Testing the initial-final mass relationship of white dwarfs

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

Abstract

The initial-final mass relationship connects the mass of a white dwarf with the mass of its progenitor in the main-sequence. Although this function is of fundamental importance to several fields in modern astrophysics, it is not well constrained either from the theoretical or the observational points of view. In this contribution we revise the present semi-empirical initial-final mass relationship by re-evaluating the available data. The distribution obtained from grouping all our results presents a considerable dispersion, which is larger than the uncertainties. We have carried out a weighted least-squares linear fit of these data and a careful analysis to give some clues on the dependence of this relationship on metallicity. Finally, we have also performed a test of the initial-final mass relationship by studying its effect on the luminosity function and on the mass distribution of white dwarfs.

1 Introduction

The initial-final mass relationship of white dwarfs is of paramount importance for several aspects of modern astrophysiscs such as the determination of the ages of globular clusters and their distances, the study of the chemical evolution of galaxies, and also to understand the properties of the Galactic population of white dwarfs. However, we still do not have an accurate measurement of this relationship and, consequently, more efforts are needed from both the theoretical and the observational perspectives to improve it.

[1]Institut d'Estudis Espacials de Catalunya, c/ Gran Capità 2–4, 08034 Barcelona, Spain
e-mail: catalan@ieec.uab.es
[2]Institut de Ciències de l'Espai, CSIC, Facultat de Ciències, UAB, 08193 Bellaterra, Spain
[3]Departament de Física Aplicada, Escola Politècnica Superior de Castelldefels, Universitat Politècnica de Catalunya, Avda. del Canal Olímpic s/n, 08860 Castelldefels, Spain

The first attempt to empirically map this relationship was carried out by [14], who provided also a recent revision ([15]). Although many improvements have been achieved in these 30 years, the dependence of this function on different parameters is still not clear (e.g. metallicity, magnetic field, angular momentum). On the other hand, numerous works have dealt with the calculation of a theoretical initial-final mass relationship, see [4, 12], but the differences in their evolutionary codes, such as the treatment of convection, the value of the assumed critical mass or the mass loss prescriptions used lead to very different results.

From an observational perspective, most efforts up to now have focused on the observation of white dwarfs in open clusters, since this allows to infer the total age and the original metallicity of white dwarfs belonging to the cluster ([16, 8]). Open clusters have made possible the derivation of a semi-empirical initial-final mass relationship using more than 50 white dwarfs, although only covering the initial mass range between 2.5 and 7.0 $M_{\odot}$ because stellar clusters are relatively young and, hence, the white dwarf progenitors in these clusters are generally massive. Nevertheless, the recent study of [9] (based in old open clusters) and [1] (based in common proper motion pairs) have extended this mass range to smaller masses.

2 Direct test

2.1 Data used for the analysis

We have carried out a re-analysis of the available data currently used to define the semi-empirical initial-final mass relationship, which is mainly based on white dwarfs in open clusters. We have used the white dwarf atmospheric parameters ($T_{\rm eff}$ and $\log g$) derived by other authors, as well as the ages and metallicities of the clusters reported in the literature (see [2]). To obtain the final and initial masses we followed the procedure described in [1]. This procedure consists in deriving the final mass ($M_{\rm f}$) and the cooling time of each white dwarf from the atmospheric parameters and the cooling sequences of [13]. These cooling tracks consider a carbon-oxygen (CO) core white dwarf (with a larger abundance of O at the centre of the core) with a H thick envelope ontop of a He buffer, $q({\rm H}) = M_{\rm H}/M = 10^{-4}$ and $q({\rm He}) = M_{\rm He}/M = 10^{-2}$. Since we know the total ages of these white dwarfs (from the age of the cluster) we derived the main-sequence lifetimes of the progenitors, and from these, their initial masses using the stellar tracks of [4]. In the case of the common proper motion pairs, the procedure that we followed to derive the final and initial masses of the white dwarfs is explained in detail in [1].

In Fig. 1 we present the final masses versus the initial masses obtained for white dwarfs in common proper motion pairs and open clusters. The observational data that can be used to define the semi-empirical initial-final mass relationship contains now 62 white dwarfs. It is important to emphasize that all the values below 2.5 $M_{\odot}$ correspond to our data obtained from common proper motion pairs and the

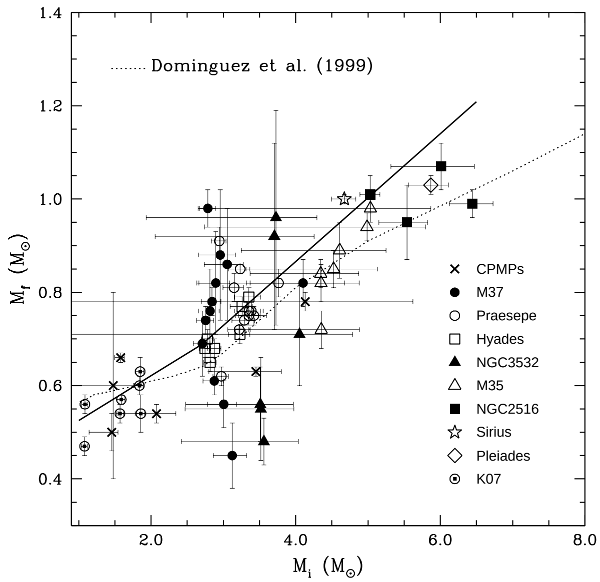

Fig. 1 Final masses versus initial masses of the available data.

recent data obtained by [9]. Before these studies no data for these small masses were available, since white dwarfs in stellar clusters are usually more massive, especially if the clusters are young. The coverage of the low-mass end of the initial-final mass relationship is specially important since it guarantees, according to the theory of stellar evolution, the study of white dwarfs with masses near the typical values, $M \sim 0.57 M_{\odot}$, which represent about 90 per cent of the white dwarf population ([10]). Thus, these new data increase the statistical significance of the semi-empirical initial-final mass relationship.

A first inspection of Fig. 1 reveals that there is a clear dependence of the white dwarf masses on the masses of their progenitors. In Fig. 1, we have also plotted the theoretical initial-final mass relationship of [4] for solar composition to be consistent with the stellar tracks used to derive the initial masses. Although the distribution presents a large dispersion, a comparison of the observational data with these theoretical relationships shows that they share the same trend. However, it should be noted that for each cluster the data presents an intrinsic spread in mass. The dispersion varies from cluster to cluster, but it is particularly noticeable for the case of M37. Nevertheless, it should be taken into account as well that the observations of M37 were of poorer quality than the rest of the data ([5]).

2.2 The semi-empirical relationship

Following closely recent works on this subject by [5, 17, 9], we assume that the initial-final mass relationship can be described as a linear function. As can be seen in Fig. 1 the theoretical initial-final mass relationship (dotted line) can be divided in two different linear functions, each one above and below 2.7 $M_\odot$, with a shallower slope for small masses probably due to the smaller efficiency of mass loss. Taking this into account we have performed a weighted least-squares linear fit for each region, obtaining

$$M_{\rm f} = (0.096 \pm 0.005) M_{\rm i} + (0.429 \pm 0.015) \quad (1)$$

for $M_{\rm i} < 2.7\ M_\odot$, whereas for $M_{\rm i} > 2.7\ M_\odot$ we obtain:

$$M_{\rm f} = (0.137 \pm 0.007) M_{\rm i} + (0.318 \pm 0.018) \quad (2)$$

where the errors are the standard deviation of the coefficients.

These expressions have been overplotted in Fig. 1 as two solid lines. Taking into account the scatter of the data and the values of the reduced χ^2 of these fits (7.1 and 4.4, respectively) we consider that the errors associated to the coefficients are underestimated. A more realistic error can be obtained computing the dispersion of the derived final masses, which is of 0.05 $M_\odot$ and 0.12 $M_\odot$ respectively. These are the errors that should be associated to the final mass when using the expressions derived here — Eqs. (1) and (2), respectively. In past works, since there was not available data in the region of low-mass white dwarfs, a least-squares linear fit led to an unconstrained result, see [5]. For this reason, a ficticious anchor point at low masses was used to represent the typical white dwarf mass, $M_{\rm f} \sim 0.57\ M_\odot$ according to [10]. In our case, this is not necessary since we are now reproducing this well-established peak of the field white dwarf mass distribution thanks to the new data in the low-mass region ([9, 1]).

The sample of white dwarfs studied here covers a range of metallicities from $Z = 0.006$ to 0.040. From a theoretical point of view it is well established that progenitors with large metallicity produce less massive white dwarfs — see [4]. Thus, one should expect to see a dependence of the semi-empirical data on metallicity. We have performed a quantitative study of the correlation between the final masses and metallicity. We have computed the differences between the observed final masses and the final masses obtained using Eqs. (1) and (2). In order to quantify this correlation we have calculated the Spearman rank correlation coefficient obtaining -0.002 ± 0.128. The error has been derived from a bootstrapping. Thus, we can conclude that the final masses and metallicities of this sample are not correlated, and that the scatter in the distribution in Fig. 1 is not due to the effect of metallicity.

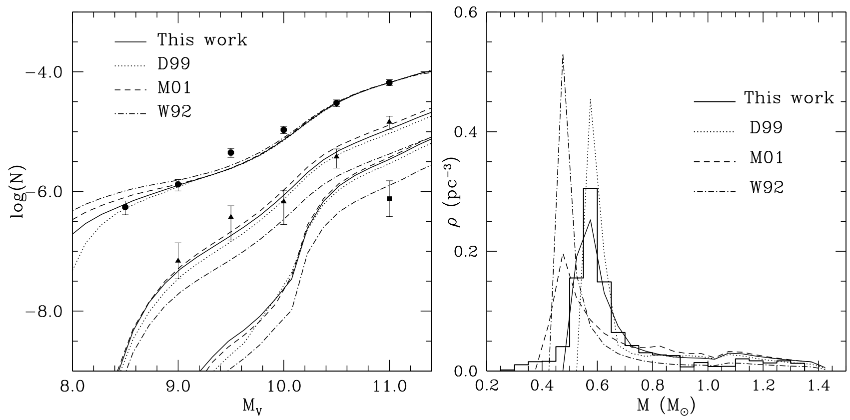

Fig. 2 Left: White dwarf luminosity functions versus visual magnitude using different initial-final mass relationships. Right: Mass distributions for WDs with $T_{\rm eff} \geq 12\,000$ K considering different evolutive stellar models and initial-final mass relationships.

3 Indirect test

We have computed a set of white dwarf luminosity functions considering an age of 11 Gyr for the Galactic disc and using bins of visual magnitude. In Fig. 2 (left) we show from top to bottom the total luminosity function and the luminosity functions of white dwarfs with masses larger than 0.7 $M_{\odot}$ and 1.0 $M_{\odot}$, respectively. The total luminosity function (that is, considering the whole range of masses) was normalized to the bin corresponding to $M_{\rm V} = 11$, and then, this normalization factor was used for the luminosity functions of white dwarfs more massive than 0.7 $M_{\odot}$ and 1.0 $M_{\odot}$. In this case, we have used the stellar evolutionary inputs of [4] (D99), [12] (M01), [18] (W92) and the semi-empirical initial-final mass relationship that we have derived in the previous section. Circles, triangles and squares correspond to the observational data of [11]. Comparing the different theoretical luminosity functions, it can be noted that the predicted number of massive white dwarfs is larger when using the inputs of [4], [12] and our semi-empirical initial-final mass relationship in comparison with the results obtained when considering the expressions of [18]. This is due to the fact that the latter favors the production of low-mass white dwarfs. Without considering the results obtained when the expressions of [18] are used, it can be noted that it is not possible to evaluate which initial-final mass relationship produces a theoretical luminosity function that better fits the observational data, since the error bars of the observational data are larger than the differences between the theoretical results. In any case, what it can be clearly seen is that all the theoretical relations predict more massive white dwarfs than the observations when a mass cut of 1.0 $M_{\odot}$ is adopted, except in the case of [18].

Following a similar procedure we have computed theoretical white dwarf mass distributions and compared our results with the recent data obtained by [3] from the SDSS — right panel of Fig. 2. Since the accuracy on the mass determinations decreases considerable when white dwarfs are cooler than 12 000 K, both the theoretical and the observational mass distributions only consider white dwarfs with $T_{\rm eff} \geq 12\,000$ K. We have considered the initial-final mass relationships of [4], [6], [18], our semi-empirical relationship and the one derived by [9]. All the white dwarf distributions have been normalized to the total density obtained in each case. As it can be noted, there is a well defined peak in all the mass distributions, the location of which is defined mainly by the initial-final mass relationship considered. On the contrary, the height of the peak depends also on the lifetime of the progenitors. The central peak is shifted to larger masses when the initial-final mass relationship considered favors the production of more massive white dwarfs for the low mass progenitors. This is the case of the semi-empirical initial-final mass relationship of [9], our relationship or the theoretical relation of [4]. If we compare the theoretical mass functions with the observational data obtained by [3] from the SDSS it can be noted how the location and height of the central peak is best fitted by the predictions corresponding to our semi-empirical relationship.

Acknowledgements This research was supported by MEC grants AYA05–08013–C03–01 and 02, by the European Union FEDER funds and by the AGAUR.

References

1. Catalán, S., Isern, J., García–Berro, E., et al., *A&A*, **4**77, 213 (2008)
2. Catalán, S., Isern, J., García–Berro, E., Ribas, I., *MNRAS*, **3**87, 1693 (2008)
3. DeGennaro, S., von Hippel, T., Winget, D. E., et al., *AJ*, **1**35, 1 (2008)
4. Domínguez, I., Chieffi, A., Limongi, M., Straniero, O., *ApJ*, **5**24, 226 (1999)
5. Ferrario, L., Wickramasinghe, D. T., Liebert, J., Williams, K. A., *MNRAS*, **3**61, 1131 (2005)
6. Girardi, L., Bertelli, G., Bressan, A., et al., *A&A*, **3**91, 195 (2002)
7. Hurley, J. R., Pols, O. R., Tout, C. A., *MNRAS*, **3**15, 543 (2000)
8. Kalirai, J. S., Richer, H. B., Reitzel, D., et al., *ApJ*, **6**18, 123 (2005)
9. Kalirai, J. S., Hansen, M. S. B., Kelson, D. D., et al., *ApJ*, **6**76, 594 (2008)
10. Kepler, S. O., Kleinman, S. J., Nitta, A., et al., *MNRAS*, **3**75, 1315 (2007)
11. Liebert, J., Bergeron, P., Holberg, J. B., *ApJS*, **1**56, 47 (2005)
12. Marigo, P., *A&A*, **3**70, 194 (2001)
13. Salaris, M., García–Berro, E., Hernanz, M., Isern, J., Saumon, D., *ApJ*, **5**44, 1036 (2000)
14. Weidemann, V., *A&A*, **5**9, 418 (1977)
15. Weidemann, V., *A&A*, **3**63, 647 (2000)
16. Williams, K. A., Bolte, M., Koester, D., *ApJ*, **6**15, 49 (2004)
17. Williams, K. A., in Napiwotzki R. and Burleigh M., eds, ASP Conf. Ser. Vol. **3**72, 15th European Workshop on White Dwarfs. Astron. Soc. Pac., San Francisco, p. 85 (2007)
18. Wood, M. A., *ApJ*, **3**86, 539 (1992)