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AXION COOLING OF WHITE DWARFS

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ABSTRACT

The cooling rate of G117-B15A has been recently measured using asteroseismology techniques. It has been found that it is a factor of 2–6 higher than expected from current theoretical models. As the modifications introduced into the standard models to accommodate such a result seem not to be satisfactory enough, we propose to interpret this high cooling rate in terms of axion emission. We show in this paper that in order to account for the properties of G117-B15A, the mass of the axions should be $0.008(\pm 0.003) \cos^2 \beta$ eV, a quantity that is compatible with the bounds obtained from red giants and SN 1987A.

Subject headings: elementary particles — stars: oscillations — white dwarfs

1. INTRODUCTION

Axions are the natural consequences of the Peccei-Quinn mechanism (Peccei & Quinn 1977) to solve the CP problem of strong interactions (Weinberg 1978; Wilczeck 1978). As the axions proposed by Weinberg and Wilczeck were incompatible with the astrophysical and laboratory evidences, alternative models of axions weakly interacting with matter were constructed. One of them, the KSVZ axions, only couple to heavy quarks, not to leptons or light quarks (Kim 1979; Shifman, Vainshtein, & Zakharov 1990). The other, the DFS axions, only couple to electron and light quarks (Dine, Fiscler, & Srednick 1981). In both cases, the coupling is proportional to the mass and it is very weak. For instance, the mean free path of an axion of mass ~ 1 eV is 10^{23} cm under solar conditions (Anselm & Uraltsev 1982). Up to now, it has only been possible to put upper and lower bounds to the mass of the axions, see Raffelt (1990) for an extensive review, but the recent advances on white dwarf asteroseismology provide the possibility of obtaining a true measure of the axion mass.

White dwarfs represent the final evolutionary phase of stars with masses smaller than 8 $M_\odot$. Such stars have a rather simple structure: an inner degenerate core made of carbon and oxygen that acts like an energy reservoir and a thin nondegenerate envelope composed by two shells made of almost pure He and H, respectively, the last one being absent in some cases, that controls the flux of energy to the space. As these stars have exhausted their nuclear fuel, they can only contract and cool down. Some of them, the DAV or ZZ Ceti and the DBV, are variables. Their pulsation period increases with time as the star cools down (Baglin & Heyvaerts 1969; Winget, Hansen, & Van Horn 1983) at a rate $P/\dot{P} \propto T/\dot{T}$, where T is the temperature of the region of the period formation (there is also a radial dependence but it can be neglected in cool white dwarfs). Therefore, if axions appreciably contribute to the total energy outflow, the period will change faster than predicted.

Recently (Kepler et al. 1991a, b) it has been found that the rate of increase of the main pulsation period, $P \sim 215$ s, of G117-B15A, a ZZ Ceti star, is $\dot{P} = (12.0 \pm 3.5) \times 10^{-15}$ s s^{-1}, which is longer than the value predicted by the current CO models (Fontaine et al. 1991), $\dot{P} = (2\text{–}6) \times 10^{-15}$ s s^{-1}, thus implying that this star cools down more quickly than expected.

Two conventional ways of solving this discrepancy have failed. One assumes that the envelope is more transparent than was previously thought (Kepler et al. 1991a, b), whereas the other one suggests a smaller than standard heat capacity of the white dwarf interior, adopting an average mass number $\bar{A} \approx 33$ for the nuclei (Fontaine et al. 1991). In the first case, the problem is that the age of the disk should be 4.8 Gyr to account for the observed luminosity function, and the second solution is incompatible with the currently well established ideas of stellar evolution. Therefore, it seems worthwhile to assume that axions provide the extra cooling necessary to account for the observed cooling rates and to use asteroseismological data to measure the mass of the axions.

2. MODELS AND RESULTS

The white dwarf G117-B15A has a mass of 0.49 ± 0.03 $M_\odot$, an effective temperature of 13,000 K and a luminosity of log $L/L_\odot \simeq -2.3$. Its core is probably made of a mixture of carbon and oxygen, the last one being more abundant in the central regions (D'Antona & Mazzitelli 1989). The temperature of the core can be directly obtained from the luminosity, but it is model-dependent. Envelope models with different metal contents give different central temperatures as well as different cooling times for the same value of the luminosity (Table 1). Although the behavior of the envelopes of white dwarfs is not yet well understood, model A can be considered as the fiducial one. The masses of its hydrogen and helium layers (10^{-10} and 10^{-4} $M_\odot$, respectively) fit the constraints imposed by the pulsation properties of DA variables, as well as the evolution of the spectral features of DA and non-DA white dwarfs (Shipman 1989), and account for the luminosity function of such stars without invoking a very short age of the galactic disk. Model B has a too thick and opaque envelope. The mass of its hydrogen layer, $M_\mathrm{H} = 3 \times 10^{-4}$ $M_\odot$, although compatible with the results of evolutionary codes, is too large to account for the pulsation properties of DAV stars which demand $M_\mathrm{H} \leq 10^{-8}$ $M_\odot$. As metals quickly diffuse downwards in the high gravity field of white dwarfs, the value of Z is also too high. As a consequence, this model cools down very slowly. Models C and D do not meet such difficulties (although the mass of the hydrogen envelope is also too large in model C) but, due to their low metal contents, they cool down so quickly

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TABLE 1

PARAMETERS OF THE MODELS ($T_{\rm eff} \simeq 13{,}000$ K) AND RESULTING AXION PARAMETERS

Model	$\log L/L_\odot$	T_c(K)	$M_{\rm core}/M_\odot$	$M_{\rm H}/M_\odot$	Z	$\lvert T/\dot{T}\rvert$(yr)	$L_{\rm ax}/L_{\rm ph}$	$m_a/\cos^2\beta$ (eV)
A[a]	−2.30	1.8×10^7	0.5	10^{-10}	10^{-3}	9.98×10^8	2.6 1.45 0.5	1.13×10^{-2} 8.41×10^{-3} 5.65×10^{-3}
B[b]	−2.30	3.0×10^7	0.564	3×10^{-4}	2×10^{-1}	1.17×10^9	4.9 3.1 2.0	6.11×10^{-3} 4.86×10^{-3} 3.90×10^{-3}
C[b]	−2.28	1.3×10^7	0.564	3×10^{-4}	10^{-5}	4.97×10^8	1.50 0.74 0.29	1.86×10^{-2} 1.31×10^{-2} 8.19×10^{-3}
D[b]	−2.35	1.3×10^7	0.564	10^{-8}	10^{-5}	3.70×10^8	0.85 0.30 0.0	1.32×10^{-2} 7.87×10^{-3} 0.0

[a] Wood 1990.

[b] D'Antona & Mazzitelli 1989.

that white dwarfs would reach the luminosity function cutoff in 5–6 Gyr, a value that could be in conflict with the age of the galactic disk. Therefore, model B and models C and D, respectively, provide lower and upper bounds to the cooling rate of white dwarfs.

As white dwarfs are dense and cool, the dominant process of axion emission is bremsstrahlung of electrons by ions and electrons (DFS axions). The specific emissivity (Nakagawa et al. 1987, 1988) is given by

$$\epsilon = 1.08 \times 10^{23} \alpha \frac{Z^2}{A} T_7^4 F \text{ ergs g}^{-1}\text{ s}^{-1} , \tag{1}$$

where F, which depends on Γ, the Coulomb coupling constant, is a factor that takes into account the Coulomb effects in the degenerate plasma and α is the axion coupling constant which is related to the Yukawa axion-electron coupling constant, g_{ae}, and the mass of the axion through

$$\alpha = \frac{g_{ae}^2}{4\pi} \tag{2a}$$

$$g_{ae} = 8.5 \times 10^{-11} c_e \left(\frac{m_a}{1\text{ eV}}\right) , \tag{2b}$$

where $c_e = \cos^2\beta/N_t$, $N_t = 3$ and $\cos^2\beta$ is a free parameter in the DFS theory (Raffelt 1990). Taking into account that white dwarfs are essentially isothermal, the total axion luminosity can be written as

$$L_{\rm ax} = 2.15 \times 10^{56} \alpha T_7^4 \int_0^{M_{\rm wd}} \frac{Z^2}{A} F\, dm . \tag{3}$$

For the cases quoted in Table 1, this expression can be approximated by $L_{\rm ax} \simeq 9.2 \times 10^{56} \alpha T_7^4 M_{\rm wd}$.

As ZZ Ceti stars are not yet crystallized, the increase of the pulsation period can be easily estimated from

$$\frac{\dot{P}}{P} = -a \frac{\dot{T}}{T} = -a \frac{L}{C_v M_{\rm wd} T} , \tag{4}$$

where L is the total luminosity, C_v is the average heat capacity, and $M_{\rm wd}$ is the mass of the white dwarf. Given L and $M_{\rm wd}$, the remaining quantities can be easily obtained from standard white dwarf models. Therefore, if it is assumed that axions induce the anomalous cooling rate observed as an increase of the pulsation period, it is possible to write

$$\frac{L_{\rm ax}}{L_{\rm phot}} = \frac{\dot{P}_{\rm obs}}{\dot{P}_{\rm noax}} - 1 = \frac{\dot{T}_{\rm obs}}{\dot{T}_{\rm noax}} - 1 , \tag{5}$$

where the suffix "noax" means values obtained from current models (in which axions are not taken into account) and $L_{\rm ax}$ is the extra luminosity due to axions necessary to account for the observations. In case A, the value of $\dot{P}_{\rm noax}$ (Table 1) was obtained as an average of the oscillation properties of pure carbon white dwarfs ($\dot{P} \simeq 4.3 \times 10^{-15}$ s s^{-1}) and pure oxygen white dwarfs ($\dot{P} \simeq 5.6 \times 10^{-15}$ s s^{-1}). The upper and lower values have been obtained from these extreme values and the observational uncertainties. In cases B, C, and D, the value of the extra axion luminosity was obtained assuming that the proportionality constant, a, in equation (4) is equal to 2 (Kepler et al. 1991a), and the upper and lower values have been obtained from the observational uncertainties only. Smaller values of a would imply smaller axion masses which could even be zero (meaning that it is not necessary to invoke axions).

The equation (3) has been integrated for four white dwarf structures of 0.5 $M_\odot$ and for the central temperatures displayed in Table 1 and the value of the axion mass ($m_a/\cos^2\beta$ strictly speaking), has been adjusted to fit the values of $L_{\rm ax}/L_{\rm phot}$ of Table 1. The mass of the axions obtained in this way is $8.4 \times 10^{-3} \cos^2\beta$ eV, although the present uncertainties due to envelope models allow a range $0.0 \leq m_a/\cos^2\beta \leq 2 \times 10^{-2}$ eV. The question now is to elucidate if this axion mass is consistent with determinations based on other aspects of stellar evolution.

3. DISCUSSION AND CONCLUSIONS

To see the influence of axions in the cooling process of white dwarfs we have computed their luminosity function in the way described by Isern et al. (1991), but neglecting the chemical sedimentation induced by solidification which can introduce a considerable delay in the cooling process. We have found that the luminosity function is only modified in the region of luminosities, $-2.8 \leq \log(L/L_\odot) \leq -0.6$, remaining compatible

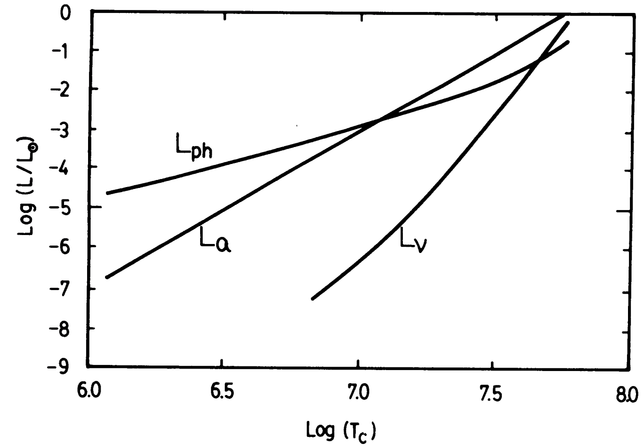

FIG. 1.—Photon luminosity, L_{ph}, neutrino luminosity, L_ν, and axion luminosity, L_a, for a carbon oxygen white dwarf of 0.6 $M_\odot$ vs. core temperature.

with the observations, and that the total cooling time is shortened by 0.8 Gyr, a quantity that is not negligible but that is small compared with the delay introduced by solidification. The reason of such a behavior can be seen in Figure 1, that displays the contribution of photons, neutrinos and axions to the luminosity. Neutrino emission, which scales as T^7, is dominant at high luminosities (or central temperatures) and photon luminosity, that roughly scales as $T^{2.5}$, is dominant at low luminosities. Axion emission, that scales as T^4, is only dominant in the short luminosity interval just mentioned, and the time spent by white dwarfs in this interval is only 0.85 Gyr. Notice that the increase of F due to the phonon contribution to axion emission, once solidification starts, is completely overwhelmed by the strong temperature dependence.

The evolution of red giants provides a very restrictive bound to the mass of axions. If axion emission were too efficient, the ignition line of helium would be shifted to higher densities or even suppressed, in contradiction with observations (Dearborn, Schramm, & Steigman 1986; Raffelt & Dearborn 1987). The maximum mass of axions compatible with the observed properties of red giants is $m_a \le 1.06 \times 10^{-2} \cos^2 \beta$ eV, a quantity slightly larger than the value found here, $8.43 \times 10^{-3} \cos^2 \beta$. This implies that, if the figure proposed in this paper were correct, axions could play an important role in the late phases of stellar evolution. Nevertheless, due to the temperature dependence of axion emission, the helium flash would never be suppressed but only delayed to slightly higher densities and temperatures. Here it is necessary to point out that the first detailed calculations were done with an incorrect emission rate $\epsilon \propto T^{2.5} e^{-\omega_0/T}$, where ω_0 is the plasma frequency, which provided a more restrictive value of g_{ae} than equation (1) (Raffelt 1990). In any case, it would be convenient to compute once more the influence of axion cooling on the properties of red giant stars.

The observed duration of the neutrino signal of SN 1987A also provides a very restrictive bound to the coupling constants of axions with nucleons (Burrows, Turner, & Brinkmann 1989, Mayle et al. 1988, 1989). In this case, the criterion is that axions cannot considerably shorten the observed neutrino pulse by more than a factor of $\frac{1}{2}$. This bound can be written as (Raffelt 1990)

$$m_a \le 0.6 \times 10^{-3\pm0.5}(0.6c_n^2 + c_p^2)^{-1/2}\ \mathrm{eV} \qquad (6)$$

$$c_p = -0.01 - 0.50 \cos^2 \beta$$

$$c_n = -0.09 + 0.33 \cos^2 \beta\,,$$

implying that the maximum mass of the axion is 5×10^{-3} eV, a quantity slightly smaller than that obtained here. This discrepancy cannot be considered as significant, at least for the moment, since the uncertainties introduced by numerical supernova codes, correction factors due to many-body effects and the few observed neutrinos from SN 1987A, on one hand, and the sensitivity of the temperature of the core of white dwarfs to the adopted model of envelope, on the other hand, are very large.

Finally we want to strengthen the need of continuing the observations aimed not only to improve the value of $\dot{P}$ for G117-B15A, but also to isolate any other effect contributing to it, as well as to constrain the physical properties of the envelope of this star.

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