AXIONS AND THE COOLING OF WHITE DWARF STARS

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ABSTRACT

White dwarfs are the end product of the lives of intermediate- and low-mass stars and their evolution is 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. We show here that the shape of the bright branch of this function is only sensitive to the averaged cooling rate of white dwarfs and we propose to use this property to check the possible existence of axions, a proposed but not yet detected weakly interacting particle. Our results indicate that the inclusion of the emission of axions in the evolutionary models of white dwarfs noticeably improves the agreement between the theoretical calculations and the observational white dwarf luminosity function. The best fit is obtained for \( m_a \cos^2 \beta \approx 5 \text{ meV} \), where \( m_a \) is the mass of the axion and \( \cos^2 \beta \) is a free parameter. We also show that values larger than 10 meV are clearly excluded. The existing theoretical and observational uncertainties do not yet allow the confirmation of the existence of axions, but our results clearly show that if their mass is of the order of a few meV, the white dwarf luminosity function is sensitive enough to detect their existence.

Subject headings: elementary particles — stars: luminosity function, mass function — white dwarfs

1. INTRODUCTION

One solution to the strong CP problem of quantum chromodynamics is the Peccei-Quinn symmetry (Peccei & Quinn 1977a, 1977b). This symmetry is spontaneously broken at an energy scale that gives rise to the formation of a light pseudoscalar particle named the “axion” (Weinberg 1978; Wilczek 1977a, 1977b). This symmetry is spontaneously broken at an energy scale that gives rise to the formation of a light pseudoscalar particle named the “axion” (Weinberg 1978; Wilczek 1977a, 1977b). This symmetry is spontaneously broken at an energy scale that gives rise to the formation of a light pseudoscalar particle named the “axion” (Weinberg 1978; Wilczek 1977a, 1977b). This symmetry is spontaneously broken at an energy scale that gives rise to the formation of a light pseudoscalar particle named the “axion” (Weinberg 1978; Wilczek 1977a, 1977b).

The existing theoretical and observational uncertainties do not yet allow the confirmation of the existence of axions, but our results clearly show that if their mass is of the order of a few meV, the white dwarf luminosity function is sensitive enough to detect their existence.

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accurate photometry and proper motions culled from the SDSS Data Release 3 and the USNO-B catalog, whereas the second one (DeGennaro et al. 2008) was constructed from a sample of 3528 spectroscopically identified DA white dwarfs from the SDSS Data Release 4 (see Fig. 1). The monotonic behavior of this function clearly proves that the evolution of white dwarfs is just a cooling process. The sharp cutoff at low luminosities is a consequence of the finite age of the Galactic disk. The luminosity function of white dwarfs can be computed as

\[ n(M_{\text{bol}}) = \int_{M_i}^{M_*} \phi(M) \psi(T_c - t_{\text{cool}} - t_{\text{ps}}) \tau_{\text{cool}} dM, \]  
(1)

where \( M_{\text{bol}} \) is the bolometric magnitude, \( M \) is the mass of the parent star—for convenience all white dwarfs are labeled with the mass of its progenitor—\( T_c \) is the age of the population under study, \( t_{\text{cool}} \) is the time that a white dwarf with a progenitor of mass \( M \) takes to cool down to a bolometric magnitude \( M_{\text{bol}} \), \( \tau_{\text{cool}} \) is the characteristic cooling time of the white dwarf, and \( t_{\text{ps}} \) is the lifetime of the parent star. In equation (1) \( M_* \) is the maximum mass of white dwarf progenitors and \( M_i \) is the mass of the progenitor that satisfies the condition \( T_c - t_{\text{cool}} - t_{\text{ps}} = 0 \), i.e., the minimum mass of a star able to produce a white dwarf of the required luminosity. The remaining quantities are the initial mass function, \( \phi \) (here we have used Salpeter’s law), and the star formation rate, \( \psi \), which is not known a priori and depends on the population under study.

Since neither the star formation rate nor the total density of white dwarfs are known, theoretical luminosity functions are normalized to a given observational bin, usually the one with the smallest error bar. Figure 1 displays the observed luminosity functions and several luminosity functions obtained with the same DA cooling sequences (Salaris et al. 2000) and different star formation rates and ages of the Galaxy. The cooling models assume a nonhomogeneous 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. Since a relationship connecting the mass of the white dwarf and the mass of its progenitor is also necessary we have adopted the one that best reproduces the mass distribution of white dwarfs (Catalán et al. 2008).

An interesting feature of Figure 1 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, equation (1) can be written as

\[ n \propto \left( \tau_{\text{cool}} \right)^{-1} \int_{M_i}^{M_*} \phi(M) \psi(T - t_{\text{cool}} - t_{\text{ps}}) dM. \]  
(2)

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. Therefore, if \( \psi \) is a well-behaved function 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. Here we use this property of the white dwarf luminosity function, together with the recently obtained high-precision observational luminosity function, to study the influence of the emission of axions, and to check which mass of the axion is compatible with observations. The idea of using the cooling times of white dwarfs to constrain the properties of axions is not new (Raffelt 1986), but the crudeness of the theoretical models and of the observational data prevented a definite conclusion and just a loose upper bound was obtained, \( m_a < 30 \) meV.

3. AXIONS AND THE WHITE DWARF LUMINOSITY FUNCTION

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 KV SZ (Kim 1979; Shifman et al. 1980) and the DFSZ models (Dine et al. 1981; Zhitnitskii 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 2 shows the energy losses for an otherwise 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...
\[ m_a \cos^2 \beta \] The axion emission rate (in erg g\(^{-1}\) s\(^{-1}\)) has been computed (Nakagawa et al. 1987, 1988) as 
\[ e_a = 1.08 \times 10^7 \alpha(Z/\text{A})^2 F, \] 
where \( F \) is a function of the temperature and the density which takes into account the properties of the plasma, and \( \alpha = g_a^2/4\pi \) is related to the axion-electron coupling constant 
\[ g_a = 2.8 \times 10^{-11} m_a \cos^2 \beta / \text{eV}. \] Since the core is almost isothermal it turns out that 
\[ L_a \propto T^4 \] 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 \( L_a \propto T^8 \), with \( a \approx 2.6 \), since this value changes as the white dwarf cools down. The thin solid line represents the neutrino luminosity, which scales as \( L_{\nu} \propto T^8 \) and is also dominated by the plasma and bremsstrahlung processes (Itoh et al. 1996). Therefore, since the temperature dependence of the different energy-loss processes is not the same, the luminosity function allows us to disentangle the different contributions.

Figure 2 shows that in the region \( M_{\text{bol}} \approx 10 \) the axion luminosity can be comparable with the photon and neutrino ones, depending on the adopted axion mass. It also shows that the region around \( M_{\text{bol}} \approx 12 \) 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 3 displays several luminosity functions obtained using different axion masses, adopting a constant star formation rate and an age of the Galactic disk of 11 Gyr. As already mentioned, it is important to realize 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 \( \log (L/L_\odot) \approx -3 \) or, equivalently, \( M_{\text{bol}} \approx 12.2 \). The best-fit model—namely that which minimizes the \( \chi^2 \) test in the region \(-1 \leq \log (L/L_\odot) \leq -3\) (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 \( m_a \cos^2 \beta \approx 5 \) meV and solutions with \( m_a \cos^2 \beta > 10 \) meV are clearly excluded. Figure 4 displays the behavior of \( \chi^2 \) as a function of the mass of the axion in our fiducial case (solid line) and in the case in which we use the initial-final mass relationship of Wood (1992) which is marginally compatible with the white dwarf mass distribution (Catalán et al. 2008). In both cases the behavior of the luminosity function is similar and gives similar values for the mass of the axion once one takes into account the present uncertainties. It is also important to note that the largest contribution to the lack of accuracy comes from the brightest bins of the luminosity function, which have large error bars.

This result is completely compatible with the previously existing constraints (Raffelt 2007). Furthermore, these values are also compatible with the bounds imposed by the drift of the pulsational period of the ZZ Ceti star G117-B15A (Isern et al. 1992; Córresco et al. 2001; Bischoff-Kim et al. 2008). It is worthwhile to mention here that axions with \( m_a \approx 5 \) meV would change the expected period drift of variable DB white dwarfs—
which have values between $\dot{P} \sim 10^{-13}$ and $10^{-14}\text{ s}^{-1}$ (Córresco \\& Althaus 2004)—by a factor 2, the exact value depending on the adopted temperature of the stellar core and that the detection of such a drift would provide a strong additional argument in favor of the existence of axions.

The results presented here are not a definite proof of the existence of axions, since there are still some observational and theoretical uncertainties. However, the calculations reported here show that the hot branch of the white dwarf luminosity function is a powerful tool to test the existence of weakly interacting massive particles because it is only sensitive to the averaged cooling rate of white dwarfs and not to the details of the star formation rate or the initial mass function, as shown in § 2. Moreover, our results are probably the first evidence that the shape of the white dwarf luminosity function could be affected by the emission of axions and that this change can be measured. If this is indeed the case the mass of the axion would be of about 5 meV. In addition, we have derived an upper bound to the mass of the axions of 10 meV, which is compatible with other recent determinations (Bischoff-Kim et al. 2008). It is also worth mentioning that this result is relevant for other research fields and, in particular, for cosmology. Specifically, assuming $\cos^2 \beta = 1$, the contribution of axions to dark matter would be of the order of 0.2% (Raffelt 2007). In view of this, we consider it of the largest importance to improve the observational determination of the white dwarf luminosity function, especially in the region of the hottest white dwarfs (see Fig. 3). Thus, the extension of the SDSS is of the maximum interest not only for astronomers and cosmologists, but also for particle physicists. However, not only observational efforts are needed, since in order to obtain a reliable determination of the mass of the axion it is also important to decrease the uncertainties in the plasmon neutrino emission rates at the relevant temperature range. Furthermore, it would be also convenient to intensify the study of the drift of the pulsational periods of variable white dwarfs in order to obtain additional independent evidence.

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REFERENCES

Bischoff-Kim, A., Montgomery, M. H., & Winget, D. E. 2008, ApJ, 675, 1512
Catalán, S., Isern, J., García-Berro, E., & Ribas, I. 2008, MNRAS, in press (arXiv:0804.3034)
Córresco, A. H., & Althaus, L. G. 2004, A&A, 428, 159
Córresco, A. H., Benvenuto, O. G., Althaus, L. G., Isern, J., & García-Berro, E. 2001, NewA, 6, 197
D’Antonna, F., & Mazzitelli, K. 1989, ApJ, 347, 934
DeGennaro, S., von Hippel, T., Winget, D. E., Kepler, S. O., Nitta, A., Koester, D., & Althaus, L. 2008, AJ, 135, 1
Dine, M., Fischler, W., & Srednicki, M. 1981, Phys. Lett. B, 104, 199
García-Berro, E., Hernanz, M., Isern, J., & Mochkovitch, R. 1988a, Nature, 333, 642
García-Berro, E., Hernanz, M., Mochkovitch, R., & Isern, 1988b, A&A, 193, 141
Harris, H. C., et al. 2006, AJ, 131, 571
Isern, J., García-Berro, E., Hernanz, M., & Chabrier, G. 2000, ApJ, 528, 397
Isern, J., García-Berro, W., Hernanz, M., & Mochkovitch, R. 1998, J. Phys. Condensed Matter, 10, 11263
Isern, J., Hernanz, M., & García-Berro, E. 1992, ApJ, 392, L23
Isern, J., Mochkovitch, R., García-Berro, E., & Hernanz, M. 1997, ApJ, 485, 308
Itoh, N., Hayashi, H., Nishikawa, A., & Kohyama, Y. 1996, ApJS, 102, 411
Kim, J. E. 1979, Phys. Rev. Lett., 43, 103
Nakagawa, M., Adachi, T., Kohyama, Y., & Itoh, N. 1988, ApJ, 326, 241
Nakagawa, M., Kohyama, Y., & Itoh, N. 1987, ApJ, 322, 291
Peccei, R. D., & Quinn, H. R. 1977a, Phys. Rev. D, 16, 1791
Peccei, R. D., & Quinn, H. R. 1977b, Phys. Rev. Lett., 38, 1440
Raffelt, G. G. 1986, Phys. Lett. B, 166, 402
Raffelt, G. G. 2007, J. Phys. A, 40, 6607
Salaris, M., Domínguez, I., García-Berro, E., Hernanz, M., Isern, J., & Mochkovitch, R. 1997, ApJ, 486, 413
Salaris, M., García-Berro, E., Hernanz, M., Isern, J., & Saumon, D. 2000, ApJ, 544, 1036
Shifman, M. A., Vainshtein, A. I., & Zakharov, V. I. 1980, Nucl. Phys. B, 166, 493
Weidemann, V. 1968, ARA&A, 6, 351
Weinberg, S. 1978, Phys. Rev. Lett., 40, 223
Wilczek, F. 1978, Phys. Rev. Lett., 40, 279
Wood, M. A. 1992, ApJ, 386, 539
Zhitnitskii, A. P. 1980, Soviet J. Nucl. Phys., 31, 260