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Non-luminous sources of cooling in pulsating white dwarfs

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Abstract

White dwarfs cool through several processes, including the emission of weakly interacting particles such as neutrinos. By their very nature, weakly interacting particles are difficult to observe. In pulsating white dwarfs, however, the effect they have on the cooling rate translates into an observable change in the pulsation periods. Namely, the periods of some modes vary on long time scales that are consistent with a rate of change due to cooling. Such changes in periods have been measured and have allowed us to place limits on the cooling of white dwarfs due to weakly interacting particles. We discuss the technique and present results from such studies, including an update on the mass determination of hypothetical weakly interacting particles called axions, candidate dark matter particles.

1 Introduction

Neutrino emission is expected to dominate white dwarf cooling down to the point where they reach the blue edge of the DBV instability strip ($\sim 28,000$K). In the degenerate, free electron rich interior of white dwarfs, the dominant process of neutrino production would be that of the decay of plasmons (Winget *et al.*, 2004). The fact that neutrino emission dominates the cooling into the DBV instability strip is important, as pulsations offer a way to measure the rate of cooling of a white dwarf. White dwarfs are g-mode pulsators. In the asymptotic limit, the period spacing reaches a constant spacing with each period obeying the relation (Unno *et al.*, 1989)

$$P_k = \frac{k\pi}{[\ell(\ell+1)^{1/2}]}\left[\int_{r_1}^{r_2}\frac{N}{r}dr\right]^{-1}, \tag{1}$$

where N is the Brunt-Väisälä frequency and the limits of integration are the turning points of the mode. In an actual star, the modes do not follow the limit perfectly (trapping occurs), but the relation above sets the average spacing of the observed modes. As the interior cools, the plasma becomes less and less compressible and also more degenerate. This causes the Brunt-Väisälä frequency to decrease and the period spacing to increase . An increase in spacing means a slow drift of each period toward higher values. This drift over time may be measured as a positive dP/dt or $\dot{P}$.

The drift itself is very slow ($\sim 10^{-13}$ s/s for DBVs and $\sim 10^{-15}$ s/s for DAVs) and so years and decades are required in order to obtain a measurement. Further complications arise from the fact that factors other than cooling influence the stability of the modes (for instance the convection zone for modes trapped near the surface). Only a handful of hot DBVs are known and measurements of $\dot{P}$'s for modes in those stars have been attempted, but so far have not helped place constraints on the emission rates of neutrinos in these stars. The first attempts at measuring $\dot{P}$'s for hot DBVs was with EC20058, but none of the measured $\dot{P}$'s in that star appeared to be attributed to the cooling of the interior (Dalessio *et al.*, 2013). More recent attempts were made with the DBV KIC 8626021, but again, no cooling rate measurement was possible for that star (Dalessio *et al.*, 2015; Zong *et al.*, 2017).

Similar ideas and techniques can be applied to other sources of non-luminous cooling. One particular source that has been considered is axion emission. Axions are particles that were introduced in order to solve an observed violation of charge parity conservation (Christenson *et al.*, 1964; Dine *et al.*, 1981), which cannot be explained within the framework of the standard model of particle physics. Axions became interesting in Astrophysics when Weinberg suggested that they may account for at least some of the dark matter (Weinberg, 1989).

Axions in the electron rich, degenerate interiors of white dwarfs would be produced via Bremmstrahlung events, where an axion is emitted in place of a photon when an electron passes near a nucleus (DFSZ axions). The energy emission rate of such an event depends on two parameters: the axion mass m_a and a coupling parameter β. Both are free parameters. More specifically,

$$\epsilon_a \sim m_a^2 \cos^4\beta. \tag{2}$$

Constraints placed on the mass of DFSZ axion truly are constraints placed on the combination $m_a \cos^2\beta$. For the remainder of this work, we shall use the term "axion mass" with that understanding.

When it comes to pulsating white dwarfs, it is important to note that depending on the axion mass (which again is a free parameter), axion cooling could be significant in DAVs as well as in hotter white dwarfs (Kim *et al.*, 2005). Since there are many more known DAVs than DBVs and they have been observed for longer, we have more measurements of $\dot{P}$'s available for DAVs than we do for DBVs, including some that appear to be due to cooling. In this work, we focus first on R548, with a new asteroseimsic fit of the star and a new limit placed on the axion mass. We then place the result in the context of other studies, including those based on the analysis of other DAVs and pull all the results together to give a picture of the current status of the determination of the axion mass based on $\dot{P}$'s of pulsating white dwarfs.

2 Asteroseismic fitting of R548

We present here an update on the fitting of R548 and corresponding limit on the axion mass, based on modes detected and identified since 2007. When we first looked at R548 in that context (Bischoff-Kim *et al.*, 2008a), we did not have all the identified triplets we now have. And also, there was no measurement of any $\dot{P}$'s available yet for that star. The periods we fitted, along with identified multiplets, are listed in

Table 1: List of observed period for R548 (Mukadam *et al.*, 2013) and their counterpart for the best fit model. The starred periods are members of multiplets.

Observed Period [s]	Calculated Period [s]	Mode identification (ℓ, k)
186.71*	186.47	(1,2)
212.95*	212.08	(1,3)
274.52*	274.24	(1,4)
318.*	318.07	(2,9)
335.	335.04	(2,10)

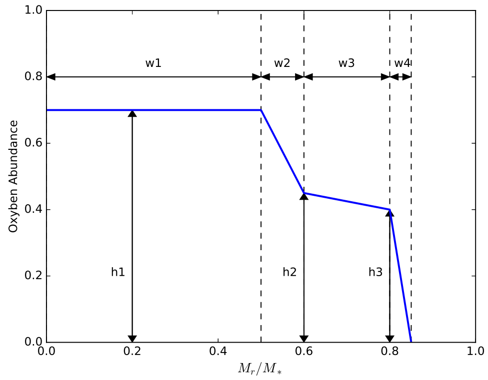

Figure 1: Parameterization of the oxygen abundance profile.

table 1.

Models were computed using the White Dwarf Evolution Code (Bischoff-Kim & Montgomery, 2018). We began the fitting process by limiting ourselves to the spectroscopic "box" ($T_{\rm eff} = 11990 \pm 200K$, $M_* = 0.590 \pm 26$ $M_\odot$, Bergeron *et al.* (2004)). We fitted the core first, fixing the envelope layer masses to canonical values ($M_{\rm He} = 10^{-2}$, $M_{\rm H} = 10^{-4}$). We parameterized the core as shown in Fig. 1. Of the width parameters, $w1, w2$ and $w4$ were free parameters (within bounds), while $w3$ was set to be equal to the difference between the size of the core and the sum of the three free parameters. The vertical height parameters obeyed $h1 \geq h2 \geq h3$ to force a monotonous decrease in the oxygen abundance. To the list of fitting parameters, we added the diffusion coefficient for the sharpness of the transition at the carbon/helium interface ($\alpha_{\rm He}$).

We forced the first three modes (Table 1) observed in the star to be $\ell = 1$, and the fourth mode to be $\ell = 2$ consistent with the observed multiplets. In the initial fits, the last mode fit clearly better as an $\ell = 2$ mode, so we adopted that mode identification in further fitting. Fits proved highly sensitive to the parameters $\alpha_{\rm He}$, $w1$, and $w2$, with essentially a single set of those three parameters that led to significantly better fits. We fixed these three parameters to those optimal values in further fitting.

We used those results as a setup for a 7 parameter optimization. We varied the effective temperature and mass within the bounds shown in Fig. 2, the hydrogen layer mass between 10^{-4} (canonical) and 10^{-7}, and the central oxygen abundance ($h1$) between 0.5 and 1.0. In addition, we varied the width parameters shown in Fig. 1 and discussed above. The chemical profiles and corresponding Brunt-Väisälä frequency are shown in Fig. 3. Fig. 2 shows the location of the best fits in the effective temperature-stellar mass plane. The best fit is indicated with a dot and listed in table 3. The value

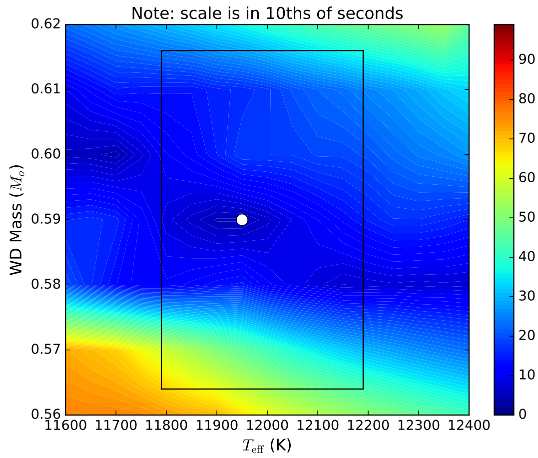

Figure 2: Contour map of quality of fit in the effective temperature-stellar mass plane. The rectangle marks the location of the one sigma spectroscopic box.

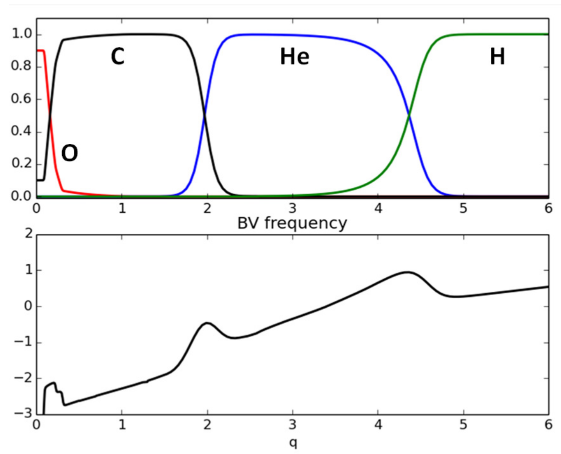

Figure 3: Chemical profiles (upper panel) and Brunt-Väisälä frequency (lower panel) for the best fit model listed in table 3. $q = -\log(1 - M_r/M_*)$ is a mass coordinate, equal to 0 at the center.

of the fitting parameter given in the table 3 is calculated using the equation

$$\sigma_{\rm RMS} = \sqrt{\frac{\sum_1^{n_{\rm obs}} (P_{\rm obs} - P_{\rm calc})_i^2}{n_{\rm obs}}}. \quad (3)$$

3 Limits on axion mass

We used the best fit model described in the previous section as a basis to compute $\dot{P}$'s to compare with observations. Mukadam *et al.* (2013) determined a $\dot{P}$ for the 213 second mode of $(3.3 \pm 1.1) \times 10^{-15}$ s/s. Without having any recourse to sources of cooling other than that due to the emission of photons, we find a $\dot{P}$ that is entirely consistent with the measured value (Fig. 4). However, there is room to add extra cooling in the models before the $\dot{P}$ rises above the error bars of the measured $\dot{P}$. In addition to the error bars on the measured $\dot{P}$, we estimated error bars on the $\dot{P}$'s calculated for the models. We used those formally determined based on similar models and approach in Kim (2007). We find that

Table 2: Axion mass determination over time, along with published $\dot{P}$'s. For G117-B15A the $\dot{P}$ refers to the 215 s mode, while for R548 it refers to the 213 s mode. For other stars, the modes are indicated.

Year	Star	Axion mass or $\dot{P}/10^{-15}$	Source
1991	G117-B15A	12.0 ± 3.5 s/s	Kepler *et al.* (1991)
1992	G117-B15A	$\lesssim 20$ meV	Isern *et al.* (1992)
2000	G117-B15A	2.3 ± 1.4 s/s	Kepler *et al.* (2000)
2001	G117-B15A	$\lesssim 6$ meV	Córsico *et al.* (2001)
2005	G117-B15A	3.57 ± 0.82 s/s	Kepler *et al.* (2005)
2008	G117-B15A	$\lesssim 12$ meV, 17.5 ± 7.5 meV	Bischoff-Kim *et al.* (2008b)
2010	G117-B15A	9.25 ± 1.35 meV, 5.3 ± 1.6 meV	Isern *et al.* (2010)
2011	G117-B15A	4.19 ± 0.73 s/s	Kepler (2012)
2011	PG 1351+489	$(2.0 \pm 0.9) \times 10^2$ (489 s mode)	Redaelli *et al.* (2011)
2012	G117-B15A	$17.4^{+2.3}_{-2.7}$ meV	Córsico *et al.* (2012a)
2012	R548	3.3 ± 1.1 s/s	Mukadam *et al.* (2013)
2012	R548	16.2 ± 5 meV	Córsico *et al.* (2012b)
2015	L19-2	4.0 ± 0.6 s/s (113 and 192 s modes)	Sullivan & Chote (2015)
2016	L19-2	$\lesssim 25$ meV	Córsico *et al.* (2016)
2016	PG 1351+489	$\lesssim 19.5$ meV	Battich *et al.* (2016)
2018	R548	$\lesssim 17$ meV	Present work

Table 3: Parameters for the best fit model.

Parameter	Value
$T_{\rm eff}$	11700 K
M_*	0.590 $M_\odot$
$M_{\rm He}$	10^{-2} (fixed)
$M_{\rm H}$	$10^{-4.3}$
$\alpha_{\rm He}$ (see text)	6 [a]
h_1 (Fig. 1)	0.90
h_2	0.40
h_3	0.20
w_1	0.20 [a]
w_2	0.21 [a]
w_4	0.20
$\sigma_{\rm RMS}$	0.424

[a]Fixed after initial fitting

we can add cooling due to axions of mass up to 17 meV before the calculated $\dot{P}$'s get too large to be consistent with the measured value.

To place the results in context, it is worth going back and summarize the body of work that was done using methods similar to those presented above. We do so in table 2, and in Fig. 5. PG 1351+489, one of the pulsating white dwarfs used to place limits on the axion mass, is a DBV and not a DAV. It should be noted that as such, the extra source of cooling is complicated by the fact that neutrino emission can still contribute. Neutrino emission rates were assumed exactly known and only the axion emission rate was allowed to vary in the models.

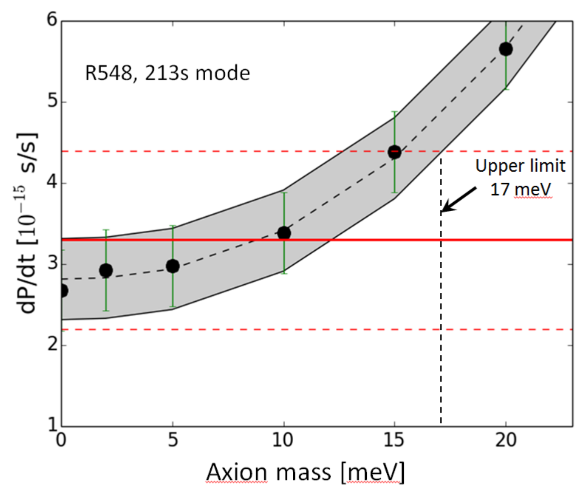

Figure 4: $\dot{P}$ for the 213 s mode as a function of axion mass for the best fit model. The horizontal line with the dashed lines on either side represents the measured value of the $\dot{P}$ for R548. The corresponding upper limit on the axion mass is indicated.

4 Conclusions

Because they are dark matter candidates, axions have been the subject of a great number of searches, both in physics and in astronomy. In this work, we revisited the axion mass limit based on $\dot{P}$'s for R548 and summarized the body of work done in determining the mass of the axion based on the effect of the additional cooling axions would cause on the periods. Across two groups and over three decades, the limits have

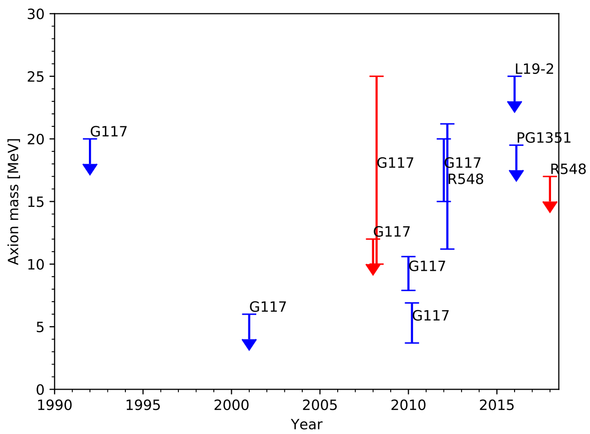

Figure 5: A plot of the limits on the axion mass over time, from table 2. The red and the blue colors distinguish two sets of limits determined independently from one another. Each limit is labeled with the star used in the study.

been remarkably consistent. While the limits cover a wide range, we can safely conclude that if the axion mass were much above 25 meV, we would have observed the effect of axion cooling in pulsating white dwarfs. It would be worth revisiting PG 1351+489 and turn the problem around: if we ignore axion cooling (or assume, until their existence is confirmed, that axions do not exist), what constraints can we place on plasmon neutrino cooling?

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