White dwarfs as physics laboratories: the case of axions

J. Isern[1,2], L. Althaus[3,4], S. Catalán[5], A. Córsico[3,4], E. García–Berro[6,2], M. Salaris[7], S. Torres[7,2]

[1]Institut de Ciències de l'Espai ICE(CSIC/IEEC), Campus UAB, 08193 Bellaterra, Spain
[2]Institut d'Estudis Espacials de Catalunya (IEEC), Ed. Nexus, c/Gran Capità, 08034 Barcelona, Spain
[3]Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Argentina
[4]CONICET, Argentina
[5]Center for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK
[6]Departament de Física Aplicada, Universitat Politècnica de Catalunya, c/Esteve Terrades 5, 08860 Castelldefels, Spain
[7]Astrophysics Research Institute, Liverpool John Moores University, 12 Quays House, Birkenhead, CH41 1LD, UK

DOI: http://dx.doi.org/10.3204/DESY-PROC-2011-04/isern_jordi

White dwarfs are almost completely degenerate objects that cannot obtain energy from thermonuclear sources, so their evolution is just a gravothermal cooling process. Recent improvements in the accuracy and precision of the luminosity function and in pulsational data of variable white dwarfs suggest that they are cooling faster than expected from conventional theory. In this contribution we show that the inclusion of an additional cooling term due to axions able to interact with electrons with a coupling constant $g_{\rm ae} \sim (2-7) \times 10^{-13}$ allows to fit better the observations.

1 Introduction

During the cooling process, white dwarfs experience some phases of pulsational instability powered by the κ- and the convective-driven mechanisms [1]. Depending on the composition of the atmosphere, variable white dwarfs are known as DAV (atmospheres dominated by H) and DOV, DBV (atmospheres non dominated by H). These objects are experiencing g-mode non-radial pulsations, where the main restoring force is gravity. An important characteristic of these pulsations is that their period experiences a secular drift caused by the evolution of their temperature and radius. For a semi-qualitative purpose this drift can be well approximated by [2]: $d \ln \Pi/dt \simeq -a\, d \ln T/dt + b\, d \ln R/dt$, where a and b are constants of the order of unity that depend on the details of the model, and R and T are the stellar radius and the temperature at the region of period formation, respectively. This equation reflects the fact that, as the star cools down, the degeneracy of electrons increases, the buoyancy decreases and, as a consequence, the spectrum of pulsations gradually shifts to lower frequencies. At the same time, since the star contracts, the radius decreases and the frequency tends to increase. In general, DAV and DBV stars are already so cool (and degenerate) that the radial term is negligible and the change of the period of pulsation can be directly related to the change in the core temperature of the star. Therefore, the measurement of such drifts provides an effective method to test the theory of white dwarf cooling. This, in turn, allows to obtain a simple relationship [3, 4] to estimate the influence of an additional sink of energy, axions for instance, on the period drift of variable white dwarfs:

$$(L_{\rm X}/L_{\rm model}) \approx (\dot{\Pi}_{\rm obs}/\dot{\Pi}_{\rm model}) - 1 \tag{1}$$

where the suffix "model" refers to those models built using standard physics and $L_{\rm X}$ is the extra luminosity.

Another way to test the theory of white dwarf cooling is based on their luminosity function. This function is defined as the number density of white dwarfs of a given luminosity per unit magnitude interval:

$$n(l) = \int_{M_{\rm l}}^{M_{\rm u}} \Phi(M)\,\Psi(t)\tau_{\rm cool}(l,M)\,dM \tag{2}$$

where t satisfies the condition $t = T - t_{\rm cool}(l,M) - t_{\rm PS}(M)$ and $l = -\log(L/L_\odot)$, M is the mass of the parent star (for convenience all white dwarfs are labeled with the mass of the main sequence progenitor), $t_{\rm cool}$ is the cooling time down to luminosity l, $\tau_{\rm cool} = dt/dM_{\rm bol}$ is the characteristic cooling time, $M_{\rm s}$ and $M_{\rm i}$ are the maximum and the minimum masses of the main sequence stars able to produce a white dwarf of luminosity l, $t_{\rm PS}$ is the lifetime of the progenitor of the white dwarf, and T is the age of the population under study. The remaining quantities, the initial mass function, $\Phi(M)$, and the star formation rate, $\Psi(t)$, are not known a priori and depend on the properties of the stellar population under study. In order to compare theory with observations and since the total density of white dwarfs is not well known yet, the computed luminosity function is usually normalized to the bin with the smallest error bar, traditionally the one with $l = 3$. An important property of Eq. (2) is that the bright branch of the luminosity function is only sensitive to the average characteristic cooling time of white dwarfs at the corresponding luminosity when this function is normalized.

$$n = \langle\tau_{\rm cool}\rangle \int_{M_{\rm l}}^{M_{\rm u}} \phi(M)\psi(T - t_{\rm cool} - t_{\rm ps})\,dM. \tag{3}$$

The reason [4, 5] is that the stellar population is dominated by low-mass stars and, since the lifetime of stars increases very sharply when the mass decreases, the lower limit of the integral in Eq. (3) is almost independent of the luminosity, so the value of the integral is absorbed by the normalization constant.

2 The case of G117–B15A and the luminosity function

The measurement of the secular drift of the period of pulsation has been performed in the case of G117–B15A [6], a member of the ZZ Ceti (DAV) stars. The most recent value obtained so far is [7]:

$$(d\Pi/dt)_{\rm obs} = (4.89 \pm 0.53 \pm 1.56) \times 10^{-15}\ {\rm s/s} \tag{4}$$

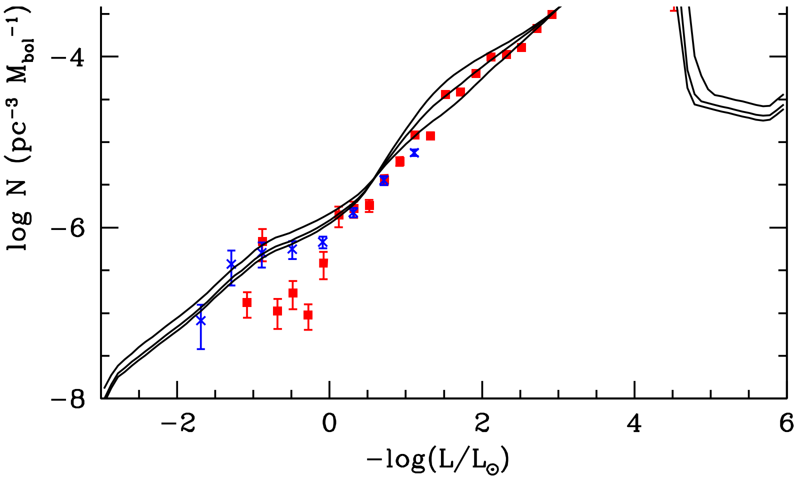

Figure 1: White dwarf luminosity function. The solid lines represent the models obtained with (up to down) $g_{\rm aee}/10^{-13} = 0, 2.2, 4.5$ respectively.

with an estimated proper motion correction $\dot{\Pi} = -(7.0 \pm 0.2) \times 10^{-16}$ s/s. Theoretical predictions [8] indicate that this star should experience a secular drift of only $\dot{\Pi} = 1.2 \times 10^{-15}$ s/s. Similar values ($\dot{\Pi} = 1.92 \times 10^{-15}$ s/s or $\dot{\Pi} = 2.98 \times 10^{-15}$ s/s depending on the adopted mass of the envelope) have been independently obtained [9]. These results suggest that white dwarfs are cooling faster than expected (it important to confirm this statement by measuring this drift in other stars). There are three possible reasons for this. i) An observational error. This measurement is difficult and it has been obtained by only one team on just one star. Although the measurement tends to stabilize, it suffered strong fluctuations in the past [10]. ii) A modelling error. Models have been noticebly improved during the last ten years and the two independent models computed up to now [8, 9] are in a qualitative agreement. iii) An additional sink of energy is responsible of the accelerated cooling rate [3].

Under the conditions of temperature and density in the interior of G117-B15A, the axion emission rate is dominated by electron bremsstrahlung (only the DFSZ axion model) that behaves as $\dot{\epsilon}_{\rm ax} \propto g^2_{\rm aee} T_7^4$ erg/g/s, where T_7 is the temperature in units of 10^7 K and $g_{\rm aee}$ is the strength of the axion–electron Yukawa coupling [11]. Thus it is possible to include the axion emissivity in Eq. (1) and adjust $g_{\rm aee}$ to fit the observed values. The value that best fits the observations is in the range of $g_{\rm aee} \sim (3-7) \times 10^{-13}$.

Figure 1 displays the white dwarf luminosity function, DA and non–DAs [12]. The values from the DR4 of the SDSS [13] (squares) were complemented at high luminosities with those obtained using the more recent DR7 [14] (crosses). It is important to notice that models without axions [15] predict an excess of white dwarfs in the region $\log(L/L_\odot) \sim -2$ as in the case of the pure-DA sample [4]. If axions are included, the best fit is obtained for $g_{\rm aee} \sim (2-3) \times 10^{-13}$. The luminosity function at high luminosities is still poorly known from both the theoretical and observational point of views, but it is clear that will provide strong constrains.

3 Conclusions

There are two independent pieces of evidence, the luminosity function and the secular drift of DAV white dwarfs, that white dwarfs are cooling down more rapidly than expected. The introduction of an additional sink of energy linked to the interaction of electrons with a light boson (axion, ALP,. . .) with an strength $g_{\rm aee} \sim (2-7)\times10^{-13}$ solves the problem satisfactorily. Naturally, the uncertainties that still remain, both observational and theoretical, still prevent to claim the existence of such interaction. A systematic analysis aimed to discard any possible conventional solution is under way.

Acknowledgments

This work has been supported by the MICINN grants AYA08-1839/ESP and AYA2008-04211-C02-01, by the ESF EUROCORES Program EuroGENESIS (MICINN grant EUI2009-04170), by SGR grants of the Generalitat de Catalunya and by the EU-FEDER funds.

References

[1] L.G. Althaus, A.H. Córsico, J. Isern, & E. García-Berro, "Evolutionary and pulsational properties of white dwarfs", Astron. & Astrophys. Rev., **18**, 47 (2010)

[2] D.E. Winget, C. J. Hansen, & H. M. Van Horn, "Do pulsating PG1159-035 stars put constraints on stellar evolution?", Nature, **303**, 781 (1983)

[3] J. Isern, M. Hernanz, & E. García-Berro, "Axion cooling of white dwarfs", Astrophys. J., **392**, L23 (1992)

[4] J. Isern, & E. García-Berro, "White dwarfs as physics laboratories: the axion case", Mem. Soc. Astr. It., **79**, 545 (2008)

[5] J. Isern, S. Catalán, E. García-Berro, & S. Torres, "Axions and the white dwarf luminosity function", J. Phys.: Conf. Ser., **172**, 012005 (2009)

[6] S.O. Kepler *et al.*, "Measuring the evolution of the most stable optical clock G117-B15A", Astrophys. J., **634**, 1311 (2005)

[7] S.O. Kepler, "White dwarf stars: Pulsations and Magnetism", Proc. of "The 61st Fujuhara Seminar: Progress in solar/stellar physics with helio and asteroseismology", in press (2011)

[8] A. H. Córsico, L.G. Althaus, A.D. Romero, M.H. Miller Bertolami, E. García–Berro, & J. Isern, "Constraining the axion mass through the asteroseismology of the ZZ Ceti star G117–B15A", Proc. of "The 61st Fujuhara Seminar: Progress in solar/stellar physics with helio and asteroseismology", in press (2011)

[9] A. Bischoff–Kim, M.H. Montgomery, & D.E. Winget, "Strong limits on the DFSZ axion mass with G117-B15A", Astrophys. J., **675**, 1512 (2008)

[10] J. Isern, E. García-Berro, L.G. Althaus, & A.H. Córsico, "Axions and the pulsation periods of variable white dwarfs revisited", Astron. & Astrophys., **512**, A86 (2010)

[11] M. Nakagawa, Y. Kohyama, & N. Itoh, "Axion bremsstrahlung in dense stars", Astrophys. J., **322**, 291 (1987)

[12] J. Isern, E. García-Berro, M. Hernanz, & R. Mochkovitch, "The physics of white dwarfs", J. Phys. Cond. Matter, **10**, 11263 (1998)

[13] H.C. Harris *et al.*, "The white dwarf luminosity function from Sloan Digital Sky Survey Imaging data", Astron. J., **131**, 571 (2006)

[14] J. Krzesinski, *et al.*, "A hot white dwarf luminosity function from the Sloan Digital Sky Survey", Astron. Astrophys, **508**, 339 (2009)

[15] M. Salaris *et al.*, "A large stellar evolution database for population synthesis studies. VI. White dwarf cooling sequences", Astrophys. J., **716**, 1241 (2010)

[16] J. Isern, E. García-Berro, S. Torres, & S. Catalán, "Axions and the cooling of white dwarf stars", Astrophys. J., **682**, L109 (2008)