AGES OF CENTRAL STARS OF PLANETARY NEBULAE

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ABSTRACT The determination of ages of central stars of planetary nebulae (CSPN) is a complex problem, and there is presently no single method that can be generally applied. Our group has pioneered in the treatment of this problem, and we have developed several methods to estimate the ages of the PN progenitor stars, based both on the observed nebular properties and in some properties of the stars themselves. In principle, the traditional methods to derive the ages of galactic stars can be applied to CSPN, such as the use of theoretical isochrones. However, the physical properties of these objects are not as well known as in the case of normal stars, so that the derived isochrones are generally uncertain, leading to the need of alternative methods. In this work, we will discuss several methods developed so far by our group, such as (i) the use of an age-metallicity relation that also depends on the galactocentric radius, (ii) the determination of ages from the central star masses obtained from the observed nitrogen abundances, and (iii) the use of an age-metallicity relation obtained for the galactic disk. Also, theoretical isochrones for AGB stars have been used to derive ages of CSPN in the SMC. We estimate the expected age distribution of the CSPN based on the observed distribution of white dwarf stars, and compare the results with the distributions obtained by the methods mentioned above and with available mass distributions of CSPN.

1. INTRODUCTION

Planetary nebulae (PN) are the offspring of intermediate mass stars with main sequences masses between 0.8 and 8 $M_\odot$ approximately. As a consequence, their properties reflect different physical conditions depending on the masses – and therefore ages – of their central stars (CSPN), which makes these objects extremely important in the study of the chemical evolution of their host galaxies. As an example, some recent theoretical models predict a time flattening of the observed radial abundance gradients in the galactic disk, while other models predict the opposite behaviour. This can be analyzed on the basis of abundances of PN and open cluster stars, and in both cases the results depend on the ages of the objects considered.

The determination of ages of CSPN is a complex problem, and there is presently no single method that can be generally applied. Our group has pioneered in the treatment of this problem, and we have developed several methods to estimate the ages of the PN progenitor stars, based both on the observed nebular properties and in some properties of the stars (cf. Maciel et al. 2003, 2005, 2008). We have obtained a large sample of well observed nebulae, located in the solar neighbourhood, in the galactic bulge and anticenter, and in the Magellanic Clouds, so that we can apply our methods to objects in different environments with different ages and metallicities. In this work, we will discuss several methods to estimate the ages of CSPN developed so far by our group, namely (i) the use of an age–metallicity–radius relation; (ii) the estimate of central star masses and ages from the observed nitrogen abundance, and (ii) the use of an age–metallicity relation. We have also considered the use of theoretical isochrones obtained for AGB stars for CSPN in the SMC. We estimate the expected age distribution of the CSPN based on the observed distribution of white dwarf stars, and compare the results with the distributions based on the masses of CSPN and those obtained by the methods mentioned above.

2. AGE DETERMINATION OF CSPN

METHOD 1: THE AGE-METALLICITY-RADIUS RELATION

The first method to be considered was initially developed by Maciel et al. (2003), in the framework of an estimate of the time variation of the radial abundance gradients in the galactic disk. Using the oxygen abundance measured in the nebula, the [O/H] abundance relative to the Sun can be obtained, adopting the solar value $\log(\mathrm{O/H})_{\odot} + 12 = 8.7$ (see for example Asplund et al. 2004). We have used the relation between the metallicity [Fe/H] and the oxygen abundance is given by Maciel et al. (2003). Finally, the ages of the PN progenitor stars are given by an age–metallicity–radius relation developed by Edvardsson et al. (1993), so that some knowledge of the distance to the PN must be assumed. Results for the sample containing 234 galactic PN from Maciel et al. (2003) are shown in Fig. 1. It can be seen that the age distribution shows a prominent peak, located around 4–5 Gyr, which is about the age of the Sun, suggesting that most PN come from stars having masses close to one solar mass in the main sequence.

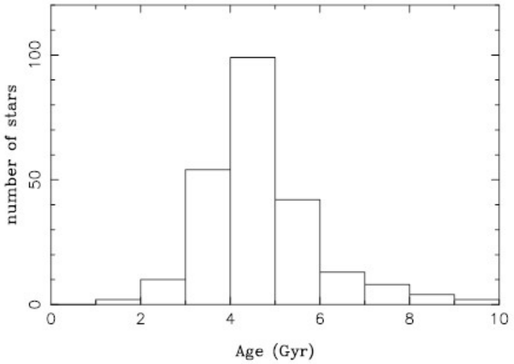


Fig. 1

METHOD 2: N/O MASSES OF CSPN

This method was also employed by Maciel et al. (2003), and assumes a relationship between the central star mass m_{CS} and the N/O abundance, which is expected from several theoretical and observational investigations. In order to obtain the stellar mass on the main sequence, we adopted a simple initial mass–final mass relation as in Maciel et al. (2003). For the mass–age relation, we have adopted a simple relation given by $t \propto m_{MS}^{-1}$, which we refer to as case A, so that we have $t = 10$ Gyr for $m_{MS} = 1\ M_{\odot}$. Alternatively, we may use a more realistic relationship such that the lifetimes decrease more strongly for larger masses, such as $t \propto m_{MS}^{-2}$ (case B), and finally we adopt the well known mass–age relation by Bahcall and Piran (1983, see also Maciel et al. 2003) (case C). The results for a sample of 122 PN for which all necessary data was available is shown in Figs. 2, 3, and 4, for cases A, B, and C, respectively. These results are similar to the age–metalllicity–radius method, in the sense that most objects have ages lower than about 10 Gyr, and there is a sharp maximum in the probability distribution, the location of which depends on the calculated lifetimes as a function of the main sequence mass. From case A to case C the lifetimes of the more massive stars decrease [cf. Fig. 7], so that the final probability at larger lifetimes decreases, and the whole peak moves to the left, as shown by inspecting Figs. 2, 3, and 4. The best agreement with the results of Method 1 occurs for case B, which gives more reasonable lifetimes than case A.

Fig. 2

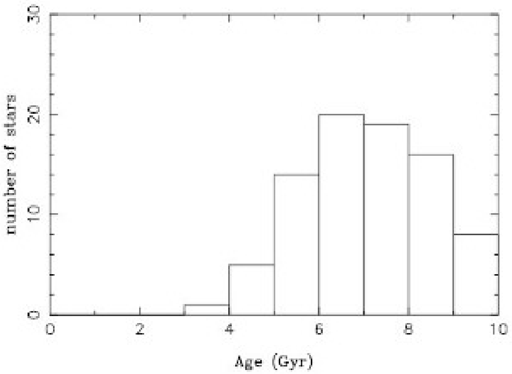


Fig. 3

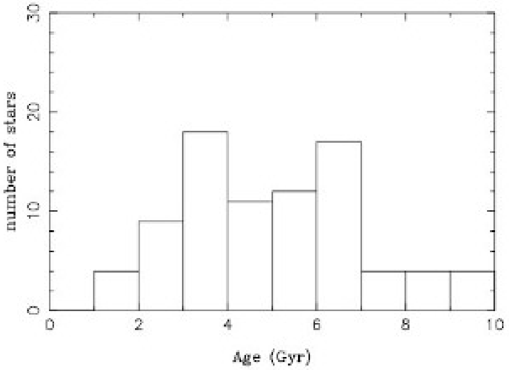
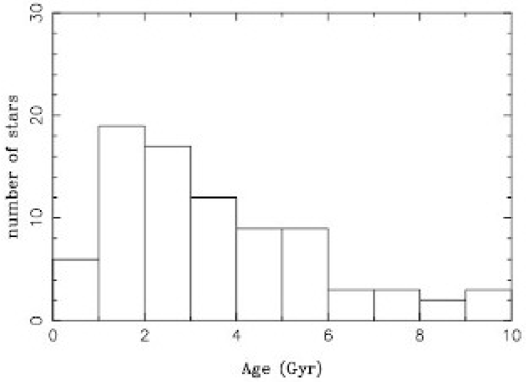


Fig. 4



METHOD 3: THE AGE–METALLICITY RELATION

Rocha-Pinto et al. (2000) derived an age–metallicity relation for the galactic disk based on chromospheric ages and accurate metallicities (cf. Table 3 of Rocha-Pinto et al. 2000). This relation can be approximated by a second order polynomial, which can be used to derive the stellar lifetimes once the metallicity is fixed. We can apply the same procedure as in Method 1, and obtain [Fe/H] from the oxygen abundance O/H. The results resemble those of Method 1, or case B of Method 2, in the sense that most stars have ages under about 6 Gyr, and the distribution peaks around 4–7 Gyr, although the expected number of stars at lower ages is higher. Other methods have been studied, including the use of both PN abundances and theoretical isochrones of AGB stars in the SMC, with results similar to Method 2, case C, although the sample is relatively small (cf. Idiart et al. 2007).

3. THE EXPECTED AGE DISTRIBUTION OF CSPN

The expected age distribution of CSPN can be estimated by analyzing the better known mass distribution of the white dwarf stars, most of which are essentially CSPN which have already entered the cooling track, having lost the ionized nebula to the interstellar medium. Since the average mass loss rates during the PN phase amount to about dM/dt $\sim 10^{-8}$ to 10^{-6} $M_\odot$/yr and the PN phase duration is about $\Delta t \sim 1$ to 2×10^4 yr, the total mass lost during this phase is $\Delta m \sim (dM/dt)\, \Delta t \sim 10^{-4}$ to 2×10^{-2} $M_\odot$, which is much smaller than the CSPN masses. Therefore, in a first approximation, the mass distribution of the CSPN must be similar to that of the white dwarfs, except for the very low mass stars with $m_{CS} < 0.55\ M_\odot$. Such stars are not expected from theoretical models, since main sequence stars leading to white dwarfs with masses lower than about 0.55 $M_\odot$ probably go directly do the white dwarf phase. Recent work on the mass distribution of white dwarfs by Madej et al. (2004) and Kepler et al. (2007) lead to a distribution which is strongly peaked at about 0.56 $M_\odot$, as shown in Fig. 5a (Madej et al. 2004). The mass distributions of CSPN and white dwarfs have also been previously considered by Stasinska et al. (1997) and more recently by Gesicki and Zijlstra (2007), based on a dynamical method which allows mass determinations within 0.02 $M_\odot$. It results that both the CSPN (Fig. 6a) and white dwarf distributions peak around 0.6 $M_\odot$ as in the works previously mentioned, although the white dwarf distribution shows a broader mass range. These results are in good agreement with our own N/O masses, as discussed by Maciel et al. (2008).

The white dwarf and the CSPN mass distributions can be very well fitted by a Gaussian probability distribution. As before, we will assume a simple relation between the masses of CSPN and main sequence stars, so that we can derive the probability distribution of the latter. We have adopted both linear and quadratic relations, but the results are not particularly sensitive to this assumption.

In order to derive the age distribution of the observed CSPN, we also need a mass–age relation, so that we will adopt cases A, B, and C, as before. Fig. 7 shows the stellar ages as a function of the main sequence masses for cases A, B and C.

Assuming that the star formation rate has remained approximately constant along the lifetime of the Galaxy, the expected CSPN age distributions can be estimated. Figs. 5b,c and Figs. 6b,c show the CSPN age distributions using the white dwarf (Madej et al. 2004) and CSPN (Gesicki and Zijlstra 2007) mass distributions, respectively. The obtained age distributions are shown for cases A (Figs. 5b and 6b) and B (Figs. 5c and 6c). It can be seen that the expected age distribution is also strongly peaked, with a maximum around 5–7 Gyr for case A and 2–5 for case B.

For the white dwarf distribution of Fig. 5a, the approximation leading to the age distribution artificially increases the probability at very large ages, greater than about 12 to 15 Gyr, in view of the unrealistic assumption adopted for the initial mass–final mass relation, but the general behaviour of the age distribution is unchanged. In fact, excluding the main sequence stars that do not lead to the formation of CSPN, namely those with the lowest masses, the main effect is a sharp decrease in the probability for ages greater than 12 Gyr. On the other hand, the age distributions shown in Figs. 6bc are more realistic, as they are based on the actual masses of the observed CSPN.

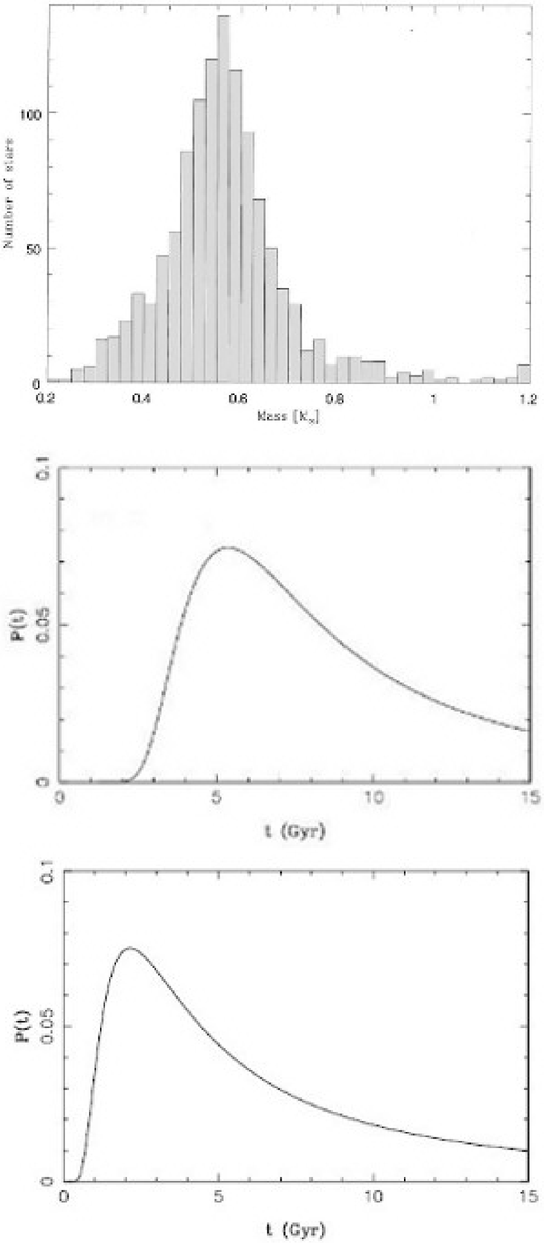

Number of stars
0
50
100
0.2
0.4
0.6
0.8
1
1.2
Mass [M⊙]
P(t)
0
0.05
0.1
0
5
10
15
t (Gyr)
P(t)
0
0.05
0.1
0
5
10
15
t (Gyr)

Fig. 5

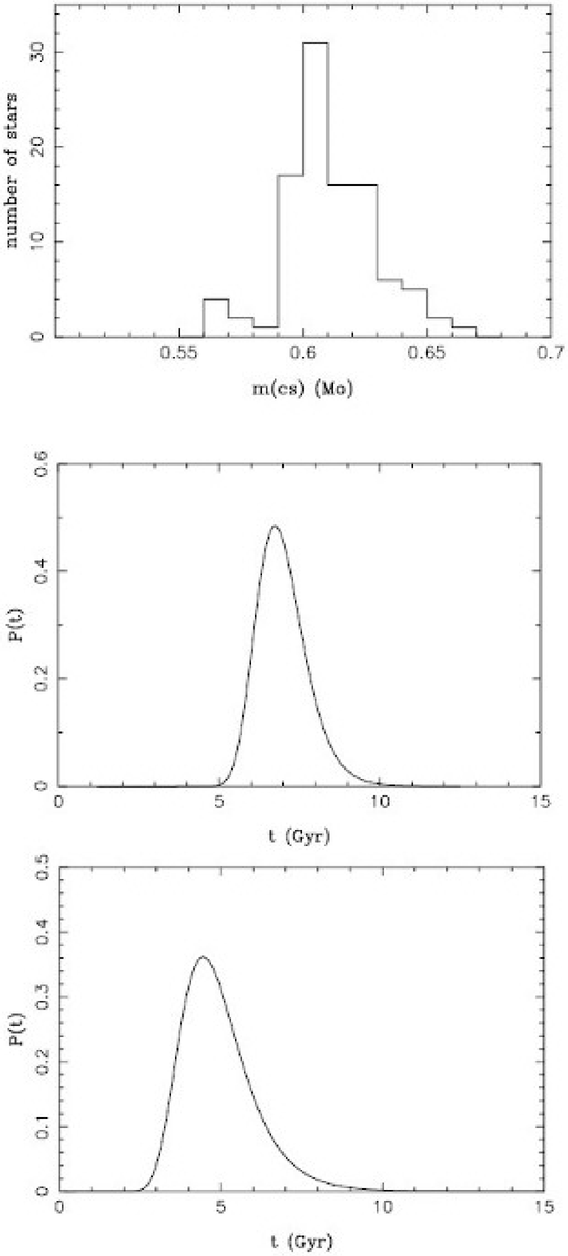

number of stars
0
10
20
30
0.55
0.6
0.65
0.7
m(cs) (Mo)
P(t)
0
0.2
0.4
0.6
0
5
10
15
t (Gyr)
P(t)
0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
t (Gyr)

Fig.6

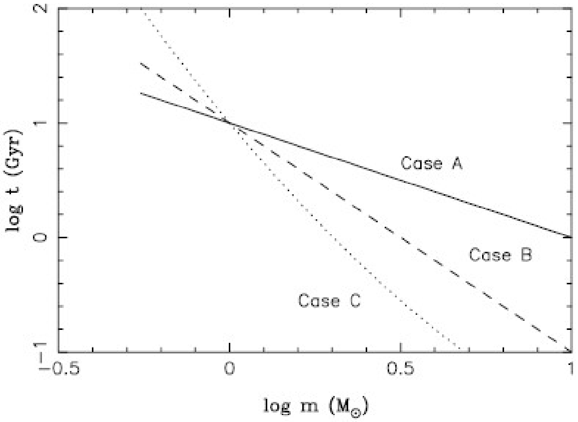


Fig.7

Taking into account the distributions shown in Figs. 5bc and 6bc, the main conclusion that can be drawn is that a peaked distribution can be expected, but the precise location of the peak depends somewhat on the adopted assumptions, namely the initial mass–final mass relation and especially the stellar lifetimes as a function of the main sequence mass. Case A gives larger lifetimes for masses greater than one solar mass, which pushes the peak of the age probability distribution to the right, while for cases B and C these lifetimes are shorter, so that the peak of the probability distribution moves to the left, as shown in Figs. 5c and 6c for case B. Case C (not shown) considers even shorter lifetimes for these stars, so that the peak of curve is further shifted to the left. Comparing Figs. 5 and 6 with the results of Figs. 1 to 4, it can be concluded that all three methods considered in section 2 produce reasonable results in agreement with the expected age distribution, but the details involving the mass–age calibration and the individual age determinations still need to be worked out.

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