

Testing the internal physics of white dwarfs from their pulsational properties

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Abstract

White dwarfs are well studied objects. The relative simplicity of their physics allows to obtain very detailed models which can be ultimately compared with their observed properties. Among white dwarfs there is a specific class of stars, known as ZZ-Ceti objects, which have a hydrogen-rich envelope and show periodic variations in their light curves. The rate of change of the period is closely related to the star's cooling timescale, which can be accurately computed. In this paper we study the pulsational properties of G117-B15A and we use the observed rate of change of the period to impose constraints on the axion emissivity. This upper bound turns out to be $4 \cos^2 \beta$ meV. Although there are still several observational and theoretical uncertainties, we conclude that G117-B15A is a very promising stellar object to set up constraints on particle physics.

Introduction

Astrophysical arguments and observations have become a well known tool to obtain empirical information or constraints on existing or hypothetical elementary particles. One of the most important reasons for this is that the dense environment of stars is potentially a powerful source of low-mass weakly interacting particles. Since these particles subsequently escape from the star this mechanism constitutes a sink of energy that ultimately modifies the stellar lifetimes, thus allowing a comparison with the observed lifetimes. This is particularly useful since, as it is well known, the different non-standard theories leave open the possibility that several exotic particles (like axions or gravitons) could exist. Moreover, for several of these particles there are not yet laboratory experiments in the relevant mass range that could eventually impose tight constraints on their existence.

Among other weakly interacting massive particles, axions are the most promising candidates for non-baryonic dark matter and, therefore, a great deal of attention has been paid to them. There are two types of axion models, the KVSZ model and the DFSZ model. The first one couples to hadrons and photons whereas the second one also couples to charged leptons. The coupling strength depends on the specific implementation of the Peccei-Quinn mechanism through dimensionless coupling constants that are related to the mass. Both models do not set any constraint on the mass of the axion which must be obtained from experimental tests.

One way to constrain the mass of the DFSZ axion is the following (Isern et al. 1992, 1993): the observed rate of change of the pulsational period \dot{P}_{obs} and the rate of change of the period given by the models \dot{P}_{mod} when axion emission is considered are related through the following expression:

$$\frac{L_{\text{phot}} + L_{\text{ax}}}{L_{\text{phot}}} = \frac{\dot{P}_{\text{obs}}}{\dot{P}_{\text{mod}}} \quad (1)$$

since the axion luminosity is proportional to the mass of the axion, it is possible to obtain it if \dot{P}_{mod} is known.

Characteristics of G117-B15A

G117-B15A is a typical DA (hydrogen-rich) white dwarf star whose variability was first discovered by McGraw & Robinson (1976). Since then on, it has been monitored almost continuously. Its mass and effective temperature have been spectroscopically estimated to be $0.59 M_{\odot}$ and $11,620 \text{ K}$, respectively (Bergeron et al. 1995). Regarding the variability of this star, its observed periods are (Kepler et al. 1982) 215.2 , 271 and 304.4 s together with harmonics and linear combinations of the quoted periods. Of particular interest for this work is the fact that for the 215.2 s mode it has been possible to find its rate of change, \dot{P} . The first published value of \dot{P} (Kepler et al. 1991) was calculated using all the data obtained from 1975 to 1990 and was $\dot{P} = (12.0 \pm 3.5) \times 10^{-15} \text{ s s}^{-1}$, much larger than the theoretical predictions. Very recently, with a much longer time interval of acquired data, Kepler et al. (2000) re-determined \dot{P} finding a significantly lower value of $\dot{P} = (2.3 \pm 1.4) \times 10^{-15} \text{ s s}^{-1}$.

We have looked for a model that matches the three observed modes as good as possible. After having such a fiducial model, the computation of the theoretical \dot{P} for different values of the axion mass is rather straightforward (Córscico et al. 2001). Our results clearly indicate that the mass of G117-B15A should be very close to $0.55 M_{\odot}$ and that the hydrogen mass fraction present in the star should also be close to $M_{\text{H}}/M_{\star} = 10^{-4}$. In fact, the value we derive for the mass of G117-B15A is nicely bracketed by the independent spectroscopic determinations of Bergeron et al. (1995), who obtained $0.59 M_{\odot}$, and Koester & Allard (2000), who obtained $0.53 M_{\odot}$. The model that provides the best fit to the observations ($M_{\star} = 0.55 M_{\odot}$, $l = 1$, $k = 2, 3, 4$ and $\log M_{\text{H}}/M_{\star} = -4.0$) will be hereafter referred to as the fiducial model. The rate of change of the period for this model is $\dot{P} = 3.9 \times 10^{-15} \text{ s s}^{-1}$.

After examining all the possible uncertainties a few words are necessary to justify the discrepancy between this value and the measured rate of change of the period of the 215.2 s mode, $\dot{P} = (2.3 \pm 1.4) \times 10^{-15} \text{ s s}^{-1}$, and its computed value for the fiducial model. First, the theoretical uncertainties can account for a spread of about $\pm 1 \times 10^{-15} \text{ s s}^{-1}$. Second, the proper motion and parallax (Pajdosz 1995, Kepler et al. 2000) contribute as much as $\dot{P} = (9.2 \pm 0.5) \times 10^{-16} \text{ s s}^{-1}$. We thus conclude that taking into account all these uncertainties our preferred model could be safely considered as satisfactory and that our value for \dot{P} is fully consistent with the observed rate of change of the period.

The effects of enhanced cooling due to axion emission

Now, we turn our attention to compute the effects of axion emission on the evolutionary timescale of G117-B15A and its effect on the expected value of \dot{P} for the $l = 1$, $k = 2$ mode (Córscico et al. 2001). In order to do this in a self-consistent way we have run an additional set of cooling sequences with different axion masses (and considered the pulsational characteristics in the relevant effective temperature range) for our fiducial model, starting from the same initial conditions used for the models computed without axion emission. We have found that, even considering a wide range for the mass of the axion, the period of

the $l = 1$, $k = 2, 3$, and 4 modes show a very small variation for the whole considered interval. This is indeed a very fortunate situation that allowed us to employ the procedure of identifying first the structure of the fiducial model without considering axion emission and then to incorporate the axion emissivity. This would have not been the case should we have had to identify a white dwarf structure for each value of the axion mass. In such a case we would have had no fiducial model, thus complicating our analysis enormously. In sharp contrast with the small variation of the computed values of the periods of all the modes with the axion emissivity found previously, the value of \dot{P} for the three identified modes is extremely sensitive. Therefore, we can compute the value of \dot{P} of the $l = 1$, $k = 2$ mode of the fiducial model at $T_{\text{eff}} = 11,620$ K as a function of the mass of the axion. Now we can look for an upper limit to the axion mass by imposing that the value of \dot{P} should be lower than the observed value plus two times the standard deviation, that is, lower than $5.1 \times 10^{-15} \text{ s s}^{-1}$. A close inspection of the data shows that for this to be the case, the axion mass must be lower than $3.97 \cos^2 \beta \text{ meV}$, where $\cos^2 \beta$ is a free parameter in the theory of axions. This is the main result of the present work.

Conclusions

We have used this ZZ Ceti star to put constraints on the mass of the axion. Since G117-B15A is the most stable optical clock yet known, with a rate of period change of the 215.2 s mode of $\dot{P} = (2.3 \pm 1.4) \times 10^{-15} \text{ s s}^{-1}$, the cooling timescale of this white dwarf is well constrained (Kepler et al. 2000). This fact has allowed us to set up tight constraints on any additional cooling mechanism different to the standard ones. In particular we have obtained an upper bound to the mass of the axion which is $\simeq 4 \cos^2 \beta \text{ meV}$ at the 95% confidence level. This upper limit is a factor of 2.5 smaller than the previously existing limits.

From the above analysis it seems clear that in order to have more stringent upper limits to the mass of axions, we should have a smaller uncertainty in the observed value of \dot{P} , since the uncertainties in the models of white dwarf stars are clearly of lower relevance in this context. To this regard it is important to realize that at the 1σ level the stability of the dominant period of G117-B15A seems to rule out the existence of the DFSZ axion, provided that our current knowledge of the origin, structure and evolution of white dwarf stars turns out to be correct. Thus, clearly more observations are required but these observations are on their way.

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