The rate of cooling of the pulsating white dwarf star G117−B15A: a new asteroseismological inference of the axion mass

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ABSTRACT

We employ a state-of-the-art asteroseismological model of G117−B15A, the archetype of the H-rich atmosphere (DA) white dwarf pulsators (also known as DAV or ZZ Ceti variables), and use the most recently measured value of the rate of period change for the dominant mode of this pulsating star to derive a new constraint on the mass of axion, the still conjectural non-baryonic particle considered as a candidate for dark matter of the Universe. Assuming that G117−B15A is truly represented by our asteroseismological model, and, in particular, that the period of the dominant mode is associated with a pulsation g mode trapped in the H envelope, we find strong indications of the existence of extra cooling in this star, compatible with emission of axions of mass $m_a \cos^2 \beta = \left(17.4^{+2.3}_{-2.7}\right)$ meV.

Key words: asteroseismology – elementary particles – stars: individual: ZZ Ceti stars – stars: interiors – stars: oscillations – white dwarfs.

1 INTRODUCTION AND CONTEXT

Axions are hypothetical weakly interacting particles whose existence was proposed about 35 years ago as a solution to the strong charge-parity problem in quantum chromodynamics (Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978). They are well-motivated candidates for dark matter of the Universe, and their contribution depends on their mass (Raffelt 2007), a quantity that is not given by the theory that predicts their existence. There are two types of axion models: the KVSZ model (Kim 1979; Shifman, Vainshtein & Zakharov 1980), where the axions couple with photons and hadrons, and the Dine, Fischler & Srednicki and Zhimitshii (DFSZ) model (Dine et al. 1981; Zhimitskii 1980), where they also couple with charged leptons like electrons. In this paper, we are interested in DFSZ axions, i.e. those that interact with electrons. The coupling strength of DFSZ axions to electrons is defined through a dimensionless coupling constant, g_{ae}, which is related to the mass of the axion, m_a, through the relation:

$$g_{ae} = 2.8 \times 10^{-14} \frac{m_a \cos^2 \beta}{1 \text{ meV}}, \tag{1}$$

where $\cos^2 \beta$ is a free, model-dependent parameter that is usually set equal to unity.

Because theory does not place any constraint on the mass of axions, it must be inferred from terrestrial experiments or by using astrophysical and cosmological arguments. In particular, stars can be used to put constraints on the mass of the axion (Raffelt 1996). In this paper we focus on white dwarf stars, which represent the final evolutionary stages of low- and intermediate-mass stars (see Althaus et al. 2010a and references therein). White dwarfs are excellent candidates to test the existence of weakly interacting particles, as it was recognized early by Raffelt (1986) for the case of axions. Because white dwarfs are strongly degenerate and do not have relevant nuclear energy sources, their evolution is described as a slow cooling process in which the gravothermal energy release is the main energy source driving their evolution. At the typical temperatures and densities found in the cores of white dwarfs, the emission of DFSZ axions is supposed to take place at the deepest regions of these stars through Compton, pair annihilation and bremsstrahlung processes, although the last mechanism is the most relevant one (Raffelt 1986). In this last case, the axion emission rate is given by (Nakagawa, Kohyama & Itoh 1987; Nakagawa et al. 1988)

$$\epsilon_a = 1.08 \times 10^{23} \frac{g_{ae}^2}{4\pi} \frac{Z^2}{A} T_7^4 F(T, \rho) \text{ (erg g}^{-1}\text{ s}^{-1}). \tag{2}$$

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The mass of the axions determines how strongly they couple with electrons (equation 1) and, then, how large the axion emissivity is (equation 2). Since axions can (almost) freely escape from the interior of white dwarfs, their existence would increase the cooling rate, with more massive axions producing larger additional cooling. Isern et al. (2008) and Isern, Catalán & García-Berro (2009) included axion emissivity in evolutionary models of white dwarfs and found an improved agreement between the theoretical calculations and the observational white dwarf luminosity function. This provided the first, although preliminary, indication that axions might indeed exist.

Pulsating DA (namely stars with H-rich atmospheres) white dwarfs, also called ZZ Ceti or DAV stars, are the most numerous class of degenerate pulsators, with over 148 members known today (Castanheira et al. 2010). They are characterized by multiperiodic brightness variations caused by spheroidal, non-radial *g* modes of low degree ($\ell \leq 2$) with periods between 70 and 1500 s (Winget & Kepler 2008; Fontaine & Brassard 2008; Althaus et al. 2010a). The star G117−B15A (also called RY LMi and WD 0921+354) is the best studied member of this class of variables. This star shows oscillation periods Π (amplitudes *A*) of 215.20 s (17.36 milli modulation amplitude, mma), 270.46 s (6.14 mma) and 304.05 s (7.48 mma) that correspond to genuine eigenmodes (Kepler et al. 1982), and also shows the harmonic of the largest amplitude mode and two linear combinations. The 215 s mode is a $\ell = 1$ mode, as inferred by comparing the UV pulsation amplitude (measured with the *Hubble Space Telescope*) to the optical amplitude (Robinson et al. 1995). The rate of change of this period with time ($\dot{\Pi} \equiv d\Pi/dt$) is very small, although still detectable, $\dot{\Pi} \approx 4 \times 10^{-15}\,\mathrm{s\,s^{-1}}$ (Kepler et al. 2011). In fact, the stability of this period is comparable to that of the most stable millisecond pulsars (Kepler et al. 2005). G117−B15A has been the subject of numerous asteroseismological analysis; the more relevant ones being those of Bradley (1998), Córsico et al. (2001), Castanheira & Kepler (2008), Bischoff-Kim, Montgomery & Winget (2008a) and Romero et al. (2012). In particular, the approach of Romero et al. (2012) allowed us to solve the degeneracy of asteroseismological solutions for G117−B15A found in previous analysis by taking into account the predictions of full stellar evolution calculations on the structure of DA white dwarfs.

The rates of period change of pulsation *g* modes in white dwarfs are a very important observable quantity that can yield information about the core chemical composition. As a variable white dwarf evolves, its oscillation periods vary in response to evolutionary changes in the mechanical structure of the star. Specifically, as the temperature in the core of a white dwarf decreases, the plasma increases its degree of degeneracy so the Brunt–Väisälä frequency – the most important physical quantity in *g*-mode pulsations – decreases, and the pulsational spectrum of the star shifts to longer periods. On the other hand, residual gravitational contraction (if present) acts in the opposite direction, thus shortening the pulsation periods. The competition between the increasing degeneracy and gravitational contraction gives rise to the detectable temporal rate of change of periods. In particular, it has been shown (Winget, Hansen & van Horn 1983) that the rate of change of the pulsation period is related to the rates of change of the temperature at the region of the period formation, $\dot{T}$, and of the stellar radius, $\dot{R}$:

$$\frac{\dot{\Pi}}{\Pi} \approx -a\frac{\dot{T}}{T} + b\frac{\dot{R}}{R}, \tag{3}$$

where *a* and *b* are constants whose values depend on the details of the white dwarf modelling (however, both *a* and *b* $\approx$ 1). The first term in equation (3) corresponds to the rate of change in period induced by the cooling of the white dwarf, and it is a positive contribution, whereas the second term represents the rate of change due to gravitational contraction, and it is a negative contribution. In principle, the rate of change of the period can be measured by observing a pulsating white dwarf over a long time interval when one or more very stable pulsation periods are present in the light curves. In the case of pulsating DA white dwarfs, cooling dominates over gravitational contraction in such a way that the second term in equation (3) is usually negligible, and only positive values of the observed rate of change of period are expected.

Isern, Hernanz & García-Berro (1992) raised for the first time the possibility of employing the measured rate of period change in G117−B15A to derive a constraint on the mass of axions. By assuming that the rate of change of the 215 s period of G117−B15A is directly related to the evolutionary time-scale of the star, they considered the evolution of DA white dwarfs models with and without axion emissivity, and compared the theoretical values of $\dot{\Pi}$ for increasing masses of the axion with the observed rate of period change of G117−B15A at that time. Employing a semi-analytical treatment, they obtained $m_a = 8.7$ meV, assuming $\cos^2\beta = 1$. Later, Córsico et al. (2001) found $m_a\cos^2\beta \leq 4.4$ meV using a detailed asteroseismological model for G117−B15A. At the same time, the observational and theoretical uncertainties of the rate of period change were large enough that precluded to be conclusive about the necessity of an extra cooling mechanism such as axion emission. A few years later, Bischoff-Kim, Montgomery & Winget (2008b) derived an upper limit of 13.5–26.5 meV for the axion mass using an improved asteroseismological model for the star and a better treatment of the uncertainties involved.

Since the value of the measured $\dot{\Pi}$ for the 215 s period of G117−B15A has been changing over the years and now it seems to have reached asymptotically a rather stable value around $4 \times 10^{-15}\,\mathrm{s\,s^{-1}}$, and since the modelling of DA white dwarf pulsators has recently experienced major improvement (Althaus et al. 2010b), we feel that now is the right time to reanalyze the issue of the asteroseismological determination of the axion mass. This is precisely the aim of the present paper. Specifically, we employ the very detailed asteroseismological model for G117−B15A derived by Romero et al. (2012) and use the most recent measurement of the rate of change of the 215 s period to set new constraints on the mass of the axion. Preliminary results of this research have been presented in Córsico et al. (2011). The paper is organized as follows. In Section 2 we give a succint account of the measurements of the rate of period change in G117−B15A, while in Section 3 we briefly present our asteroseismological model of G117−B15A and describe in detail some propagation properties of the pulsation modes. In this section we also discuss at length the uncertainties involved in our analysis. In Section 4 we describe the impact that the inclusion of the axion emissivity in the asteroseismological model has on the pulsation modes. Section 5 is devoted to place an improved constraint on the axion mass. Finally, in Section 6 we summarize our findings and present our concluding remarks.

2 MEASUREMENTS OF $\dot{\Pi}$ FOR THE PERIOD AT 215 S

Kepler and collaborators have been observing G117−B15A since 1974 to measure the rate of period change with time for the largest amplitude periodicity at 215 s. This is a challenging endeavour that requires a huge investment of telescope time to achieve the necessary precision (Winget & Kepler 2008). After

about 15 years of scrutiny, the first detection of $\dot{\Pi}$ was reported by Kepler et al. (1991) using observations performed with the Whole Earth Telescope. They found $\dot{\Pi} = (12.0 \pm 3.5) \times 10^{-15}\,\mathrm{s\,s^{-1}}$, a value substantially larger than the published theoretical calculations of the rate of period change due to cooling available at that time, $\dot{\Pi} = (2\text{--}5) \times 10^{-15}\,\mathrm{s\,s^{-1}}$, which were based on DA white dwarf models with pure C cores. This discrepancy led Isern et al. (1992) to postulate that axion emission could provide the additional cooling necessary to account for the large observed rate of period change.

About a decade later, Kepler et al. (2000) reported a value $\dot{\Pi} = (2.3 \pm 1.4) \times 10^{-15}\,\mathrm{s\,s^{-1}}$ for the rate of change of the 215 s period. This value was about five times smaller than the value estimated in 1991, being the apparent reason a scatter of the order of 1.8 s present in the measured times of maxima (Kepler et al. 1995; Costa, Kepler & Winget 1999). The value of $\dot{\Pi}$ of Kepler et al. (2000) was the value used by Córsico et al. (2001) to infer, for the first time, an asteroseismological upper limit for the axion mass.

In 2005 – after a total of 31 years of observations – Kepler et al. (2005) obtained a 4σ measurement $\dot{\Pi}_{\mathrm{obs}} = (4.27 \pm 0.80) \times 10^{-15}\,\mathrm{s\,s^{-1}}$. Taking into account the proper motion effect, a rate of change of the 215 s period with time $\dot{\Pi} = 3.57 \pm 0.82 \times 10^{-15}\,\mathrm{s\,s^{-1}}$ was obtained. This value is consistent with the cooling rate of white dwarf models only if cores made of pure C or of a mixture of C and O are considered, and not with models in which cores made of heavier elements are used, as previously suggested (Kepler et al. 1990). This improved measurement of $\dot{\Pi}$ was used by Bischoff-Kim et al. (2008b) to infer new upper limits for the axion mass.

Very recently, Kepler et al. (2011) report the last measured value of the rate of period change, $\dot{\Pi}_{\mathrm{obs}} = (4.89 \pm 0.53) \times 10^{-15}\,\mathrm{s\,s^{-1}}$. Applying the proper motion correction, $\dot{\Pi}_{\mathrm{proper}} = (-0.7 \pm 0.2) \times 10^{-15}\,\mathrm{s\,s^{-1}}$, the rate of change of the 215 s period is $\dot{\Pi} = (4.19 \pm 0.73) \times 10^{-15}\,\mathrm{s\,s^{-1}}$. This is the value that we use in the present analysis to constrain the mass of the axion (see Section 5).

Finally, we would like to point out at this point of the discussion that a summary of the different measurements of $\dot{\Pi}$, and the variations reported over the years, is graphically illustrated in fig. 1 of Isern et al. (2010). It is quite apparent that the measured value of $\dot{\Pi}$ has now stabilized, being the variations between the different measurements due to a number of observational artefacts [see Isern et al. (2010) for further details].

3 ASTEROSEISMOLOGICAL MODEL FOR G117−B15A

Here, we briefly introduce the asteroseismological model for G117−B15A, and refer the interested reader to Romero et al. (2012) for further details. Romero et al. (2012) performed a detailed asteroseismological analysis of G117−B15A using a grid of DA white dwarf evolutionary models characterized by consistent chemical profiles for both the core and the envelope, and covering a wide range of stellar masses, thicknesses of the hydrogen envelope and effective temperatures. These models were generated with the LPCODE evolutionary code (see e.g. Althaus et al. 2005 and references therein). The evolutionary calculations were carried out from the zero-age main sequence through the thermally pulsing and mass-loss phases on the asymptotic giant branch (AGB), and finally to the domain of planetary nebulae and white dwarfs. The effective temperature, the stellar mass and the mass of the H envelope of our DA white dwarf models vary within the ranges $14\,000 \gtrsim T_{\mathrm{eff}} \gtrsim 9\,000\,\mathrm{K}$, $0.525 \lesssim M_* \lesssim 0.877\,\mathrm{M_\odot}$,

Table 1. Characteristics of G117−B15A as according to spectroscopy and according to the asteroseismological model of Romero et al. (2012).

Quantity	Spectroscopy	Asteroseismological model
T_{eff} (K)	11 430–12 500	$11\,985 \pm 200$
$M_*/\mathrm{M_\odot}$	0.530–0.622	0.593 ± 0.007
$\log g$	7.72–8.03	8.00 ± 0.09
$\log(R_*/\mathrm{R_\odot})$	–	-1.882 ± 0.029
$\log(L_*/\mathrm{L_\odot})$	–	-2.497 ± 0.030
M_{He}/M_*	–	2.39×10^{-2}
M_{H}/M_*	–	$(1.25 \pm 0.7) \times 10^{-6}$
$X_{\mathrm{C}}, X_{\mathrm{O}}$ (centre)	–	$0.28^{+0.22}_{-0.09}, 0.70^{+0.09}_{-0.22}$

Notes. The ranges of values in Column 2 have been derived by taking into account the spectroscopic analysis of Robinson et al. (1995), Koester & Allard (2000), Koester & Holberg (2001) and Bergeron et al. (1995, 2004). The quoted uncertainties in the asteroseismological model are the internal errors of our period-fit procedure.

Table 2. The observed (G117−B15A) and theoretical (asteroseismological model) periods and rates of period change.

Π^{o} (s)	Π^{t} (s)	ℓ	k
–	189.19	1	1
215.20	215.22	1	2
270.46	273.44	1	3
304.05	301.85	1	4
$\dot{\Pi}^{\mathrm{o}}$ ($10^{-15}\,\mathrm{s\,s^{-1}}$)	$\dot{\Pi}^{\mathrm{t}}$ ($10^{-15}\,\mathrm{s\,s^{-1}}$)	ℓ	k
–	3.01	1	1
4.19 ± 0.53	1.25	1	2
–	4.43	1	3
–	4.31	1	4

$-9.4 \lesssim \log(M_{\mathrm{H}}/M_*) \lesssim -3.6$, where the value of the upper limit of M_{H} is dependent on M_* and fixed by prior evolution. For simplicity, the mass of He was kept fixed at the value predicted by the evolutionary computations for each sequence.

In order to find an asteroseismological model for G117−B15A, Romero et al. (2012) sought the model that minimizes a quality function that measures the distance between theoretical (Π^{t}) and observed (Π^{o}) periods. The theoretical periods were assessed by means of the pulsation code described in Córsico & Althaus (2006). A single best-fitting model with the characteristics shown in Table 1 was found. For the first time, Romero et al. (2012) have broken the degeneracy of solutions for this star reported in previous studies. This degeneracy of the solutions involves the thickness of the H envelope, and depends on the k-identification of the three periods exhibited by G117−B15A. We found $k = 2, 3$ and 4 for $\Pi^{\mathrm{o}} = 215.20, 270.46$ and 304.05 s, respectively, as the only possible identification in the frame of our set of pulsation models. The second column of Table 1 contains the ranges of T_{eff}, $\log g$ and M_* of G117−B15A according to the spectroscopic studies of Robinson et al. (1995), Koester & Allard (2000), Koester & Holberg (2001), Bergeron et al. (1995, 2004) (see Romero et al. 2012). The parameters characterizing the asteroseismological model are shown in Column 3.

In Table 2, we compare the observed and theoretical periods and rates of change of the period. The model nearly reproduces the observed periods. This is particularly true for the case of the 215 s
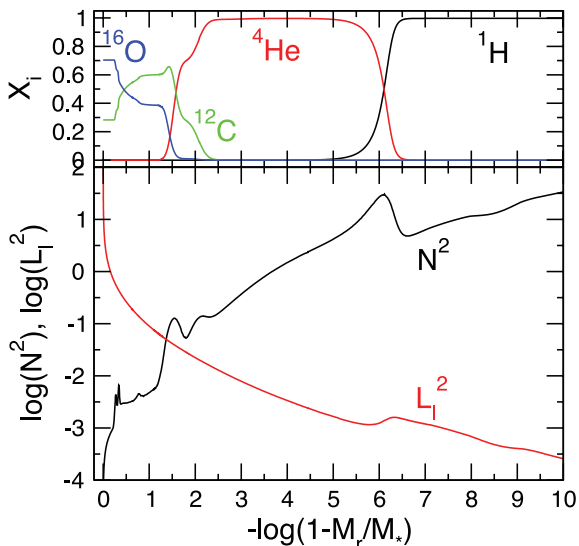
Figure 1. The internal chemical stratification (upper panel) and a propagation diagram (lower panel) of our asteroseismological model for G117−B15A.

period. The most important fact shown in Table 2 is, however, that the observed rate of change of the 215 s period is more than three times larger than the theoretically expected value. If we assume that the rate of period change of this mode reflects the evolutionary time-scale of the star, then the disagreement between the observed and theoretical values of $\dot{\Pi}$ would be a hint that G117−B15A could be cooling faster than that predicted by the standard theory of white dwarf evolution.

The internal chemical stratification and the propagation diagram – the run of the critical frequencies, namely the Brunt–Väisälä frequency, N, and the Lamb frequency, L_ℓ – of our asteroseismological model are shown in Fig. 1. Each transition between regions with different composition patterns produces clear and distinctive features in N, which are eventually responsible for the mode trapping properties of the model (Bradley 1996; Córsico et al. 2002). In the core region, there are several peaks at $-\log(q) \approx 0.4$–0.5 (at $q \equiv 1 - M_r/M_*$) resulting from steep variations in the inner CO profile which are caused by the occurrence of extra mixing episodes beyond the fully convective core during central helium burning. The extended bump in N^2 at $-\log(q) \approx 1$–2 is caused by the chemical transition of He to C and O resulting from nuclear processing in the prior AGB and thermally pulsing AGB stages. Finally, there is the transition region between H and He at $-\log(q) \approx 6$, which is smoothly shaped by the action of time-dependent element diffusion.

3.1 Mode trapping

Table 2 also reveals that the rate of period change for the $k = 2$ mode is substantially smaller than for the modes with $k = 1$, 3 and 4. This is because the modes have distinct mode trapping properties. Briefly, mode trapping is a mechanical resonance between the local pulsation wavelength of a pulsation mode with the thickness of one of the compositional layers (e.g. the H envelope or the He buffer). Mode trapping can reduce the rate of period change of a mode by up to a factor of 2 if it is trapped in the outer H envelope (Bradley 1996). The trapping properties of pulsation modes can be studied by examining their radial eigenfunction ($\delta r/r$) and weight function (w) (see Fig. 2). The weight function of a given mode allows us
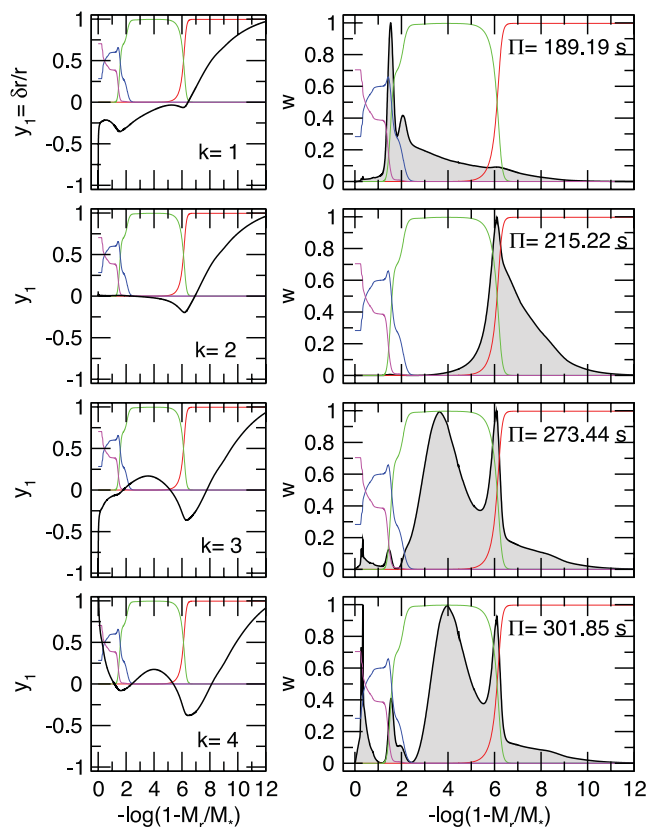

Figure 2. The radial eigenfunction y_1 (left-hand panels) and the normalized weight function w (right-hand panels, shaded) in terms of the outer mass fraction, corresponding to the modes with $k = 1$, 2, 3 and 4 of the asteroseismological model. The internal chemical abundances are also included for reference.

to infer the regions of the star that most contribute to the period formation (Kawaler, Winget & Hansen 1985). Clearly, $\delta r/r$ and w for the mode with $k = 2$ have appreciable amplitudes only in the region bounded by the He/H interface and the stellar surface, and so it is a mode strongly trapped in the outer H envelope. This property for the $k = 2$ mode holds also for all the models with structural parameters (M_*, M_H, T_{eff}) in the vicinity of the best-fitting model. Since this mode is concentrated closer to the surface, gravitational contraction (that is still appreciable in these regions) acts reducing the period change due to evolutionary cooling (Bradley 1996). This is the reason why the rate of period change of the $k = 2$ mode is small. In contrast, the remainder modes are either partially trapped between the He/H interface and the He/C/O chemical transition region (the $k = 1$ mode) or have non-zero amplitude through the entire star (the modes with $k = 3$ and 4). Since these modes are not affected by gravitational contraction, they have larger rates of period change.

The fact that the rate of period change for the $k = 2$ mode is somewhat affected by gravitational contraction, rendering it less sensitive to the evolutionary cooling, could lead us to conclude that the mode is not useful to derive constraints on the mass of the axion. However, it is important to note that the change of the period due to the increasing degeneracy resulting from cooling is still larger than the change due to residual contraction, and so $\dot{\Pi} > 0$. As a result, the period of the $k = 2$ mode is still sensitive to cooling and is quite useful for our analysis. This statement will be proven in Section 4.

3.2 Uncertainties in the theoretical value of $\dot{\Pi}$

Here, we assess the uncertainties affecting the value of the rate of period change for the $k = 2$ mode of our asteroseismological model. This is a crucial point in order to estimate the uncertainties in the derived axion mass. We shall focus on two main sources of errors: the poorly known $^{12}C(\alpha, \gamma)^{16}O$ nuclear reaction rate and the uncertainties in the parameters of the asteroseismological model (M_*, T_{eff} and M_H).

3.2.1 The central abundances of carbon and oxygen

The $^{12}C(\alpha, \gamma)^{16}O$ nuclear reaction plays a crucial role in the chemical structure of the cores of white dwarfs. Indeed, the final CO stratification of a newly born white dwarf strongly depends on the efficiency of this reaction rate towards the late stage of core helium burning (see e.g. Althaus et al. 2010a). In our evolutionary computations, the rate employed for the reaction $^{12}C(\alpha, \gamma)^{16}O$ is that of Angulo et al. (1999) (see Althaus et al. 2010b). Unfortunately, the rate of this reaction is not accurately known. Table 4 of Kunz et al. (2002) gives the estimated uncertainties of this rate according to their own study and the work by other authors. The uncertainties are between a factor of ~ 1.4 and ~ 0.6.

In order to estimate the uncertainties of the theoretical value of $\dot{\Pi}$ for the $k = 2$ mode introduced by our lack of knowledge of the value of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate, we should compute a large number ($\gtrsim 20\,000$) of DA white dwarf evolutionary models like those computed in Romero et al. (2012), employing different values of this nuclear reaction rate to account for its uncertainties. Afterwards, for each value of the adopted reaction rate period fits to G117−B15A to find a suitable asteroseismological model should be performed. Then, the comparison between the theoretical values of $\dot{\Pi}$ corresponding to the various best-fitting models should allow us to estimate the uncertainties in the rate of period change induced by the uncertainty in the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate. At present, due to the heavy computational load involved, this procedure is not feasible and is far beyond the reach of the present paper. Instead, we have performed a two-step approximate estimate as described below.

The first step consists in assessing the variation of the central abundances of C and O for different values of the nuclear reaction rate. To this aim, we computed two additional evolutionary sequences from the central He burning stage, assuming an enhanced and a reduced rate of the $^{12}C(\alpha, \gamma)^{16}O$ reaction. Specifically, we multiplied by a factor $f = 1.5$ and a factor $f = 0.5$ the rate of Angulo et al. (1999), thus comfortably covering the quoted range of uncertainty for this rate. In Table 3 we show the resulting central abundance of C and O in terms of the adopted rate. The case with $f = 1.0$ corresponds to the standard rate given by Angulo et al. (1999). Note that an increase of 50 per cent in the rate translates into a modest enhancement of ~ 12 per cent in the O abundance, although a reduction of 50 per cent in the rate results in a strong de-

Table 3. The central abundances by mass of ^{12}C and ^{16}O for a normal ($f = 1.0$), an enhanced ($f = 1.5$) and a reduced ($f = 0.5$) rate of the $^{12}C(\alpha, \gamma)^{16}O$.

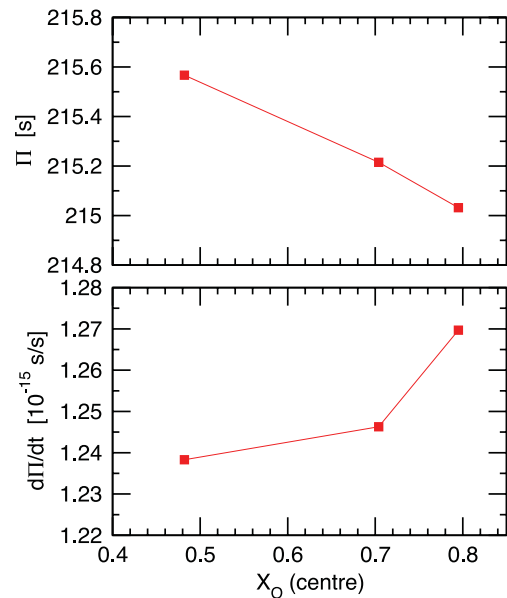| f	$X_{^{12}C}$	$X_{^{16}O}$
0.5	0.505	0.482
1.0	0.283	0.704
1.5	0.193	0.795

Figure 3. Upper panel: the pulsation period of the mode with $\ell = 1, k = 2$ in terms of the central abundance of ^{16}O. Lower panel: same as upper panel, but for the rate of period change.

crease of ~ 46 per cent in the O abundance, C being more abundant than O in this case (see Table 3).

In a second step, we estimate how the theoretical values of Π and $\dot{\Pi}$ of the asteroseismological model are affected when the central O is enhanced or reduced. To do so, we considered two white dwarf cooling sequences with different internal CO ratios, but keeping the same structure parameters as those of the asteroseismological model. Specifically, we artificially modified the O and C chemical profiles of the asteroseismological model at very high effective temperatures ($T_{eff} \sim 80\,000\,K$) in such a way that the unphysical transitory associated with this procedure finishes long before the models reach the instability strip of ZZ Ceti stars. The change consisted in replacing the values of $X_{^{16}O}$ and $X_{^{12}C}$ from the stellar centre to the edge of the homogeneous CO core corresponding to the case $f = 1$ (normal rate) by the values obtained for $f = 1.5$ (enhanced rate) and $f = 0.5$ (reduced rate) according to Table 3. After our ad hoc procedure, we allowed the models to cool down until they reached the effective temperature of G117−B15A. At this stage, we computed the periods and rates of period change.

The results for the mode with $k = 2$ are displayed in Fig. 3. Due to the fact that this mode is trapped in the outer H envelope, it is almost insensitive to the details of the CO core chemical profile (see Section 3.1). As a result, its pulsation period experiences a quite small decrease of ~ 0.25 per cent when the central ^{16}O abundance strongly increases from $X_{^{16}O} = 0.482$ to $X_{^{16}O} = 0.795$ (upper panel). This is at variance with the periods of the non-trapped modes ($k = 1$, 3 and 4, not shown in the figure), which undergo large changes, up to ~ 21 per cent in the case of the $k = 4$ mode. We found that the radial eigenfunction of the $k = 2$ mode remains almost unchanged for the very different central O abundances, but the opposite holds for the modes with $k = 1$, 3 and 4. In the lower panel of Fig. 3 we depict how the rate of period change for the $k = 2$ mode changes as a consequence of a varying central O abundance. Not surprisingly, the value of $\dot{\Pi}$ for this mode exhibits a modest increase of about 2.5 per cent. Again, this is because this mode is trapped in the outer envelope. In sharp contrast, the other modes considered experience quite a large changes, up to ~ 60 per cent for

the mode with $k = 4$. The increase in the rate of period change for the $k = 2$ mode for increasing central O abundances can be readily explained using a simple relation obtained using the Mestel cooling law (Mestel 1952): $\dot{\Pi} = (3-4) \times 10^{-15}(A/14)$ (s s^{-1}) (see Kepler et al. 2005).

The previous procedure, although not fully consistent, allows us to assess in an approximate way the impact of the uncertainties of the ^{12}C(α, γ)^{16}O reaction rate on the value of the rate of change of the mode with $k = 2$. We adopt an uncertainty $\varepsilon_1 \sim 0.03 \times 10^{-15}$ s s^{-1} for $\dot{\Pi}^t$ (Fig. 3). This is, indeed, a quite small uncertainty.

3.2.2 Asteroseismological model

Another source of error in the theoretical values of $\dot{\Pi}$ comes from the uncertainties in the asteroseismological model for G117−B15A. In this sense, we are able to account for the *internal* errors of the period-fit procedure. Examining the errors in the values of the stellar mass, the effective temperature and the thickness of the H envelope, we estimate that the uncertainty in the rate of period change for the mode with $k = 2$ is $\varepsilon_2 \sim 0.06 \times 10^{-15}$ s s^{-1} at most. This value is twice the error due to the ^{12}C(α, γ)^{16}O reaction rate.

4 THE RATES OF PERIOD CHANGE WITH AXION EMISSION

In the previous section we have presented results of periods and rates of period change for G117−B15A that do not take into account other energy source than gravothermal energy for the evolutionary cooling of the star. We have found that the theoretically expected rate of period change of the mode with $k = 2$ is markedly smaller than the value measured for G117−B15A, suggesting the existence of some additional cooling mechanism in this star. In this section we shall assume that this additional cooling can be entirely attributed to the emission of axions.

Following Córsico et al. (2001), we have computed a set of DA white dwarf cooling sequences incorporating axion emission. This has been done considering different axion masses and the same structural parameters (M_*, M_H) than those of the asteroseismological model. We have adopted a range of values for the mass of the axion $0 \leq m_a \cos^2 \beta \leq 30$ meV, and have employed the axion emission rates of Nakagawa et al. (1988). The evolutionary calculations including the emission of axions were started at evolutionary stages long before the ZZ Ceti phase to ensure that the cumulative effect of axion emission has reached an equilibrium value before the models reach the effective temperature of G117−B15A. In our models, axion emission occurs mainly in the innermost regions at $0 \lesssim -\log(q) \lesssim 1.6$, reaching a peak at $-\log(q) \sim 0.24$, although there is also a non-negligible contribution from regions at $1.6 \lesssim -\log(q) \lesssim 5$.

The pulsation periods for the modes with $\ell = 1$ and $k = 1, 2, 3$ and 4 of the asteroseismological model for increasing values of m_a are depicted in the upper panel of Fig. 4. The variation in the periods is negligible, in spite of the rather wide range of axion masses considered. This result, which was first noted by Córsico et al. (2001), implies that due to this additional cooling mechanism, the structure of the asteroseismological model itself is somewhat affected, but in such a way that, for a fixed value of the effective temperature, the pulsation periods are largely independent of the adopted value of m_a.

In the lower panel of Fig. 4 we display the rates of period change for the same modes. At variance with what happens with the pulsation periods, the values of $\dot{\Pi}^t$ are visibly affected by the additional
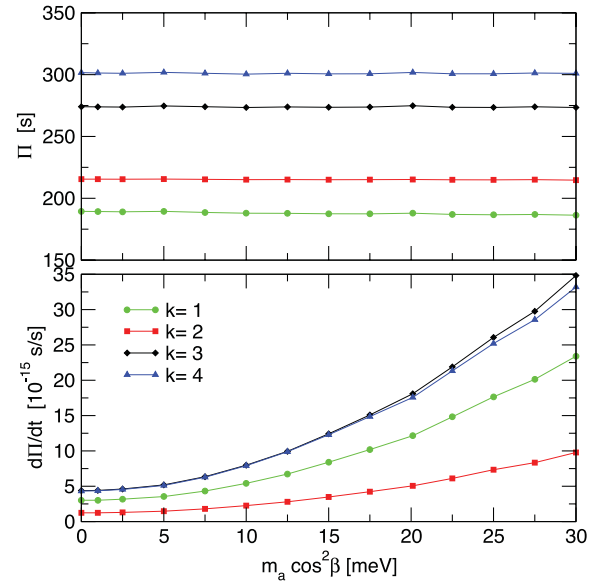

Figure 4. Upper panel: the pulsation periods of the modes with $\ell = 1, k = 1, 2, 3$ and 4, corresponding to our asteroseismological model for G117−B15A in terms of the axion mass. Lower panel: same as upper panel, but for the rates of period change.

cooling source, substantially increasing for increasing values of m_a. In particular, the rate of period change of the mode with $k = 2$, which is the relevant one in the present analysis, increases by a factor of about 10 in the range of axion masses considered. This convincingly demonstrates that, in spite of the fact that this mode is less sensitive to the evolutionary cooling of the star due to its mechanical properties (mode trapping), it is still an excellent tool to constrain the mass of the axion, as shown below.

5 INFERENCE OF THE AXION MASS

Here, we focus on the mode with $k = 2$, for which we have a measurement of its rate of period change. In Fig. 5 we display the theoretical value of $\dot{\Pi}$ corresponding to the period $\Pi = 215$ s for increasing values of the axion mass (red solid curve). The dashed curves embracing the solid curve represent the uncertainty in the theoretical value of $\dot{\Pi}$, $\varepsilon_{\dot{\Pi}} = 0.09 \times 10^{-15}$ s s^{-1}. This value has been obtained considering the uncertainty introduced by our lack of precise knowledge of the ^{12}C(α, γ)^{16}O reaction rate – $\varepsilon_1 \sim 0.03 \times 10^{-15}$ s s^{-1} (see Section 3.2.1) – and that due to the errors in the asteroseismological model – $\varepsilon_2 \sim 0.06 \times 10^{-15}$ s s^{-1} (see Section 3.2.2). We are assuming that the uncertainty for the case in which $m_a > 0$ is the same as that computed for the case in which $m_a = 0$. If we consider one standard deviation from the observational value, we conclude that the axion mass is $m_a \cos^2 \beta = \left(17.4^{+2.3}_{-2.7}\right)$ meV. This value is about four times larger than the upper limit found by Córsico et al. (2001), and compatible with the more recent results of Bischoff-Kim et al. (2008b). Note that *if* we assume that the anomalous rate of cooling of G117−B15A is *entirely* due to the emission of axions, this value is an indirect measurement of the mass of the axion, and not just an upper bound.

6 DISCUSSION AND CONCLUSIONS

In this paper we have derived a new value of the mass of the (up to now) elusive particle called axion. For this purpose we used a new asteroseismological model for G117−B15A, an archetypical
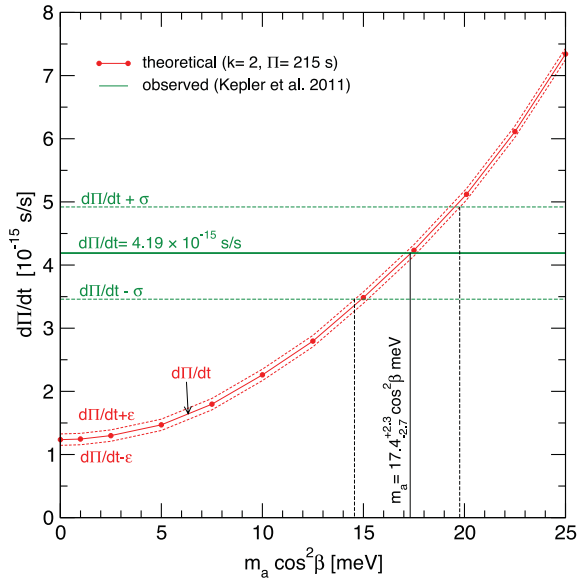
Figure 5. The rate of period change for the mode with $\ell = 1$, $k = 2$ of our asteroseismological model in terms of the axion mass (solid red curve with dots). Dashed curves represent the errors in $\dot{\Pi}$ due to *internal* uncertainties in the modelling and in the asteroseismological procedure. The horizontal green lines indicate the observed value with its corresponding uncertainties (Kepler et al. 2011).

ZZ Ceti star, derived from fully evolutionary computations of DA white dwarfs (Romero et al. 2012), and employed the most recent determination of the rate of period change for the largest amplitude mode ($\ell = 1$, $k = 2$, $\Pi \approx 215$ s) of this star (Kepler et al. 2011).

We first compared the observed rate of period change for this mode, $\dot{\Pi} = (4.19 \pm 0.73) \times 10^{-15}$ s s^{-1}, with the rate of period change of our asteroseismological model, $\dot{\Pi}^t = (1.25 \pm 0.09) \times 10^{-15}$ s s^{-1}, computed under the assumption that the cooling of this star is governed only by the release of gravothermal energy. The fact that the observed value is more than three times larger than the theoretically expected one strongly suggests that this star is cooling faster than the standard theory of white dwarf evolution predicts. We have carefully taken into account the possible sources of uncertainties in the theoretical value of the rate of period change. We found that the uncertainties affecting the poorly determined ^{12}C(α, γ)^{16}O reaction rate have no appreciable impact on the theoretical value of the rate of period change, because the mode is largely trapped in the outer H envelope of the asteroseismological model. This feature renders this mode almost insensitive to the fine details of the chemical structure of the CO core. We also accounted for the internal uncertainties of the asteroseismological model, and found that in this case also the errors are of modest magnitude, and substantially smaller than the errors affecting the observed value of $\dot{\Pi}$.

Next we assumed, following the idea first put forward by Isern et al. (1992), that the additional cooling necessary to account for the large observed rate of period change of G117−B15A can be attributed to axion emission. Following Córsico et al. (2001), we introduced axion emission in our asteroseismological model, considering a wide range of values for the axion mass (between 0 and 30 meV). We found that the periods do not change, but the rates of period change are strongly affected by an increasing value of the axion mass. We found that the mass of axion necessary to account for the observed rate of period change is $m_a \cos^2 \beta = \left(17.4^{+2.3}_{-2.7} \right)$ meV, where the errors in the axion mass come mainly from errors

in the measurement of the observed rate of period change. This value of the axion mass is substantially larger than the upper limit derived by Córsico et al. (2001), $m_a \cos^2 \beta \leq 4.4$ meV, but still in good agreement with the range of values obtained by Bischoff-Kim et al. (2008b), $12 \lesssim m_a \cos^2 \beta \lesssim 26.5$ meV.

We must emphasize at this point that the conclusion of our analysis of the existence of an extra cooling in G117−B15A due to axion emission, and the determination of a new value for the axion mass, is based on the fact that our set of full DA white dwarf evolutionary models predicts that the $k = 2$ mode (215 s period) is strongly trapped in the outer H envelope. Had this mode not been largely trapped in the outer layers, higher values of its rate of period change would have resulted, thus markedly weakening the potential of G117−B15A as a tool to constrain the axion mass. In this case, the uncertainties in our derived value for the axion mass should have been larger. We can estimate these uncertainties by considering the value of the rate of period change that the $k = 2$ mode would have if it were non-trapped. A very simple way to do this is to assume that the mode should have a $\dot{\Pi}^t$ similar to the typical value of the rate of period change of the non-trapped modes with $k = 1, 3$ and 4, that is $\langle \dot{\Pi}^t_{nt} \rangle \sim 3.9 \times 10^{-15}$ s s^{-1}. Thus, the value of $\dot{\Pi}^t$ for the $k = 2$ mode of the asteroseismological model could be $\sim 2.7 \times 10^{-15}$ s s^{-1} higher if it were a non-trapped mode. By taking into account this uncertainty, we cannot discard the non-existence of the axion.

All in all, we can safely conclude that, if the period at 215 s of G117−B15A is associated with a pulsation mode trapped in the H envelope, then the theoretical models strongly indicate that it would be necessary the presence of an extra mechanism of energy loss in this pulsating white dwarf, consistent with the existence of axions of $m_a \cos^2 \beta \sim 17.4$ meV. In the context of our full DA white dwarf evolutionary models, we found that the $k = 2$ mode is a trapped one for all the models characterized by structural parameters that place them in the neighbourhoods of the asteroseismological model. So, the trapping of this mode in the H envelope appears very likely in the models, thus reinforcing our conclusion about the existence of axions with the quoted mass value.

Besides G117−B15A, the DAV star R548 (ZZ Ceti itself) is known to exhibit a change in its pulsation period at ~ 213 s with time (Mukadam et al. 2003). This star is a potential objective to study axions by employing methods like the one presented in this paper. Based on observations from 1970 to 2007, Mukadam et al. (2009) have determined a value of $\dot{\Pi}$ between $(0.8 \pm 1.9) \times 10^{-15}$ s s^{-1} and $(4.3 \pm 1.2) \times 10^{-15}$ s s^{-1}, depending on the method employed. Although these values cannot be considered still as a *measurement* of the rate of period change, it is expected that a conclusive result in the near future will be obtained.

Isern et al. (2010) have drawn attention towards the possibility of employing also pulsating DB (with He-dominated atmospheres) white dwarfs (DBVs) to provide additional constraints on the axion mass. There exist two pulsating DBVs for which a rate of period change measured is expected to be available in the next years. One of them is EC20058−5234, a hot DBV star for which a preliminary estimate of $\dot{\Pi} = 8 \times 10^{-13}$ s s^{-1} for the period at 257 s has been reported (Dalessio et al. 2010). The other star is KIC 8626021, the recently discovered DBV star in the *Kepler* mission field (Østensen et al. 2011). According to the asteroseismological analysis of Bischoff-Kim & Østensen (2011) and Córsico et al. (2012), this star is also a hot DBV star. It will be further monitored with *Kepler* in the following years, which will probably allow the measurement of $\dot{\Pi}$.

Clearly, asteroseismology of pulsating DA and DB white dwarf stars constitutes a very exiting avenue to study particle physics,

and in particular axions. Future continued observations and possible measurements of their period drifts will allow us to confirm, although in an indirect way, the existence of axions.

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