NGC 7027	5.78	5.48	>1.05
IC 2165	5.29	5.05	>0.66

In Table 1 we list the PNNi which have log T > 5.2. The second column gives the Zanstra temperatures calculated from the data recently compiled by Stasińska & Tylenda (1987). In all cases T_Z(HI) was greater than or comparable to T_Z(HeII) so we took the mean value from the two estimates. The third column contains the Stoy temperature calculated by Preite-Martinez & Pottasch (1983). The lower limits to the PNN mases are given in the last column. They have been derived from Eq.(2) using T_Z or T_S if the former was not available. All PNNi listed in Table 1 have masses well above the canonical value of 0.6 $M_{\odot}$. But in three cases, i.e. NGC 2440, 6302, and 7027, the PNNi are very massive. For NGC 6302 no PNN has been observed as yet. It has one of the highest Stoy temperatures. Since the Stoy method underestimates the effective temperature (Stasińska & Tylenda, 1986) it is clear that this PN has a PNN much more massive than 0.8 $M_{\odot}$. NGC 7027 has been extensively discussed in Tylenda (1984). This PN has an extended, very faint halo observed in Hα by Atherton et al.(1979). The nature of the halo is not clear but it may suggest that the PN is now in the recombination phase. An analysis of the observational data in the frame of this hypothesis leads to the mass estimate for the NGC 7027 nucleus of 1.0 ± 0.2 $M_{\odot}$ (Tylenda, 1984). Observations of the halo in other lines, in particular in [OIII], would serve as a conclusive test to this hypothesis.

Finally, as it is often argued (e.g. Renzini, 1983) and as it has been mentioned in the beginning of this section we should expect to find massive stars among hot, low-luminosity PNNi. At present an investigation of this sort is difficult and cannot give conclusive results, mostly because of the distance problem. However, we can mention 5 candidates, i.e. A 21, A 31, Jn 1, K 2-2, and PW 1. The observational data available at present indicate that these PNNi have log $L/L_{\odot} < 1.5$, log T = 5.0 - 5.1, and M_v > 8.0 (Stasińska & Tylenda, 1987). Consequently, they lie in the region occupied by evolved, massive model PNNi both in the H-R diagram and in the Abell's diagram.

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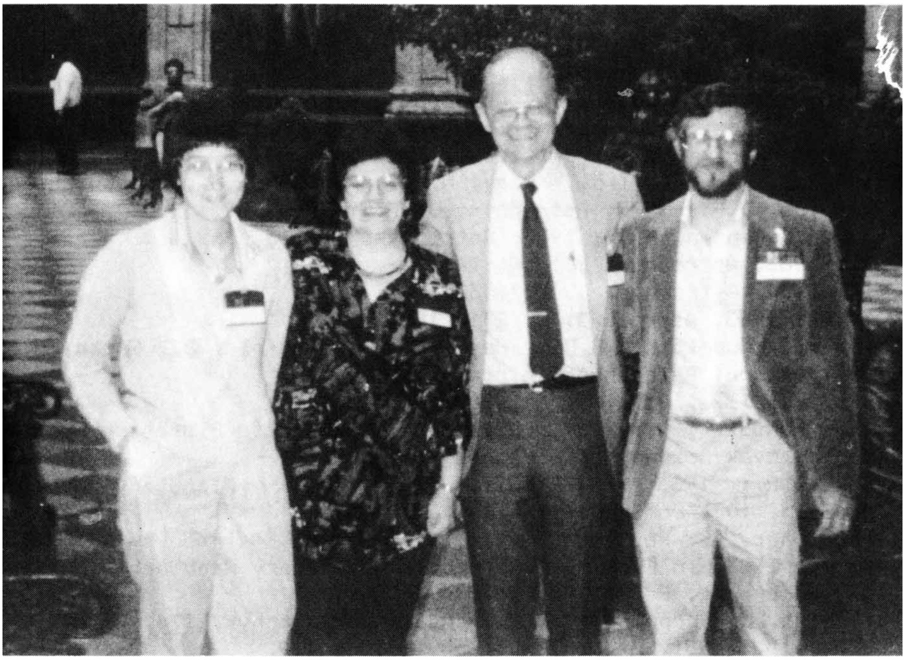

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