Axions and White Dwarfs

J. Isern[1,2], S. Catalán[3], E. García–Berro[4,2], M. Salaris[5], S. Torres[4,2]

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

DOI: http://dx.doi.org/10.3204/DESY-PROC-2010-03/isern_jordi

White dwarfs are almost completely degenerate objects that cannot obtain energy from the thermonuclear sources and their evolution is just a gravothermal process of cooling. The simplicity of these objects, the fact that the physical inputs necessary to understand them are well identified, although not always well understood, and the impressive observational background about white dwarfs make them the most well studied Galactic population. These characteristics allow to use them as laboratories to test new ideas of physics. In this contribution we discuss the robustness of the method and its application to the axion case.

1 Introduction

White dwarfs are almost completely degenerate objects that cannot obtain energy from the thermonuclear sources and their evolution is just a gravothermal process of cooling. Globally, the evolution of the luminosity of a white dwarf can be written as:

$$L + L_\nu + L_{\rm X} = -\int_0^{M_{\rm WD}} C_{\rm v}\frac{dT}{dt}\,dm - \int_0^{M_{\rm WD}} T\Big(\frac{\partial P}{\partial T}\Big)_{V,X_0}\frac{dV}{dt}\,dm + \quad (l_{\rm s}+e_{\rm s})\dot{M}_{\rm s} + \dot{\epsilon}_{\rm X} \qquad (1)$$

where the l.h.s. of this equation represents the sinks of energy, photons, neutrinos and any additional exotic term, while the r.h.s. contains the sources of energy, the heat capacity of the star, the work due to the change of volume, the contribution of the latent heat and gravitationl settling upon crystallization (the term $\dot{M}_{\rm s}$ is the rate of crystallization) and, finally, the last term represents any additional exotic source of energy [1]. There are two ways to test the theory of white dwarf evolution, namely, studying the white dwarf luminosity function and using the secular drift of the pulsation period of variable white dwarfs.

During the cooling process, white dwarfs experience some phases of pulsational instability powered by the κ- and the *convective driven*-mechanisms [2]. Depending on the composition of the atmosphere variable white dwarfs are known as DOV, DBV and DAV. These stars also known as PG1159 or GW Vir stars, V777 He stars and ZZ Ceti stars respectively. Variable white dwarfs of different compositions occupy different regions in the Hertzsprung–Russell diagram. The value of the pulsation period indicates that these objects are experiencing g–mode non–radial pulsations, where the main restoring force is gravity. One of the main characteristics of these pulsations is that they experience a secular drift caused by the evolution of the temperature and radius. For qualitative purposes this drift can be approximated by [3]:

$$\frac{d\ln\Pi}{dt} \simeq -a\frac{d\ln T}{dt} + b\frac{d\ln R}{dt} \tag{2}$$

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 the plasma increases, the buoyancy decreases, the Brunt-Väisälä frequency becomes smaller 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. The timescales involved are of the order of $\sim 10^{-11}$ s/s for DOVs, $\sim 10^{-13}$ to $\sim 10^{-14}$ s/s for DBVs and $\sim 10^{-15}$ to $\sim 10^{-16}$ s/s for DAVs. Therefore, the measurement of such drifts provides an effective method to test the theory of cooling white dwarfs. This measurement is a difficult but feasible task, as it has been already proved in the case of G117–B15A, a ZZ Ceti star [4]. These properties allow to build a simple relationship [5, 6] to estimate the influence of an extra sink of energy, axions for instance, on the period drift of variable white dwarfs: $(L_{\rm X}/L_{\rm model}) \approx (\dot{\Pi}_{\rm obs}/\dot{\Pi}_{\rm model}) - 1$ where the suffix "model" refers to those models built using standard physics.

The white dwarf luminosity function is defined as the number density of white dwarfs of a given luminosity per unit of magnitude interval:

$$n(l) = \int_{M_{\rm i}}^{M_{\rm s}} \Phi(M)\,\Psi(t)\tau_{\rm cool}(l,M)\,dM \tag{3}$$

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. The computed luminosity function is usually normalized to the bin with the smallest error bar, traditionally the one with $l = 3$, in order to compare theory with observations. Equation (3) shows that in order to use the luminosity function as a physical laboratory it is necessary to have good enough observational data and to know the galactic properties that are used in this equation (the star formation rate, the initial mass function and the age of the Galaxy). Fortunately, the bright branch of the luminosity function is only sensitive to the average characteristic cooling time of white dwarfs at the corresponding luminosity when the function is properly normalized. The reason is twofold [7], on one hand the stellar population is dominated by low mass stars and on the other the lifetime of stars increases very sharply when the mass decreases. The result is that the old galactic populations are still producing bright white dwarfs and the number of such stars at each luminosity bin is the sum of the contributions of all the different episodes of star formation.

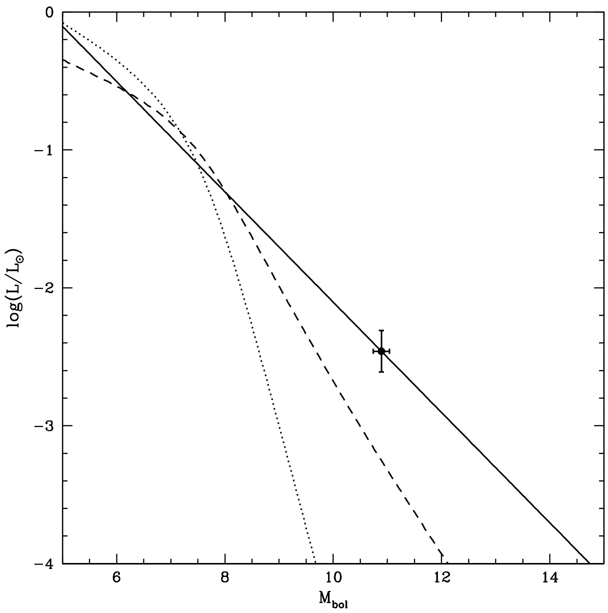

Figure 1: Power emitted in the form of photons (continuous line), neutrinos (dotted line) and axions (dashed line, arbitrary $g_{\rm aee}$) by a 0.6 $M_\odot$ white dwarf versus its bolometric magnitude, a function that monotonically increases with time. The cross represents the position of G115-B15A.

2 The axion case

We note that in white dwarf case only DFSZ axions have to be taken into account, since electron bremsstrahlung is the dominant process in white dwarf interiors. The axion emission rate under these conditions is given by [8]: $\dot{\epsilon}_{\rm ax} = 1.08 \times 10^{23} (g^2_{\rm aee}/4\pi)(Z^2 A)\, T_7^4 F(T,\rho)$ erg/g/s where F takes into account the Coulomb plasma effects, T_7 is the temperature in units of 10^7 K, Z and A are the atomic and mass numbers of the plasma components, respectively, and $g_{\rm aee}$ is the strength of the axion-electron Yukawa coupling. Figure 1 shows the energy losses of a typical white dwarf star. Since the neutrino emission is $\dot{\epsilon}_\nu \propto T^8$ and $L_{\rm phot} \propto T^{2.7}$ the luminosity function allows to disentangle the contribution of the different mechanisms of energy loss. When this method is applied to the luminosity function of white dwarfs the value of $g_{\rm aee}$ that best fits the luminosity function is 1.1×10^{-13}, but variations of a factor two are still compatible with the observations [9, 7]. Finally, the most recent analysis of G117-B15A shows that the value of g_{aee} quoted here is compatible with the secular drift of the pulsation period, which gives support to the necessity to include an extra cooling term in the white dwarf models [10].

3 Conclusions

There are two independent evidences, the luminosity function and the secular drift of DAV white dwarfs, that these stars are cooling down more rapidly than predicted. The introduction of an additional sink of energy linked to the interaction of electrons with a light boson (axion, ALP,...) with an strength $g_{\mathrm{aee}} \sim 10^{-13}$ solves the problem satisfactorily. Of course, the remaining uncertainties, both observational and theoretical, still prevent to claim the existence of such interaction. A direct detection under laboratory conditions, like those of the CAST helioscope [11] or the shining through the wall experiments [12], could provide unambiguous evidences. In this sense, if the current result is interpreted as due to axions, such particles should have a mass, $m_{\mathrm{a}} \sim$ meV and should be coupled with photons with $g_{\mathrm{a}\gamma} \sim 10^{-12}$ GeV^{-1}.

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

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

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

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

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

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

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

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

[9] J. Isern, E. García-Berro, S. Torres, & S. Catalán, "Axions and the cooling of white dwarf stars", Astrophys. Jour., **682**, L109 (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] T. Papaevangelou, "CAST, recent results results and future outlook", http: axion-wimp.desy.de and these proceedings.

[12] P. Arias, J. Jaeckel, J. Redondo, A. Ringwald "Improving the discovery potential of future light-shining-through-the-wall experiments", aerXiV:1009.1519 [hep-ph], http: axion-wimp.desy.de and these proceedings.