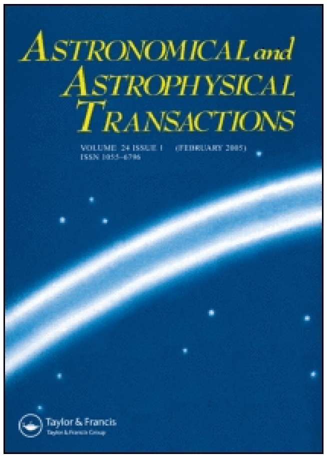

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Planetary nebulae in open clusters and the mass boundary between the progenitors of white dwarfs and neutron stars

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PLANETARY NEBULAE IN OPEN CLUSTERS AND THE MASS BOUNDARY BETWEEN THE PROGENITORS OF WHITE DWARFS AND NEUTRON STARS

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The mass boundary between progenitors of white dwarfs and neutron stars is discussed. We propose obtaining the upper mass limit of WD progenitors from PNe in open clusters. The maximum mass on the main sequence for the OC member stars should be a good estimate of the WD progenitor star's mass in view of the negligible lifetime of PNe. This is a direct and more reliable way for the estimation of the mass boundary between progenitors of WDs and NSs, not having the uncertainties in the progenitor masses found by studying WDs in OCs. Observational and theoretical studies indicate preliminary values about 6-8$M_\odot$ for the mass boundary between WDs and NSs. PN-OC associations are also necessary to study the connections between masses, chemical abundances and other properties of the PNe, their nuclear stars and the progenitors of these objects on the main sequence. We discuss the association of PNe with OCs and globular clusters. One new association of a PN with GC is found (GC M 15 and PN PK 65-27.2).

KEY WORDS Planetary nebulae, open clusters, white dwarfs

1 INTRODUCTION

Until now investigations of the mass boundary between white dwarf (WD) and neutron star (NS) progenitors have relied on observations of WDs in relatively young open clusters (OCs) in which the turn-off mass is approximately equal to the possible mass boundary between the NSs and WDs. The first such young OC shown to contain WDs was the Pleiades. It is very important to find a WD in a still younger OC for the determination of the upper mass limit of WD progenitors, which is belived to be $8^{+3}_{-2}M_\odot$ (Weidemann, 1990).

Here we propose that PN in open clusters will lead to more accurate determination of the mass boundary. Searching for PN-OC associations will also be easier.

While nowadays very hot WDs can be observed only out to several hundred pc, PN can be easily observed from as far as the Galactic bulge. The optical luminosities of massive central stars of PNe are of the order of 10^{33}–10^{34} erg s^{-1} while massive and hot WDs ($T_{\rm eff}$ = 40 000 K) typically have $L_{\rm opt} = 10^{32}$ erg s^{-1}. The radio emission makes PNe detectable out to about 10 kpc in the Galaxy and even farther for extragalactic sources, like the sources in the Magellanic Clouds. PN–OC associations are neverthless rarely observed, as the lifetime of massive PNe is only about 10^4 yrs. However, although a short lifetime is a disadvantage for the number density of the objects, it is advantageous for estimating the mass of the progenitor as we do not have the uncertainty associated with the cooling times and age of the OC in the case of WD–OC associations. The cooling times of hot and massive WDs with $T_{\rm eff}$ = 40 000 K can be as large as 4×10^7 yrs, therefore their number density is high but the volume in which they can be detected is very small. As we want to examine the mass boundary between WD and NS progenitors, it is necessary to search for WDs or PNe in OCs with turn-off masses in the range 6–$8M_\odot$ where the mass boundary is expected to lie, corresponding to ages of approximately (3–6) $\times 10^7$ yrs. As is known, due to selection effects such OCs are typically less than 3 kpc away from the Sun. There are known WDs with distances about 0.4–0.9 kpc but observing such distant WDs is a very difficult problem. We propose that PN–OC associations will provide a better clue for the upper mass limit of WD progenitors.

The other aspect of the problem of the mass boundary is the lower mass limit of supernova (SN) progenitors. We can obtain a lower limit of SN progenitors in the solar neighbourhood by using the initial mass function (Parker and Garmany, 1993 and references therein). The explosion frequency of SNe in the Galaxy coincides with the death rate of stars with masses $\sim$ 5–$10M_\odot$ depending on the initial mass function. The lower mass limit of neutron star progenitors is always given with a large spread of masses. Lorimer *et al.* (1993) estimate the pulsar birth frequency in the Galaxy as 1 in 150 yrs. They put a lower mass limit of $5M_\odot$ for neutron star progenitors. Strom (1994) also estimates a $5M_\odot$ lower mass limit for SN progenitors, although he derives a rate of 6 SNe in 100 yrs from historical SNe.

The boundary derived from the upper mass limit of WD progenitors and the lower mass limit of SN progenitors is subject to errors. Changing the value of the mass boundary will not have any significant influence on the birth rates of WDs and PNe, while the birth rates of neutron stars or the rate of SN explosions will be affected significantly since the initial mass function decreases sharply with increasing mass of the stars. An interesting problem may arise if the progenitor masses for WDs and neutron stars are found to overlap with an overlap range of about (2–3)$M_\odot$. The data do not exclude this possibility (Weidemann and Koester, 1983; Amnuel *et al.*, 1984, 1985; Iben, 1995; Weidemann, 1990; Wegner and Reid, 1991; Wegner *et al.*, 1991; Stasinka and Tylenda, 1994 and Koppen *et al.*, 1991).

We review previous estimates of the mass boundary from theory and from WDs in OCs in Section 2. In Section 3 we discuss PN–OC associations and the current upper limits to the mass boundary of the progenitors of PNe. The conclusion are given in Section 4.

2 ESTIMATES OF THE MASS BOUNDARY FROM THEORY AND FROM WHITE DWARFS IN OPEN CLUSTERS

Nomoto (1984) has considered the problem of the limiting mass for a WD progenitor, allowing for evolution with mass loss. This theoretical work gave a limiting value of $8M_\odot$ for the progenitor mass. Taking into account the well-known neutronization process (slow electron capture) in a strongly degenerate electron gas (Zel'dovich and Novikov, 1971), Nomoto (1984) calculated the upper mass limit for WDs to be $1.3M_\odot$, about $0.1M_\odot$ smaller than the classical Chandrasekhar limit for WDs, $1.44M_\odot$. It is for this revised Chandrasekhar limit of $1.3M_\odot$ that Nomoto obtained the maximum progenitor mass to be $8M_\odot$. Consideration of the general theory of relativity additionally decreases the upper mass limit for cool and non-rotating WDs down to $1.2M_\odot$ (Zel'dovich and Novikov, 1971). "Young" WDs with masses above $1.2M_\odot$ must therefore undergo collapse in the future. However, as the neutronization rates are very small for WDs with masses 1.2–$1.3M_\odot$, their collapse times are comparable with the age of the Galaxy. WDs with large rotation rates can be more massive than $1.3M_\odot$ (Ostriker and Bodenheimer, 1968). Such massive WDs often also have magnetic fields which make them spin down quickly. Thus only the masses of young (hot) WDs may be more than $1.3M_\odot$, through rotation support. The progenitor masses of such relatively more massive young (hot) WDs may be greater than $8M_\odot$ (if the evolution scheme given by Nomoto 1984 is applicable). The progenitor masses of older cool WDs must be smaller than $8M_\odot$. Theoretically, the progenitor masses have a range extending to either side of $8M_\odot$, depending on alternatives like the presence of rotational support, and the extent of slow electron capture.

Six WDs have been observed in relatively young OCs, one in the Pleiades with $T_{\rm eff} = 32\,000$ K and masses about $1M_\odot$ (Wegner *et al.*, 1991), two in NGC 2168 with $T_{\rm eff} = 37\,500$ K and 44 000 K and masses of 0.6–$0.8M_\odot$ for both WDs (Reimers and Koester, 1988). The other three WDs are in NGC 2516 with $T_{\rm eff} = 30\,000$ K, 36 000 K, 33 500 K, and $M = 0.95M_\odot$, $1.14M_\odot$, $1.17M_\odot$ respectively (Reimers and Koester, 1982). The ages of these OCs are 7.76×10^7–1.07×10^8, 1.07×10^8 and 1.07×10^8–1.54×10^8 yrs respectively (Mermilliod, 1982; Pols and Marinus, 1994). The turn-off masses of the Pleiades and NGC 2168 are about $5M_\odot$ and that of NGC 2516 is about $4M_\odot$ (Schaerer *et al.*, 1993). The cooling times of WDs with masses $> 1M_\odot$ are about (5–7) $\times 10^7$ yrs (Reimers and Koester, 1982) or 10^8 yrs (Winget *et al.*, 1987) to reach temperatures of 30 000–36 000 K. According to the model of Winget *et al.*, (1987) the cooling times of WDs in the Pleiades and NGC 2516 OCs are about 10^8 yrs, and in the NGC 2168 OC is about 2×10^7 yrs. As the lifetime of stars with masses about 7–$8M_\odot$ is (3–4) $\times 10^7$ yrs (Schraerer *et al.*, 1993), comparable or smaller than the uncertainties in the cooling times of WDs, it is very difficult to obtain progenitor masses of WDs from the current turn-off masses of OCs. The uncertainties in the determinations of the temperatures of hot WDs (Tweedy and Napiwotski, 1994) and the ages of OCs may also be very high. If we assume that the progenitor masses of hot young WDs are closer to the turn-off masses of OCs, for the known hot WDs in the Pleiades, NGC 2168 and NGC 2516 OCs, we may conclude that the progenitor masses of these WDs are $> 5\text{–}6M_\odot$. The WD NGC 3532-10 is a very cold WD with $T_{\rm eff} = 20\,400$ K (Koester and Reimers, 1993), and may have a possible progenitor mass $> 6\text{–}7M_\odot$, although the turn-off mass of the OC is about $3M_\odot$. At present we do not have any observational support to propose progenitor masses of more than $7M_\odot$ for WDs in OCs.

3 POSSIBLE ASSOCIATIONS OF PLANETARY NEBULAE WITH OPEN CLUSTERS AND GLOBULAR CLUSTERS

Although the number of OCs is 1110 (Lynga, 1987), the probability of finding PN–OC associations is very small, because the lifetime of any PN which has a massive progenitor is only about 10^4 yrs. The short lifetime of PNe reduces the probability of observable associations, while the detectability of distant PNe obviously helps. If an association is found, the short lifetime of PNe means that its progenitor has the same mass as the current maximum stellar mass in the OC. Thus we avoid the ambiguities that are involved in using WD–OC associations because of the large and uncertain cooling "ages" of WDs and the age of the OC. The uncertainty in the cooling age of a WD arises both from observational uncertainties in the temperature estimates, and from uncertainties in the cooling models.

Table 1. Positionally coincident OCs and PNe

Name *OC*	l (°	– –	b °)	α_{1950} (^{h} ^{m})	δ_{1950} (° ′)	d (*kpc*)	θ (′)	*log t* (*yrs*)
NGC 2453	243.33	–	0.94	07 45.7	–27 12	1.5	5	7.6
NGC 2818	261.98	+	8.59	09 14.0	–36 24	3.2	9	8.8–9.0
Lynga 5	324.82	–	1.19	15 38.1	–56 28		5	
NGC 6281	347.82	+	2.01	17 01.4	–37 50	0.6	8	8.3
PN							$\delta\theta$(′)	
NGC 2452	243	–	1.1	07 45.39	–27 12.6	2.6 – 3.1	4.5	
NGC 2818	261	+	8.1	09 14.01	–36 25.2	3.2	1.2	
He 2-133	324	–	1.1	15 38.04	–56 26.8	1.5	1.3	
PN Sa2-167	347	+	1.1	17 01.16	–37 49.1		3.0	

In Table 1 positionally coincident OCs and PNe are listed. 913 out of 1455 PNe are in the region $243° < l < 13°$ (Acker *et al.*, 1990), and the number of OCs in this region is 522 out of 1110. Most of the known OCs are nearer than 3 kpc to the Sun and most of the PNe are in the direction of the Galactic bulge. The probability of chance projections is therefore higher in the direction of the Galactic centre. We discuss below the possible associations in Table 1. We do not include two positionally related PN–OC pairs in Table 1: PN M 3–20 – OC Trumpler 31 and PN VV3–4 – OC IC 4725. These are believed to be chance projections because the OCs are closer to the Sun than the PNe in both cases.

We have compiled distance estimates for each OC and for each PN or for the nucleus of the PN from the literature (Lynga, 1987, Amnuel *et al.*, 1989, Koppen *et al.*, 1991, Zhang and Kwok, 1993). In some cases several different distance estimates exist for one object. If there is a distance estimate for the OC and one for the PN or its nucleus, such that the estimates of their averages roughly agree, we take the PN–OC pair as a possible association. We now briefly discuss each pair in Table 1.

Like Dufour (1984), we conclude that the association of OC NGC 2818 and PN NGC 2818 (PK 261+8.1) is real. The distance to this nebula is estimated to be 2.3 kpc (Cahn *et al.*, 1992) and 3.8 kpc (Amnuel *et al.*, 1989) with the average value close to the 3.2 kpc distance estimate for the OC. According to Pedregos (1989) the distance of OC NGC 2818 is 2.3–3.5 kpc. The progenitor mass of this nebula must be slightly more than $2M_\odot$, which is the maximum mass in NGC 2818. The mass of the central star is estimated to be $0.59M_\odot$ by Zhang and Kwok (1993) and more than $0.64M_\odot$ by Amnuel *et al.*, (1989).

For the pair OC NGC 2453 – PN NGC 2452, the distance estimates for the PN are 2.6 kpc (Shaw and Kaler, 1989) and 3.1 kpc (Stanghellini *et al.*, 1993), while the distance estimate of the OC is 1.5 kpc (Lynga, 1987), so the association is not likely. Furthermore the PN has a central star with estimated mass $< 0.56M_\odot$ (Shaw and Kaler, 1989). If this mass estimate is correct, the progenitor mass of the PN must be $< 2M_\odot$, which means the lifetime of the progenitor star is 10^9 yrs. The associated OC NGC 2453 is much younger.

Cahn *et al.*, (1992) and Amnuel *et al.* (1989) state similar distances, 1.5 kpc and 1.6 kpc, for the PN He 2–133. But lack of a distance estimate of the OC Lynga 5 makes it impossible to decide about the association.

The association of OC NGC 6281 and PN Sa 2–167 cannot be decided as there is no distance estimate for the PN.

The flux of the PN M 3–45 in the 6 cm band is 24.3 mJy and the size of the PN is 3.3 arcsec (Stasinka and Tylenda, 1994). Using these data one can find the surface brightness Σ of the PN and obtain a distance of 5 kpc from the Σ–D relation (Amnuel *et al.*, 1989). The OC Basel 5 is much closer than the PN, so this association is not real, although their coordinates well coincide.

Koester and Reimers (1989) found a new PN, G327.7 – 5.5, in the field of OC NGC 6087. The OC is 0.8 kpc away and the distance of the PN is very far from us compared to the OC. They mention that although the objects are in the same field, they are not relatives.

Unfortunately, there is only one reliable PN–OC association at present: OC NGC 2818 – PN PK 261+8.1; but for this one case the OC is too old to be of interest for the determination of the mass boundary.

In searching for associated PN–OC pairs, we have in mind also another very important problem: the relation between the different parameters of PNe and their central stars and the progenitor masses. Different authors (e.g. see Amnuel *et al.*, 1985; Shaw and Kaler, 1989, Koppen *et al.*, 1991, Stasinka *et al.*, 1991, Stasinka and Tylenda, 1994 and references therein) have studied the different parameters of the

PNe and their central stars, and investigate their connections with the progenitor masses. To study this problem it is necessary to find concrete PNe in OCs with different ages and also in globular clusters (GCs). We have therefore also looked for associations of PNe with GCs, using the catalogue of Webbink (1985) which contains 154 objects. We found one new association, of the PN PK, 65–27.2 ($\alpha_{1950} = 21^h27^m\!.6$, $\delta_{1950} = 11°57'$) in the GC NGC 7078 (M 15). We also note the known associations PK65–27.1 with M 15 (Gathier *et al.*, 1983) which is a rich cluster (Webbink, 1985, DeMarchi and Paresce, 1994) 10 kpc away, and of PN IRAS 18333–2357 which belongs to GC M 22 (distance 3.1 kpc). The central star has $T_{\rm eff} =$ 50 000 K and mass 0.55–0.6$M_\odot$ (Cohen and Gillet, 1989). Cudworth (1990) confirms the association of this PN and GC and gives a distance of 2.8 ± 0.3 kpc.

4 CONCLUSION

Theoretically, progenitor stars with $8M_\odot$ lead to the birth of WDs with mass about $1.3M_\odot$ which later undergo collapse, while progenitor masses of cool WDs without strong rotation must be 6–$7M_\odot$. From our investigation we conclude that the mass boundary between the progenitors of WDs and NSs is greater than $6M_\odot$, since known observational cases point to WD progenitors of mass $\leq 7M_\odot$.

The present observational situation based on WD–OC associations is ambigious. Available data and theory may indicate that the mass boundary for hot ($T_{\rm eff} >$ 30 000 K) WDs and SNe is about 6–$8M_\odot$, and for cool WDs and SNe is about 6–$7M_\odot$. Since rotationally supported massive ($M > 1.3M_\odot$) hot WDs may undergo collapse in a time interval smaller than the age of the Galaxy as they spin down and lose their rotational support, there may be a possible overlap between the masses of the progenitors of the hot WDs and SNe.

We have proposed that PN–OC associations will help us to indicate the progenitor masses of PNe, since PNe are short lived, so that the mass of their progenitors must be very close to the maximum mass (turn-off mass) on the main sequence for the OC, and since the turn-off masses of OCs can be determined accurately. Several good projections of PNe on to the OCs (see Table 1) and GCs are found. The true associations of PN PK 261+8.1 with OC NGC 2818 and PK 65–27.1 with GC NGC 7078 (M 15) are likely and a new association is noted, PN PK 65–27.2 and M 15. The present associations do not yield interesting limits for the boundary mass, but it is important for the investigation of the connection between the physical parameters of PNe, their nuclear stars and progenitors. We hope that this approach to the problem of the mass boundary between progenitors of WDs and neutron stars will give good results by future identifications of PNe and hot subdwarfs in OCs with larger turn-off masses, close to the mass boundary. This research will also allow us to have good calibrators connecting the masses and chemical abundances of PNe with the properties of their central stars and with the progenitor masses. We would like to attract attention to this potential method for investigating the mass boundary between the progenitors of WDs and NSs, in the hope of resolving the present ambiguities.

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