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White dwarfs as physics laboratories: the axion case

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Abstract. One of the tools for constraining the properties of some particles predicted by the different non-standard physical theories is the study of the evolutive properties of stars. The reason is that the hot and dense interior of stars is a powerful source of low-mass weakly-interacting particles that freely escape to the space. Therefore, these particles constitute a sink of energy that modifies the evolutionary timescales of stars, thus opening the door to constraint the properties of such hypothetical particles. Several stellar objects have been used up to now to this regard. Among these are the Sun, supernovae, red giants and AGB stars. However, the uncertainties and model dependences recommend the use of different astrophysical techniques to constrain or verify these new theories. Here we show that, for several reasons being the most outstanding one the their simplicity, white dwarfs can be used as excellent laboratories for testing new physics. In this paper we apply them to constrain the mass of the axions.

Key words. Stars: white dwarfs — stars: oscillations — particles: axions

1. Introduction

Several non-standard theories predict the existence of exotic particles. Since very often there are not laboratory experiments in the relevant energy range able to obtain empirical evidences of their existence or properties, it is necessary to use stars to obtain information about them Raffelt (1996). The general procedure adopted in this case consists in comparing the observed properties of selected stars with well measured properties (or of a cluster of stars) with the predictions of theoretical stellar models obtained under different assumptions about the underlying microphysics. In particular, the hot and dense interior of stars is a powerful source of low-mass weakly interacting particles that freely escape to space. These hypothetical particles constitute a sink of energy that modifies the lifetimes of stars at the different evolutionary stages, thus allowing a comparison with the observed lifetimes.

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these theories. In this sense, white dwarfs can be excellent laboratories for testing new physics since: i) Their evolution is just a simple process of cooling, ii) The basic physical ingredients necessary to predict their evolution are well identified, although not necessarily well understood, and iii) There is an impressively solid observational background to check the different theories.

2. Modelling the effects on white dwarfs

Since the core of white dwarfs is completely degenerate these stars cannot obtain energy from nuclear reactions and their evolution is just a gravothermal process of contraction and cooling that can be roughly described as:

$$L_{\rm ph} + L_{\nu} + L_{\rm es} = -\frac{d(E+\Omega)}{dt} \qquad (1)$$

where E is the total internal energy, Ω is the total gravitational energy, and $L_{\rm ph}$, L_{ν} and $L_{\rm es}$ are the photon, neutrino and extra sink luminosities, respectively. Therefore, if an additional cooling source were present, the characteristic cooling time should decrease and the individual or collective properties of white dwarfs that are sensitive to this time scale (the white dwarf luminosity function and the period of oscillation of variable white dwarfs) are modified.

2.1. The white dwarf luminosity function

We start by introducing the white luminosity function, which is defined as the number of white dwarfs of a given luminosity per unit of magnitude interval:

$$n(l) \propto \int_{M_{\rm i}}^{M_{\rm s}} \Phi(M)\,\Psi(\tau)\tau_{\rm cool}(l,M)\,dM \qquad (2)$$

where

$$\tau = T - t_{\rm cool}(l,M) - t_{\rm PS}(M) \qquad (3)$$

and l is the logarithm of the luminosity in solar units, 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 astronomical properties of the stellar population under study. Since the total density of white dwarfs is not well known, the computed luminosity function is normalized to the bin with the smallest error bars in order to compare theory with observations.

Since the characteristic cooling time does not strongly depend on the mass of the white dwarf, it is possible to write

$$n(l) \propto \langle\tau_{\rm cool}\rangle \int \Phi(M)\Psi(\tau)dM \qquad (4)$$

If we restrict ourselves to bright white dwarfs — namely, those with $t_{\rm cool} \ll T$ — Eq. (3) can be satisfied for a wide range of masses of the progenitor stars — that is, stars of different masses born at very different times. Moreover, the integral term becomes weakly dependent on Ψ if the star formation rate is a smooth function of time. In conclusion, the integral can be considered as roughly constant and, thus, can be incorporated in the normalization constant, and so the bright part of the luminosity function only depends on the characteristic cooling time. Since the number density of white dwarfs of each luminosity bin depends on the time that each star takes to cross the interval, the number density of stars of each bin changes as:

$$N = N_0 \frac{L_0}{L_0 + L_1} \qquad (5)$$

where L_0 is the luminosity of the star obtained with standard physics and L_1 is the contribution of the non-standard terms. Therefore the allowed values of L_1 are constrained by the observational uncertainties Isern et al. (2003).

Figure 1 displays the luminosity function obtained from the last SDSS release

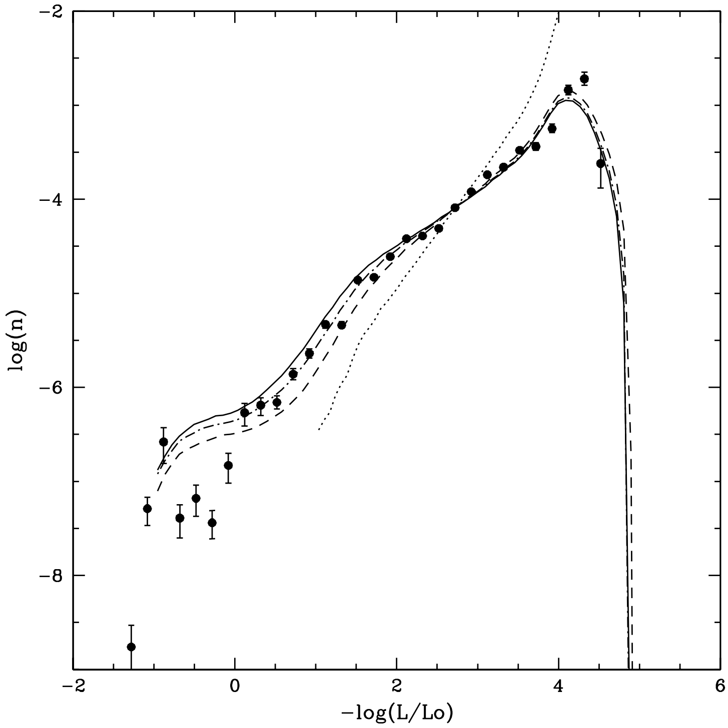

Fig. 1. Luminosity function of white dwarfs obtained under different hypothesis. The observational values (dots) were obtained from the data quoted by Harris et al. (2005). The solid line represents the computed luminosity function obtained with standard physics. The dotted line is the luminosity function computed assuming that axions have a mass irrealistically large just for illustrating purposes. The dashed line was obtained assuming $m_{\rm ax}\cos^2\beta = 10$ meV and the dotted–dashed line assuming $m_{\rm ax}\cos^2\beta = 4$ meV.

Harris et al. (2005). The solid line was obtained using the cooling sequences of Salaris et al. (2000), the initial–final mass relationship of Domínguez et al. (1999), a constant star formation rate and an age of the disk of 10.5 Gyr. The cooling models assume a non-homogeneous distribution of carbon and oxygen in the core Salaris et al. (1997), a pure helium layer of $10^{-2}\,M_*$ and on top of it a pure hydrogen layer of $10^{-4}\,M_*$, where M_* is the mass of the white dwarf.

2.2. Pulsating white dwarfs

During their cooling, white dwarfs cross some specific zones of the Hertzsprung-Russell diagram where they become unstable and pulsate. The multiperiodic character of the pulsations and the size of the periods (100 s to 1000 s), much larger than the period of radial pulsations (∼ 10 s), indicate that white dwarfs are g-mode pulsators (the restoring force is gravity). As the variable white dwarf cools down, the oscillation period, P, changes as a consequence of the changes in the mechanical structure. This secular drift can be approximated by Winget et al. (1983):

$$\frac{\dot{P}}{P} \simeq -a\frac{\dot{T}}{T} + b\frac{\dot{R}}{R} \tag{6}$$

where a and b are positive constants of the order of unity. The first term of the right hand side reflects the fact that as the star cools down the degree of degeneracy increases, the Brunt-Väisälä frequency decreases and, as a consequence, the oscillation period of stars increases. At the same time, the residual gravitational contraction, that is always present, tends to decrease the oscillation period. The later effect is accounted for by the last term in Eq. (6).

There are three types of variable white dwarfs, the DOV, the DBV and the DAV white dwarfs. In the case of the hottest ones, the DOV, the gravitational contraction is still significant and the second term in Eq. (6) is not negligible. In fact, for these stars $\dot{P}$ can be positive or negative depending of the character of the oscillation mode. If the mode is dominated by the deep regions of the star, $\dot{P}$ is positive. If the mode is dominated by the outer layers, $\dot{P}$ is negative Kawaler & Bradley (1994). The secular drift of the prototype of these kind of stars is $\dot{P} = (13.07 \pm 0.3) \times 10^{-11}$ s/s for the 516 s pulsation period. However, the uncertainties in the modelling of their interior have prevented the obtaining reliable conclusions (Winget et al. 1985; Costa et al. 1999).

The DBV stars are characterized by the lack of the hydrogen layer in their envelopes and by effective temperatures of the order of $T_{\rm eff} \sim 25,000$ K. Since they are cooler than DOV white dwarfs, the radial term is negligible and $\dot{P}$ is always positive. The expected drift ranges from $\dot{P} \sim 10^{-13}$ to 10^{-14} s/s Córsico & Althaus (2004), but it has not been yet measured with enough accuracy.

The DAV white dwarfs, or ZZ Ceti stars, are characterized by the presence of a very thin atmospheric layer made of pure hydrogen and by effective temperatures ranging from $T_{\rm eff} \sim 12,000$ to $15,000$ K. As in the case of DBV stars, they are so cool that the radial term is negligible and $\dot{P}$ is always positive. The drift has been measured for the $P = 215.2$ s mode of G117–B15A (Kepler et al. 2005, 2000), $\dot{P} = (3.57 \pm 0.82) \times 10^{-15}$ s/s, and an upper bound has been obtained for the $P = 213,13$ s mode in the case of R 548, $\dot{P} \leq (5.5 \pm 1.9) \times 10^{-15}$ s/s (Mukadam et al. 2003).

The seismological analysis of G117–B15A indicates that the best fit is obtained for $M_* = 0.55\, M_\odot$, $\log M_{\rm He}/M_* = -2$ and $\log M_{\rm H}/M_* = -4.04$ Córsico et al. (2001), that gives a cooling rate of $\dot{P} = 3.9 \times 10^{-15}$ s/s, very similar to the recently found observational value Kepler et al. (2005). A similar analysis Bisschoff-Kim et al. (2007) has found two possible fits to the seismological data, one with a hydrogen layer of $6.3 \times 10^{-7}\, M_*$ and another one with $4 \times 10^{-8}\, M_*$ and period drifts of 1.92×10^{-15} s/s and 2.98×10^{-15} s/s, respectively. It is important to notice here that in the first analysis the predicted cooling rate is larger than the observed one, while in the second analysis the calculated rates are smaller than the observed ones. This means that in the first case there is no room for any additional cooling while in the second one there is room for an extra sink of energy. In the case of R 548 the predicted change of period is $\dot{P} = 2.91 \times 10^{-15}$ s/s Bisschoff-Kim et al. (2007), in agreement with the observational bound.

This secular drift can be used to test the predicted cooling rate or, if the models are reliable enough, to test any new physical effect able to change the pulsating period of these stars.The observed rate of change of the pulsation period, $\dot{P}_{\rm obs}$ and the calculated rate of change are related by Isern et al. (2003,?):

$$\frac{L_0 + L_1}{L_0} = \frac{\dot{P}_{\rm obs}}{\dot{P}_{\rm mod}} \tag{7}$$

where L_1 is the extra emission term included in the models and L_0 is the luminosity predicted by the models incorporating only standard physics.

These methods have been succesfully applied to constrain the mass of the axions Isern et al. (2003); Córsico et al. (2001), the possible changes of the gravitational constant García–Berro et al. (1995); Isern et al. (2003); Benvenuto et al. (2004), the nature of the extra dimensions Bieisiada & Malec (2002) or the magnetic momentum of the neutrino (Blinnikov & Dunina-Barkovskaya 1994).

3. The case of axions

One of the ways to solve the strong CP problem of QCD consists in the introduction of an "ad hoc" new symmetry in the Lagrangian of the fundamental interaction Peccei & Quinn (1977). The spontaneous breaking of this symmetry gives raise to the axions. The two most simple models of axions are the KVSZ model Kim (1979); Shifman et al. (1980) and the DFSZ Zhimitskii (1980); Dine et al. (1981). In the KVSZ model, axions couple to hadrons and photons whereas in the DFSZ model, axions also couple to charged leptons. The coupling strengths depend on the specific implementation of the Peccei-Quinn mechanism through a set of dimensionless coupling constants. Both models do not set any constraint on the mass of the axion which has to be obtained from experimental measures or from observational tests. The axion mass is $m_{\rm ax} = 0.62\,{\rm eV}(10^7\,{\rm GeV}/f_\alpha)$, where f_α is the Peccei-Quinn scale and the axion coupling with matter is proportional to f_α^{-1}. Therefore, axions can interact with photons through the Primakov conversion of photons into axions and viceversa under the influence of an electromagnetic field, or with nucleons or with electrons (in the DFSZ case) through the Compton and bremsstrahlung processes.

The most restrictive constraints to the mass of axions come from astrophysical and cosmological arguments — see Raffelt (2006) for a recent review. The requirements for not overclosing the Universe imply that $m_{\rm ax} > 6\times10^{-6}$ eV. The lack of observations of photons produced by the decay of axions Massó & Toldra (1997), together with the hot dark matter limit introduces an upper bound of $m_{\rm ax} < 1$ eV. Stars in globular clusters provide an additional $m_{\rm ax} < 0.01$ eV, while the helium ignition argument provides an additional constraint to the DFASZ model $m_{\rm ax}\cos^2\beta < 9$ meV, where $\cos^2\beta$ is a fre parameter like $m_{\rm ax}$ that appears in tghe strength of the coupling of axions with electrons given by

$$g_{\rm ae} = 2.83\times10^{-11} m_{\rm ax}\cos^2\beta \tag{8}$$

Despite that the requirements imposed by the duration of neutrino signal of SN1987A are still moot, a new safe limit of $m_{\rm ax} \lesssim 10$ meV can be adopted. Finally, the CAST experiment Ziontas et al. (2005) has established a general bound on the strength of the axion-photon interaction, $g_{\alpha\gamma\gamma} \leq 1.16\times10^{-10}$ GeV^{-1} for $m_{\rm ax} \lesssim 0.02$ eV, where $g_{\alpha\gamma\gamma} \propto m_{\rm ax}$ and the constant of proportionality depends on the adopted model.

In the case of relatively cold white dwarfs, the dominat process of axion emission is bremsstrahlung. The emisiion rate is Nakagawa et al. (1988):

$$\epsilon_{\rm ax} = 1.08\times10^{23}\alpha\frac{Z^2}{A}T_7^4 F(\Gamma) \tag{9}$$

where $\alpha = g_{\rm ae}^2/4\pi$, F takes into account the plasma effects and Γ is the Coulomb parameter.

The inclusion of axions does not change the period of pulsation of the white dwarf, but strongly accelerates its secular variation Córsico et al. (2001) and, consequently, puts a strong constrain to the mass of the axion. Córsico et al. (2001) obtained $m_{\rm ax}\cos^2\beta \lesssim 4$ meV, although strictly speaking their results were suggesting to rule out the interaction of the axions with the electrons. The analysis of Bischoff-Kim et al. (2007) indicates that axions can represent an additional cooling source to white dwarfs and provide a less restrictive bound of 13 to 26 meV, depending on the adopted mass for the hydrogen layer. The weak point of the seismological analysis is that the drift period has only been measured in one case and both, observations and models, are not precise enough to rule out the interaction of electrons with axions nor to determine the mass of the axion.

The luminosity function could provide in a next future additional insight. Figure 1 displays the luminosity functions obtained when the axion emission is included. Since $\epsilon_{\rm ax} \propto T^4$, the evolution of hot white dwarfs is very rapid and are quickly transfered from the bright to the dim regios of the luminosity function where they accumulate — see Eq. (5). The dotted line in Fig. 1 clearly displays such a behavior. In this case, however, the mass of the axion was taken irrealistically large just for illustrative purposes. When the mass of the axion decreases, the luminosity function approaches to the nominal value. Interestingly, the agreement with the observed luminosity function improves when axions with a moderate mass, $m_{\rm ax} \sim 4$ meV, are included, suggesting that an additional sink of energy is necessary to fit the observations.

4. Conclusions

Because of their simplicity, white dwarfs can be considered excellent complementary laboratories for testing new physics. We have shown how the high precision luminosity functions that are progressively becoming available and the pulsation drift of degenerate variables can be used to provide independent insights on any new particle physics mechanism able to perturbate the cooling rate of such stars. In particular, we have shown that, when this method is applied to axions, it is possible to obtain a strong constraint to their ability to interact with electrons. The most recent analysis of the pulsation period drift Bisschoff-Kim et al. (2007) of G117-B15A and the new luminosity functions suggest that there is still room for the existence of axions with masses $m_{\rm ax} \sim 5$ meV. If this is ultimately proved to be true, axions could play a crucial role in the late stages of stellar evolution.

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