Mem. S.A.It. Vol. 88, 364

Memorie della

Progeny of super-AGB stars in the era of *Gaia*

R. Raddi

Department of Physics, University of Warwick, Gibbet Hill Road, Coventry CV4 7AL
e-mail: r.raddi@warwick.ac.uk

Abstract. The ESA *Gaia* mission will measure parallaxes for one billion stars, including about 200,000 white dwarfs. For the first time, a statistically significant volume-complete sample of about 2000 white dwarfs within 50 pc from the Sun will be within reach. By complementing parallaxes with ground-based photometric and spectroscopic observations, it will be possible to constrain the evolution of single and binary stars in the Solar neighbourhood and in open clusters at an unprecedented level of detail, shedding new light on the fate of the rarest super-AGB stars.

1. Introduction

White dwarfs are the remaining vestiges of low- to intermediate-mass stars (Iben 1991), which have shed into the interstellar medium most of their initial mass during and at the end of the giant branches (Herwig 2005).

The white dwarf mass distribution is found to peak at $0.62 \pm 0.11\,M_{\odot}$ (e.g. Tremblay et al. 2016), corresponding to the progeny of G- to A-type main sequence stars that develop C/O cores. A low-mass peak and a high mass tail are also observed. The first, found at $\approx 0.45\,M_{\odot}$, is caused by close-binary evolution (Marsh et al. 1995), producing He-core degenerates that could not otherwise form within the Galaxy lifetime. The high-mass tail ($M_{\rm WD} \gtrsim 1\,M_{\odot}$), instead, has been argued to be populated by both massive white dwarfs originating from higher-mass progenitors and the products of lower-mass white dwarf mergers.

Massive white dwarfs that evolved from single stars are thought to possess an O/Ne/Mg core, which is expected to form after off-centre carbon ignition takes place in super-AGB stars (Ritossa et al. 1996; García-Berro et al. 1997; Siess 2010) over a relatively small mass range (7–$11\,M_{\odot}$) that is also contended by neutron star progenitors (Nomoto 1984).

Despite the different core compositions, most white dwarfs possess very simple atmospheres (80% of the white dwarfs have H-dominated atmospheres, while 20% of them have He-dominated atmospheres) that make them spectroscopically undistinguishable one from another. This poses some uncertainty on the estimates of their cooling ages, which are directly linked to the age of the Galaxy via the luminosity function (García-Berro & Oswalt 2016). Thus, constraining the separation between white dwarf and neutron star progenitors as well as the birth-rates of both stellar remnants are crucial astrophysical problems that need detailed agreement between observations and theory (Doherty et al. 2017).

So far, direct spectroscopic evidence of super-AGB origin has been found for just a handful of white dwarfs among the $\approx 40,000$ known. Gänsicke et al. (2010) identified two white dwarfs exposing dredged-up, oxygen-rich core material ($O/C > 1$) that could have only been produced in the interiors of a super-

AGB star. More recently, Kepler et al. (2016) have spectroscopically confirmed the bare core of a super-AGB star, i.e. a white dwarf having an O-dominated atmosphere with traces of nuclearly processed elements (Ne and Mg above all). Larger white dwarf samples are necessary to build improved statistics of these rare stellar remnants.

A traditional way of assessing the properties of white dwarf progenitors is by studying those found in coeval populations, e.g. open clusters, globular clusters, and wide binaries that are assumed to have evolved as single stars. Especially open clusters have led to a semi-empirical characterisation of the initial-to-final mass relation that enables a crude estimate of the total mass-loss experienced by white dwarf progenitors with $M_{\rm MS} \lesssim 6.5\,{\rm M}_\odot$ (Williams et al. 2009). Although open clusters are ideal sites for identifying the burnt-out cores of super-AGB stars, very few of them are known and the initial-to-final mass relation remans less constrained in the upper-mass regime. Wide area, deep multi-band photometric surveys have begun to increase the sample of massive white dwarfs in open-clusters (Raddi et al. 2016; Cummings et al. 2016a), although the initial-to-final mass relation is still scarcely populated for $M_{\rm MS} > 6.5\,{\rm M}_\odot$ with just four stars. Improved results have also been achieved via the uniform re-analysis of existing cluster data, especially towards the high-mass end (Cummings et al. 2016b, see also J. Cumming's proceeding in this volume).

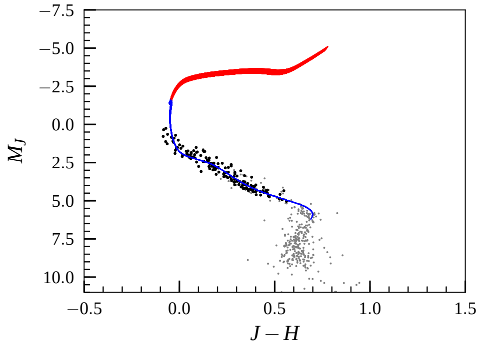

Fig. 1. Main sequence fit of 2MASS photometry for the Pleiades (black dots), which we have brought onto an absolute magnitude scale by adopting to their individual *Tycho-Gaia* parallaxes. We also plot stars that do not have parallax measurements (grey dots), but are found within the cluster area; we placed them on the same scale as the Pleiades, by adopting the average distance modulus of the cluster. The best-fitting main sequence (blue) is interpolated from the grid of MESA models by Choi et al. (2016). We also display the post-main sequence isochrones in red. The thickness of the isochrones correspond to an age uncertainty of 5 %.

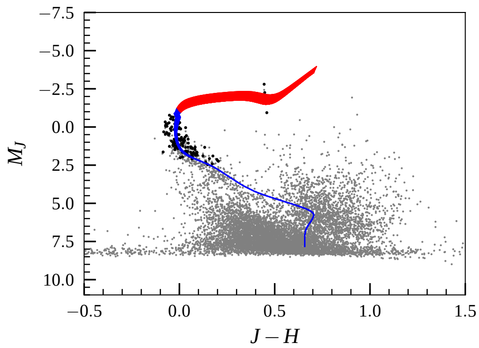

Fig. 2. Main sequence fit of 2MASS photometry for NGC 3532. For a description of the plot, please refer to Fig. 1. Here, the thickness of the isochrones correspond to an age uncertainty of 10 %.

2. Gaia and the white dwarfs

The characterisation of AGB and super-AGB stars via the study of their white dwarf progeny will greatly benefit from the astrometric mission *Gaia* that, next year, will deliver positions, proper motions, and parallaxes for about 1.2 billion stars in our Galaxy (Gaia Collaboration et al. 2016).

Gaia is expected to expand the number of known white dwarfs by an order of magnitude, identifying about 200,000 white dwarfs down to 20 mag (Carrasco et al. 2014). A comprehensive spectroscopic follow-up of the entire sample is planned from both hemispheres in the next 5–10 years through the new generation of multi-fibre facilities (e.g. WEAVE, 4MOST, and DESI; Gänsicke et al. 2016), which will lead to an unprecedented characterisation of these stellar remnants. *Gaia* will also push the boundaries of the current volume-complete sample from 13 pc to 50 pc, jumping from 45 white dwarfs to about 2,000 of them. From the study of the local white dwarfs and other stars, it will be possible to obtain an improved assessment of crucial properties of the Milky Way like the stellar mass density, star formation history, the age of the Galactic components (especially the disc).

Using the high parallax accuracy of *Gaia*, it will also be possible to bring down by a large factor the uncertainties plaguing the observational initial-to-final mass relation. In first place, *Gaia* parallaxes will better define the location of open clusters improving the assessment of cluster membership for white dwarfs. Second, the age estimates of open clusters will benefit from the unambiguous identification of the cluster main sequence. As an example, we have estimated the ages of the Pleiades (Fig. 1) and NGC 3532 (Fig. 2) with an accuracy of 5 and 10 %, respectively, just using 2MASS photometry and the *Tycho*-*Gaia* parallaxes.

Reducing the errors on cluster ages has a positive impact on the estimate of white dwarf progenitor ages, and thus masses. In fact, progenitor lifetimes are inferred by subtracting the white dwarf cooling age from the total age of the cluster. White dwarf cooling ages have typically small uncertainties, which mostly depend on the quality of the observed data (e.g. temperature and surface gravity that are derived via spectral analysis). Progenitor masses are then interpolated from evolutionary tracks. The example in Fig. 3 shows the improved estimate for the likely O/Ne/Mg core white dwarf (1.13 $M_\odot$) VPHAS J1103−5837 in NGC 3532 (Raddi et al. 2016), which is now in better agreement with a super-AGB progenitor of $8 \pm 2\,M_\odot$.

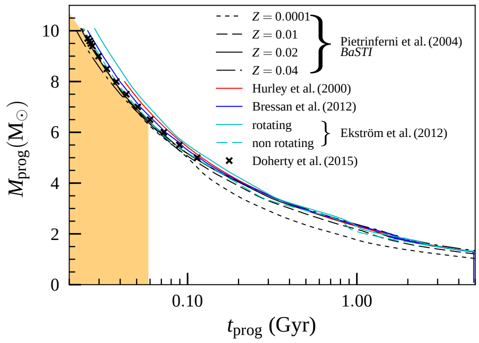

Fig. 3. Progenitor mass estimate for VPHAS J1103−5837 via interpolation with stellar evolutionary tracks. For more details, please refer to Raddi et al. (2016).

3. Summary

White dwarfs are essential astrophysical tools to study the evolution of low- to intermediate-mass stars. The astrometric mission *Gaia* will expand the present volume-complete and magnitude-limited samples with at least an order of magnitude more stars. Thus, in the era of *Gaia*, we will benefit from a reinforced role of these stellar remnant in shaping our understanding of the Milky Way.

The white dwarf mass distribution and luminosity function will be characterised at an unprecedented level, leading to a more accurate estimate of the age of the Galactic components. The ages of stellar populations in open clusters will also be constrained with higher precision, thus enabling a more robust assessment of the initial-to-final mass relation. Deep photometric surveys and multi-fibre spectroscopic facilities will deliver larger numbers and improved characterisation of the most massive white dwarfs both in the Galactic field and in open clusters, which in turn will help to discriminate between evolutionary models for super-AGB stars.

Acknowledgements. The research leading to these results has received funding from the European Research Council under the European Unions Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 320964 (WDTracer).

References

Carrasco, J. M., Catalán, S., Jordi, C., et al. 2014, A&A, 565, A11
Choi, J., Dotter, A., Conroy, C., et al. 2016, ApJ 823, 102
Cummings, J. D., et al. 2016, ApJ, 818, 84
Cummings, J. D., et al. 2016, ApJ, 820, L18

Dalton, G., Trager, S., Abrams, D. C., et al. 2014, Proc. SPIE, 9147, 91470L
Doherty, C. L., et al. 2017, arXiv:1703.06895
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016, A&A, 595, A2
Gänsicke, B. T., et al. 2010, Science, 327, 188
Gänsicke, B., Tremblay, P., Barstow, M., et al. 2016, in Multi-Object Spectroscopy in the Next Decade: Big Questions, Large Surveys, and Wide Fields, ed. I. Skillen, M. Barcells, S. Trager (ASP, San Francisco), ASP Conf. Ser., 507, 159
García-Berro, E., Ritossa, C., & Iben, I., Jr. 1997, ApJ, 485, 765
García-Berro, E., & Oswalt, T. D. 2016, New Astron. Rev., 72, 1
Herwig, F. 2005, ARA&A, 43, 435
Kepler, S. O., Koester, D., & Ourique, G. 2016, Science, 352, 67
Iben, I., Jr. 1991, ApJS, 76, 55
Marsh, T. R., Dhillon, V. S., & Duck, S. R. 1995, MNRAS, 275, 828
Tremblay, P.-E., Cummings, J., Kalirai, J. S., et al. 2016, MNRAS, 461, 2100
Nomoto, K. 1984, ApJ, 277, 791
Raddi, R., Catalán, S., Gänsicke, B. T., et al. 2016, MNRAS, 457, 1988
Ritossa, C., Garcia-Berro, E., & Iben, I., Jr. 1996, ApJ, 460, 489
Siess, L. 2010, A&A, 512, A10
Williams, K. A., Bolte, M., & Koester, D. 2009, ApJ, 693, 355