Axions and the white dwarf luminosity function

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Abstract. The evolution of white dwarfs can be described as a simple cooling process. Recently, it has been possible to determine with an unprecedented precision their luminosity function, that is, the number of stars per unit volume and luminosity interval. Since the shape of the bright branch of this function is only sensitive to the average cooling rate, we use this property to check the possible existence of axions, a proposed but not yet detected weakly interacting particle. We show here that the inclusion of the axion emissivity in the evolutionary models of white dwarfs noticeably improves the agreement between the theoretical calculations and the observational white dwarf luminosity function, thus providing the first positive indication that axions could exist. Our results indicate that the best fit is obtained for $m_a \cos^2 \beta \approx 2 - 6$ meV, where $m_a$ is the mass of the axion and $\cos^2 \beta$ is a free parameter, and that values larger than 10 meV are clearly excluded.

1. Introduction

White dwarfs are the final evolutionary stage of low- and intermediate-mass stars ($M \leq 10 \pm 2 M_\odot$). Since they are degenerate objects, they cannot obtain energy from thermonuclear reactions and their evolution is just a gravothermal process of cooling. They have a relatively simple structure composed by a degenerate core that contains the bulk of mass and acts as a reservoir of energy, and a partially degenerate envelope that controls the energy outflow. White dwarfs masses are in the range of $0.3 \leq M/M_\odot \leq 1.4$ (the Chandrasekhar’s mass). Those with $M \leq 0.4 M_\odot$ have a core made of He, while those with a $M \geq 1.05 M_\odot$ have a core made of O and Ne. The remaining ones, the vast majority, have a core made of a mixture of C and O. All of them are surrounded by a thin helium layer with a mass ranging from $10^{-2}$ to $10^{-4} M_\odot$, which, in turn, is surrounded by an even thinner layer of hydrogen with a mass between $10^{-4}$ and $10^{-15} M_\odot$, although about 25% of white dwarfs do not have such hydrogen envelopes. White dwarfs displaying hydrogen in their spectra are known as DA and the remaining ones as non-DA. Because of the different opacities involved, DA white dwarfs cool down much more slowly than non-DA white dwarfs.

Because of the simplicity of their structures, it has been proposed to use white dwarfs as laboratories to test new physics. The reasons for such a proposal are the following ones. Firstly, the evolution of white dwarfs is just a simple process of cooling. Secondly, the basic physical ingredients necessary to predict their evolution are well identified, although not necessarily well.
understood, and, finally, there is a solid and continuously growing observational background that allows to test the different theories. Therefore, if an additional source or sink of energy is added, the characteristic cooling time is modified and these changes can be detected through the anomalies introduced in the luminosity function or in the secular drift of the pulsation period of degenerate variables — see Isern & García–Berro (2008) for details. In this paper we will limit ourselves to study the changes introduced by the introduction of axions in the white dwarf luminosity function.

2. The white dwarf luminosity function

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

\[ n(l) = \int_{M_i}^{M_s} \Phi(M) \Psi(\tau) \tau_{\text{cool}}(l, M) \, dM \]  

(1)

where

\[ \tau = T - t_{\text{cool}}(l, M) - t_{\text{PS}}(M) \]  

(2)

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), \( t_{\text{cool}} \) is the cooling time down to luminosity \( l \), \( \tau_{\text{cool}} = dt/dM_\text{bol} \) is the characteristic cooling time, \( M_s \) and \( M_i \) are the maximum and the minimum masses of the main sequence stars able to produce a white dwarf of luminosity \( l \), \( t_{\text{PS}} \) 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.
Figure 2. Theoretical luminosity functions of white dwarfs. The observational data are the same represented in the right panel of figure 1. Solid lines were obtained for different ages of the Galaxy — from left to right: 10, 11, 12 and 13 Gyr — and a constant star formation rate. Dotted lines were obtained using an age of 11 Gyr but exponentially decreasing star formation rates, with $\tau = 0.5, 3$ and $5$ Gyr. All the luminosity functions have been normalized to the same observational data point.

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 1 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).

The first luminosity function was derived four decades ago (Weidemann 1968) and since then it has been noticeably improved, see the left panel of Fig. 1. The monotonic behavior of this function clearly proves that the evolution of white dwarfs is just a cooling process. The sharp cut-off at low luminosities is a consequence of the finite age of the Galaxy. The availability of data from the Sloan Digital Sky Survey (SDSS) is noticeably improving the accuracy of the new luminosity functions. The one by Harris (2006) was built from a sample of 6000 DA and non-DA white dwarfs with accurate photometry and proper motions culled from the SDSS Data Release 3 and the USNO-B catalogue, whereas the one obtained by DeGennaro et al. (2008) was constructed from a sample of 3528 spectroscopically identified DA white dwarfs from the SDSS Data Release 4 (see the right panel of Figure 1). The quality of the data, specially in the central part of the bright branch, is so good that they allow to start testing the inclusion of new physics in the cooling process of white dwarfs.

It is evident that before introducing new ingredients it is necessary to have a good model of cooling able to reproduce as accurately as possible the observations. It is worthwhile here to remember that when the luminosity is large, $M_{\text{bol}} < 8$, the evolution is dominated by neutrino emission. In this phase the main uncertainties come from our poor knowledge of the initial conditions. Fortunately, it has been shown that all the initial thermal structures converge towards a unique one. For smaller luminosities, $8 \leq M_{\text{bol}} \leq 12$, the main source of energy is of gravothermal origin. In this phase, the Coulomb plasma coupling parameter is not large and the cooling can be accurately described. Furthermore, the energy flux through the envelope is controlled by a thick non-degenerate or partially degenerate layer with an opacity dominated
by hydrogen, when present, and helium, and it is weakly dependent on the metal content since metals sink towards the base of the envelope by gravitationally-induced diffusion. Below these luminosities, white dwarfs evolve into a region of densities and temperatures where the plasma crystallizes. When this happens, two additional sources of energy appear: the release of latent heat during crystallization and the release of gravitational energy induced by phase separation of the different chemical species (García–Berro et al. 1988). When the bulk of the star is solid, the white dwarf enters into the Debye cooling phase and the only important source of energy comes from the compression of the outer layers — see Isern et al (1998) for a detailed discussion. These late phases of cooling are not yet well understood (Isern et al 2000). Figure 2 shows that it is possible to construct a good standard model with the cooling sequences of Salaris et al. (2000), the initial-final mass relationship of Catalan et al. (2008), a constant star formation rate (solid line) and an age of the disk of 10.5 Gyr. The cooling models also assume a non-homogeneous distribution of carbon and oxygen in the core (Salaris et al. 1997), a pure helium layer of $10^{-2} M_\ast$ and on top of it a pure hydrogen layer of $10^{-4} M_\ast$, where $M_\ast$ is the mass of the white dwarf.

The third condition to be fulfilled is the reliability of the Galactic data: the age of the Galaxy, the initial mass function and the star formation rate. An interesting feature of figure 2 is that the bright part of the white dwarf luminosity function — that with bolometric magnitude $M_{\text{bol}} < 13$ — is almost independent of the assumed star formation rate. This can be explained with simple arguments. Since the characteristic cooling time is not strongly dependent on the mass of the white dwarf, Eq. (1) can be written as:

\[ n = \langle \tau_{\text{cool}} \rangle \int_{M_f}^{M_u} \phi(M) \psi(T - t_{\text{cool}} - t_{\text{ps}}) \, dM. \]  

Restricting ourselves to bright white dwarfs — namely, those for which $t_{\text{cool}}$ is small — the lower limit of the integral is satisfied by low-mass stars and, as a consequence of the strong dependence of the main sequence lifetimes with mass, it takes a value that is almost independent of the luminosity under consideration (see figure 3). Therefore, if $\psi$ is a well behaved function.
Figure 4. Energy losses for a typical 0.61 $M_{\odot}$ white dwarf as a function of the bolometric magnitude. The dashed lines represent the axion luminosity for different values of $m_a \cos^2 \beta$, where $m_a$ is the mass of the axion, and $\cos^2 \beta$ is a free parameter (from top to bottom: $m_a \cos^2 \beta = 10, 5, 1, 0.1, 0.01$ meV). The thick solid line represents the photon luminosity, while the thin solid line represents the neutrino luminosity.

and $T_C$ is large enough, the integral is not sensitive to the luminosity, its value is absorbed by the normalization procedure and the shape of the luminosity function only depends on the averaged physical properties of white dwarfs. It is important to mention here that the initial-final mass relationship enters as a weight into the calculation of this average. Nevertheless, since only those functions able to provide a good fit to the mass distribution of white dwarfs are acceptable, its influence on the shape of the bright branch of the luminosity function is minor (Isern et al 2008).

3. Axions

One solution to the strong CP problem of quantum chromodynamics is the Peccei-Quinn symmetry (Peccei & Quinn 1977a, b). This symmetry is spontaneously broken at an energy scale that gives rise to the formation of a light pseudo-scalar particle named axion (Weinberg, 1978; Wilczek, 1978). This scale of energies is not defined by the theory but it has to be well above the electroweak scale to ensure that the coupling between axions and matter is weak enough to account for the lack of positive detection up to now. The mass of axions and the energy scale are related by: $m_a = 0.6(10^7 \text{ GeV} / f_a) \text{ eV}$. Astrophysical and cosmological arguments have been used to constrain this mass to the range $10^{-4}$eV $\leq m_a \leq 10^{-4}$eV. For this mass range, axions can escape from stars and act as a sink of energy. Therefore, if they exist, they can noticeably modify the cooling of white dwarf stars.

Axions can couple to photons, electrons and nucleons with a strength that depends on the specific implementation of the Peccei-Quinn mechanism. The two most common implementations are the KSVZ (Kim, 1979; Shifman et al., 1979) and the DFSZ models (Dine et al., 1981; Zhitniskii, 1980). In the first case, axions couple to hadrons and photons, while in the second they also couple to charged leptons. For the temperatures and densities of the white dwarfs under consideration, only DFSZ axions are relevant and in this case they can be emitted by Compton, pair annihilation and bremsstrahlung processes, but only the last mechanism turns out to be important. Figure 4 shows the energy losses for a typical white dwarf as a function of the bolometric magnitude. The axion emission rate (in erg/g/s) has been computed (Nakagawa
1987, 1988) as $e_a = 1.08 \times 10^{23} \alpha Z^2 / AT^4 F$, where $F$ is a function of the temperature and the density which takes into account the properties of the plasma, $\alpha = g_{ae}^2 / 4 \pi$ is related to the axion-electron coupling constant $g_{ae} = 2.8 \times 10^{-11} m_a \cos^2 \beta / 1 \text{eV}$. Since the core is almost isothermal, $L_a \propto T^4$ in the region in which axions are the dominant sink of energy. The thick solid line represents the photon luminosity (Salaris et al 2000). For the region of interest $L_\gamma \propto T^\alpha$, with $\alpha \approx 2.6$, although this value changes as the white dwarf cools down. The thin solid line represents the neutrino luminosity (Salaris et al 2000) — which scales as $L_\nu \propto T^8$ — and is also dominated by the plasma and bremsstrahlung processes. Therefore, since the temperature dependence of the different energy-loss mechanisms is not the same, the luminosity function allows to disentangle the different contributions.

Figure 4 shows that in the region $M_{\text{bol}} \sim 10$ the axion luminosity is not negligible when compared with the photon and neutrino ones. It also shows that the region around $M_{\text{bol}} \sim 12$ provides a solid anchor point to normalize the luminosity function because there the observational data have reasonably small error bars, models are reliable, neutrinos are not relevant and axions, if they exist, are not dominant.

4. Results and conclusions
Figure 5 displays the luminosity function for different axion masses, a constant star formation rate and an age of the Galactic disk of 11 Gyr. As already mentioned, it is important to remember that the bright branch of the luminosity function is not sensitive to these last assumptions. All the luminosity functions have been normalized to the luminosity bin at $\log(L/L_\odot) \simeq -3$ or, equivalently, $M_{\text{bol}} \simeq 12.2$. The best fit model — namely that which minimizes the $\chi^2$ test in the region $-1 > \log(L/L_\odot) > -3$ (that is, $7.2 < M_{\text{bol}} < 12.2$), which is the region where both the observational data and the theoretical models are reliable — is obtained for $m_a \cos^2 \beta \approx 5.5$ meV and solutions with $m_a \cos^2 \beta > 10$ meV are clearly excluded (Isern et al 2008). Figure 6 displays the behavior of $\chi^2$ as a function of the mass of the axion for different normalization points. In all cases, $\chi^2$ displays a pronounced minimum for masses in the range of roughly 2 to 6 meV except for $l = 2.51$ and 2.67 that are compatible with $m_a = 0$. However, as it can be seen from figure 6, both points deviate from the behavior of the neighbouring values.
Taken at face value, these results not only provide a strong constraint to the allowed mass of axions, but also a first evidence of their existence and a rough estimation of their mass. This is of course a strong statement and in order to be accepted it has to fulfill the following conditions: it has to be confirmed independently, it has to resist the introduction of any conventional effect not previously included, it has to provide testable predictions and it can not enter in contradiction with well established facts. A detailed discussion of the existing uncertainties is out of the scope of the present paper but it is worthwhile to enumerate some of them: influence of the metallicity in the age and core composition of the progenitor, transparency of the envelope and conversion of DA into non-DA white dwarfs, IMF, initial-final mass relationship, pathological SFRs or uncertainties in the observational luminosity function, especially on the role of He white dwarfs and the detailed shape of the brightest part of this function and others.

The results found here are completely compatible with the presently known constraints (Raffelt 2007), but since the predicted mass is near the allowed upper bound, it is natural to expect they will introduce some subtle changes in the late stages of stellar evolution as it is indeed the case of white dwarfs. A detailed discussion of this point is also out of the scope of this paper and we will just mention that these values are compatible with the bounds imposed by the drift of the pulsational period of the ZZ Ceti star G117−B15A (Isern et al. 1992; Ćorsico et al. 2001; Bischoff-Kim et al. 2008). It is also worthwhile to mention here that axions with $m_a \cos^2 \beta \approx 5$ meV would change the expected period drift of variable DB white dwarfs — which have values between $\dot{P} \sim 10^{-13}$ and $10^{-14}$ s s$^{-1}$ (Ćorsico & Althaus 2004) — by a factor of 2, the exact value depending on the adopted temperature of the stellar core. The structure of the Sun would not be modified by the emission of axions of this masses since they would represent $L_a \sim 10^{-6} L_\odot$.

However, an instrument like CAST, able to operate in the region of masses $m_a \sim$ meV and coupling constant $g_{a\gamma} \sim 10^{-12}$ GeV$^{-1}$ could be able to detect them and confirm or rule out the masses predicted here. Cosmology could also provide some insight to this problem. Axions have been proposed as dark matter candidates but if we assume $\cos^2 \beta = 1$, their contribution would
be of the order of $\Omega_\chi h^2 \sim 10^{-4}$, where $h$ is the Hubble constant normalized to 100 km/s/Mpc (Raffelt 2007), which rules out them as the main dark matter candidate. On the contrary, if dark energy is interpreted as the energy density of vacuum, axions could have an important role. The vacuum energy is obtained from the sum of the zero point energy of all the quantum fields (where bosons contribute positively and fermions negatively) and if we try to reproduce the observed value, that is positive, with just one quantum field we need a boson with a mass of the order or smaller than 10 meV (Friemann, Turner & Huterer, 2008), that is just what we have found here. This is indeed a remarkable coincidence.

To conclude, it is evident that our claim about the existence of axions has to be taken with caution, but it clearly shows that the white dwarf luminosity function can provide strong arguments to solve the long-lasting problem of the CP violation. Future work should be devoted to improving the observational data, especially for the brightest part of the white dwarf luminosity function. The theoretical models could also be improved and also additional efforts should be devoted to find new independent methods to detect axions. Finally, it is worthwhile to say that even in the case of a negative result, an accurate and precise luminosity function could be used to provide insight to many other problems like the hypothetical drift of the gravitation constant or the magnetic momentum of neutrinos just to cite two cases.

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