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R. Napiwotzki and M. R. Burleigh

Testing the Relationship between the Masses of White Dwarfs and those of their Progenitors

J. Isern,[1,2] S. Catalán,[1,2] E. García–Berro,[3,2] and M. Hernanz[1,2]

[1]*Institut de Ciències de l'Espai, CSIC, Facultat de Ciències, Campus UAB, 08193 Bellaterra, Spain*

[2]*Institute for Space Studies of Catalonia, c/ Gran Capità 2–4, 08034 Barcelona, Spain*

[3]*Departament de Física Aplicada, Escola Politècnica Superior de Castelldefels, Universitat Politècnica de Catalunya, Avda. del Canal Olímpic s/n, 08860 Castelldefels, Spain*

Abstract. The initial–final mass relationship of white dwarfs is the function that relates the mass of the white dwarfs with the mass of their main sequence progenitors. At present this function is relatively poorly known from both the observational and the theoretical points of view. In this contribution we examine several aspects that influence the initial–final mass relationship.

1. Introduction

The determination of the relationship between the mass of the white dwarfs and that of their progenitors is a key ingredient to study several important facets of modern astrophysics. Among these perhaps the most well known are the rate of core collapse supernovae — which is fixed by the number of stars able to produce a degenerate massive Fe or ONe core — or of thermonuclear supernovae — which is fixed by the number of close binaries that form a CO core with the suitable mass — the understanding of the chemical evolution of the Galaxy and of the star formation and feedback processes in the galaxies, and the study of the properties of the galactic populations of field and cluster white dwarfs.

Despite its critical importance, this function is at present relatively poorly constrained, both from the theoretical and the observational points of view. The first attempt to empirically determine the initial–final mass relationship (IFMR) was undertaken by Weidemann (1977), who has also provided the most recent revision (Weidemann 2000). One of the most critical issues to this regard is to elucidate if this function is a single or a multivalued function. That is if it just depends on the mass of the progenitor or it also depends on the metallicity, the angular momentum, the magnetic field, the binary character and other properties of the progenitors.

For instance, the influence of the magnetic field is not clear. Ferrario, Vennes, & Wickramasinghe (1998) have shown that magnetic white dwarfs are systematically more massive than the non–magnetic ones. This could be just a bias caused by the influence of the magnetic field on the shape of the Balmer lines that mimics the presence of a higher gravitational field. It seems also clear that the presence of a close companion can also modify the shape of the IFMR. In particular, the analysis of the mass distribution of DA white dwarfs in the Palomar–Green Survey (Liebert, Bergeron, & Holberg, 2005) has revealed the existence of a low mass population, with masses $\sim 0.4\,M_{\odot}$, that is interpreted as a direct consequence of the evolution of close binary systems, since single stars able to produce such cores have lifetimes larger than the present age of the Universe. In this analysis it was also found an excess of stars with masses between ~ 1.0 and $1.4\,M_{\odot}$ and a shortage of white dwarfs with masses ranging from 0.65 to $0.85\,M_{\odot}$. This high–mass tail is currently interpreted as the consequence of the merging of two wide dwarfs in close enough binary systems. However, it is important to realize that because of the lifting effect, rotation can also modify the size of the core that is finally built. Domínguez et al. (1996) have shown that the larger the angular momentum is the higher is the mass of the degenerate core that is left.

Recent evolutionary calculations have confirmed that, for the same initial mass, the lifetime of a star decreases with metallicity while the mass of the white dwarf that eventually is left shows the opposite behavior. This behavior can be easily understood taking into account that low values of Z induce a reduction of the opacity without a reduction of the radius. Therefore, in order to maintain the structure, the temperature and the luminosity have to increase with the subsequent reduction in the lifetime of the star. At the same time, the helium core that is left is larger and the white dwarf that finally results is more massive than those obtained from progenitors with the same mass but larger metallicities (Schwarzschild 1958; p. 140). The relationship between the mass of a white dwarf and that of its main sequence progenitor is more controversial because of its complicated dependence on the way in which different algorithms handle convection and breathing pulses and on which mass losses are used. See for instance Hurley et al. (2000) and Salaris et al. (1997).

Therefore, given the uncertainties, it is of paramount importance to find different criteria to constraint the IFMR. In principle there are several possibilities. Directly, using open and globular clusters (Ferrario et al. 2005; Kalirai et al. 2005) or using non–interacting binaries (Catalan et al., this volume). Although these methods allow to keep under control the influence of the metallicity, they suffer on the precision with which the age of the white dwarf, or the companion in the case of the binaries, can be determined. This uncertainty, in turn, translates into a large scatter in the masses of the progenitors, specially in the case of low mass stars. Indirectly, using the luminosity function or the mass distribution. In this contribution we restrict ourselves to discussing the role of the white dwarf luminosity function.

2. The Luminosity Function

The white dwarf luminosity function is defined as the number of white dwarfs per unit of volume and magnitude that have a luminosity L. The influence of the IFMR appears through the age that is assigned to the progenitor weighted by the initial mass function (Isern et al. 1998). This influence is more evident when the luminosity function is constrained to massive white dwarfs. The recent reanalysis by Liebert, Bergeron, & Holberg (2005) of the Palomar–Green Survey

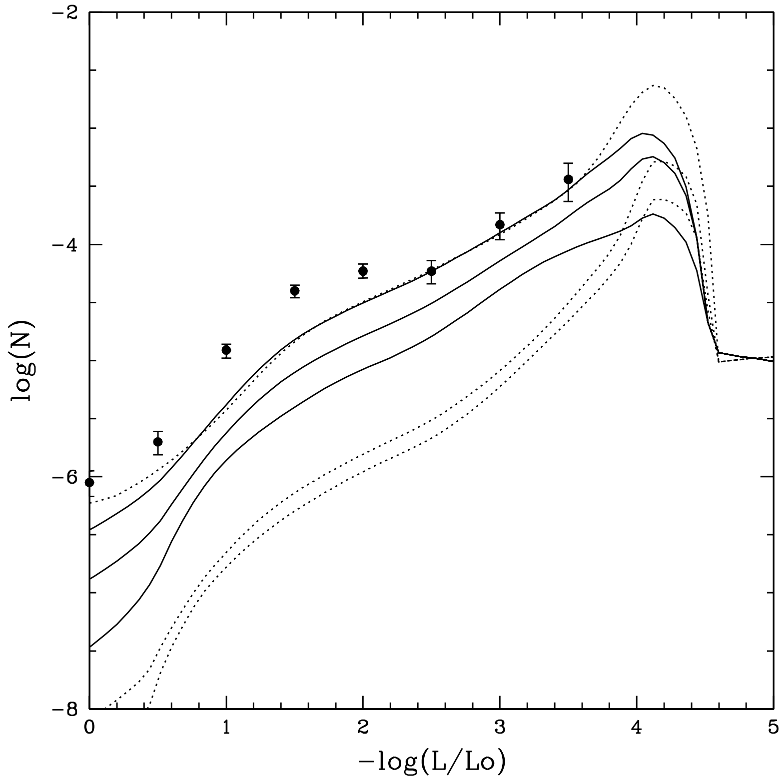

Figure 1. The upper line corresponds to the total luminosity function of white dwarfs assuming an age of the disk of 10.5 Gyr, for a constant star formation rate per unit volume (solid line) and for an exponentially decreasing ($\tau \sim 3$ Gyr) rate (dotted line). Dots correspond to the Palomar–Green survey (Liebert, Bergeron, & Holberg 2005). The figure also displays the luminosity function of white dwarfs with $M \geq 0.6\,M_{\odot}$ (middle line) and $M \geq 0.7\,M_{\odot}$ (bottom line).

provides a sample of white dwarfs with well determined masses that allows for the first time such kind of analysis.

Figure 1 shows the total and the partial luminosity functions obtained assuming an age of the disc of 10.5 Gyr for a constant and for an exponentially decreasing star formation rates for white dwarfs with different masses. The age was obtained from the fitting of the luminosity function constructed with the white dwarfs present in the Third Release of the Sloan Digital Sky Catalog (Harris et al. 2005). It is important to realize here that the bright branch of the total luminosity function is not sensitive to the shape of the star formation rate and that the differences appear near the peak, in the region of dim white dwarfs. On the contrary, the luminosity function of massive white dwarfs directly follows the star formation rate and, consequently it is extremely sensitive to the choice of this function. Figure 2 displays the percentage of white dwarfs that are more massive than 0.6 and $0.7\,M_{\odot}$ for each luminosity bin. The dotted line was obtained assuming a constant star formation rate, solar metallicity and the IFMR of Domínguez et al. (1999) which is very similar to the empirical function proposed by Weidemann (2000). As it can be seen from this figure, the agreement is only good in order of magnitude. If an exponential star formation rate is used, the number of massive white dwarfs is much smaller than observed, the reason is that massive white dwarfs are produced by massive main sequence stars which have a shorter lifetimes while low mass white dwarfs can be produced by the first generation of low mass stars. The situation is worse if an IFMR like that of Wood (1992) that produces fewer massive white dwarfs is used. Therefore, present observations seem to favor IFMRs that produce more massive white dwarfs than those predicted by Weidemann (2000). Since, as already mentioned in the introduction, stars with a lower content in metals produce larger white dwarfs, the inclusion of the influence of the metallicity could alleviate the problem.

3. The Impact of Binary Systems

It is well known that the presence of a close enough companion can strongly modify the evolution of normal stars as a consequence of the exchange of mass among them. This influence is clearly demonstrated by the existence of helium white dwarfs and by the peculiar shape of the mass distribution. The influence of binary systems in the luminosity function can be easily included if the white dwarf birthrate is expressed in terms of binary systems with masses M_1 and M_2 and initial separation A_0 at which are born at a given time and produce one or two white dwarfs after some time. The ingredients necessary to compute such function are — see Isern et al. (1997) for a detailed description and references therein:

- The initial mass function of these binaries was written as $\Phi(M_1)f(q)dM_1dq$ where Φ is the initial mass function for single stars (we have used the IMF of Salpeter) and $f(q) \propto q^\alpha$ with $q = M_2/M_1$ and $\alpha \simeq 1$. This distribution is one of the most critical inputs and its determination is heavily plagued by selection effects. This is due to the fact that this ratio can only be directly determined from double lined spectroscopy, which is strongly biased towards equal luminosities, i.e., equal masses.

- The distribution of separations was taken to be $H(A_0) = R_\odot/5\ln 10A_0$, where the constant comes from normalization within the limits $10 \leq A_0/R_\odot \leq 10^6$.

- The evolutionary models were obtained from the FRANEC model assuming solar metallicities.

- The common envelope evolution was handled with the Iben & Tutukov (1984) prescription

- In the case of merging of two white dwarfs it was assumed that all the mass of the secondary is transferred to the primary (Guerrero et al. 2004).

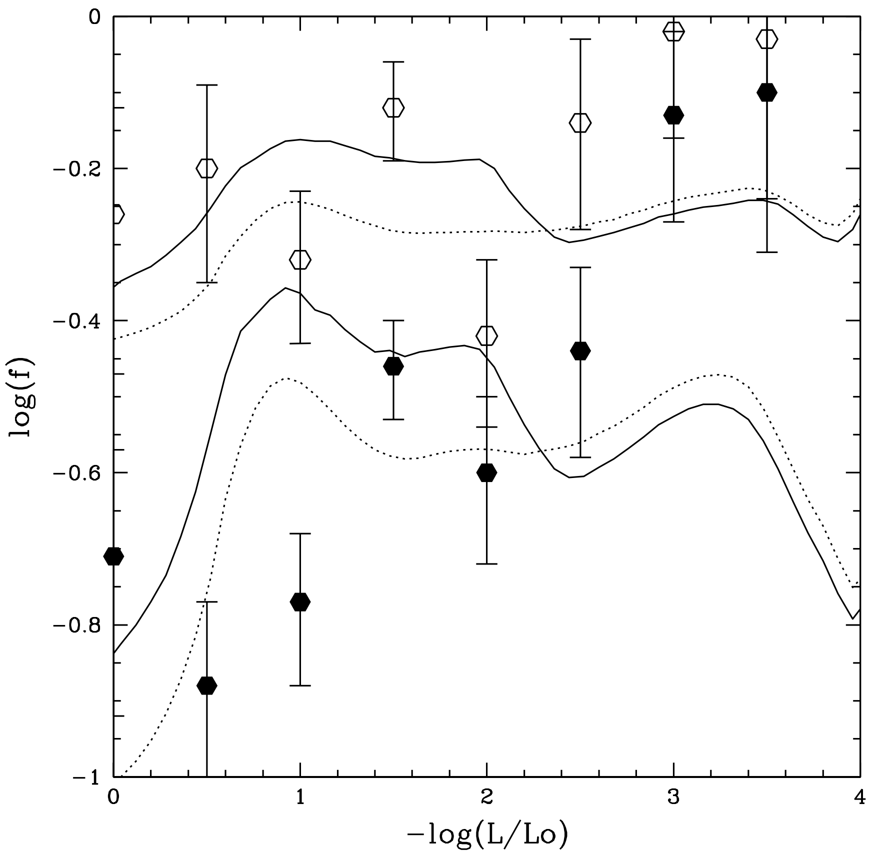

Figure 2. Percentage of white dwarfs with masses larger than $0.6\,M_\odot$ (open circles) and larger than $0.7\,M_\odot$ per unit volume and magnitude interval versus the luminosity. Lines correspond to the theoretical calculations. The upper family of curves represents white dwarfs with masses larger than $0.6\,M_\odot$, and the lower one white dwarfs with masses larger than $0.7\,M_\odot$. The solid lines were computed taking into account the influence of the close binaries.

Figure 2 displays the relative luminosity functions of the white dwarfs with masses larger than 0.6 and $0.7\,M_\odot$ obtained in this way as solid lines. As it can be seen, the agreement is better in the region of bright dwarfs but the detailed shape is still not well reproduced. The failure to reproduce the dim region can be due to the fact that the mass of cold white dwarfs cannot be measured accurately.

4. Conclusions

The accurate determination of the mass of white dwarfs belonging to the Palomar–Green Catalog puts strong constraints on the IFMR. These data suggest that this function has to be more biased towards the formation of massive white dwarfs than the semi–empirical function of Weidemann (2000) does and rules out the analytical expression of Wood (1992). Furthermore, these observations demand a star formation rate per unit volume nearly constant during the life of the galactic disc.

We have also proved that the peculiar evolution of close binary systems has a non negligible influence on the shape of the relative luminosity function opening the possibility of using these function to get insight on the evolution of binaries.

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