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On the influence of axions on Mup

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Abstract. Axions and Axion Like Particles (ALPs) are weakly interacting particles that could be produced by thermal processes in stellar interiors and escape, taking energy out. In this way, ALPs could influence stellar evolution, modifying mainly evolutionary time scales and local temperatures. We have considered stellar evolution models, including axions that couple to photons and fermions, assuming the current stringest constraints for the corresponing axion coupling constants. We have focused on the evolution of intermediate mass stars, in particular, on those stellar masses which attain the physical conditions needed for carbon burning. Our results show that Mup is shifted up by nearly 2 $M_{\odot}$, with respect to models without axions. This is mainly due to the anticipation of the second dredged-up, that halts the increase of the carbon-oxygen core mass during the early-AGB phase. Note that a value of Mup higher than the current estimations, based on models without axions, may be in conflict with the semi-empirical initial-final mass relation and with the observed progenitor masses of Core Collapse Supernova. Little room seems to be left for axion production with the assumed coupling constants.

Key words. Stars: evolution – Stars: structure – Stars: white dwarfs – Stars: supernovae – Astroparticles: axions

1. Introduction

Axions are weakly interacting particles that were introduced to explain the absence of CP violation in the strong interactions (Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978). Later on, these particles and, in general, ALPs were proposed as dark matter candidates (Sikivie 2008). Up to now, none of the dedicated experiments has detected them. The search continues and it is remarkable that the next generation of ALP experiments, like ALPSII (Bähre et al. 2013) and IAXO (Giannotti et al. 2016), will focus on the range of parameters that is being tested by stellar models.

Stars are known to be good laboratories for fundamental physics. ALPs could be produced in stellar interiors and escape, carrying energy out. In case that a good, precise observable, is modified by ALPs, it may be possible to establish an upper bound to the energy loss rate and then, constrain ALP properties.

In the DFSZ axion model (Dine et al. 1981; Zhimitskii 1980), axions couple to photons and fermions. These couplings are characterized by the corresponding coupling constants, $g_{a\gamma}$ and g_{ae}, being the energy loss rate, in both interactions, proportional to the square of the coupling constants. In stellar interiors, axions that couple to photons are expected to be produced by the Primakoff process and, if they couple to electrons, mainly by the Compton and Bremsstrahlung processes (see Raffelt 1990)

Moreover, there are several astronomical observed properties that could be better explained including axions:

(1) The observed decrease of the pulsational period of some white dwarfs (WD). Early investigations by Isern et al. (1992) show that the period decrease could be better explained by axion cooling. In this case, the most important process is the Bremsstrahlung in degenerate conditions, and the derived limit for the axion coupling to electrons is $g_{ae} \approx 5.0 \times 10^{-13}$ (Isern et al. 1992; Córsico et al. 2012).
(2) The shape of the observed WD luminosity function seems to require an extra-cooling. As in the previous case, the effect is due to axions produced by the Bremsstrahlung process in degenerate conditions. The derived axion-electron coupling constant is $g_{ae} \approx 1.4 \times 10^{-13}$ (Isern et al. 2008; Miller Bertolami et al. 2014).

Other observed stellar properties allow to impose upper bounds to axion energy loss rates:

(1) The luminosity of the RGB tip derived from globular clusters. Due to axion cooling within the degenerate He-core, a higher He-core mass is required to attain the physical conditions for He-ignition. A higher He-core mass implies a higher luminosity at the tip of the RGB. This luminosity increase is limited by the observed RGB tip luminosity in globular clusters. Viaux et al. (2013) derived, based on precise models and observations of M5, $g_{ae} \leq 4.3 \times 10^{-13}$ at 95% CL.
(2) The R parameters derived for Globular Clusters. The R parameter is defined as the ratio of the number of stars in the HB divided by the number of stars in the RGB phase. In this case, the main energy sink is due to axions that couple to photons through the Primakoff process within the convective He-burning core. A faster comsumption of He is needed to compensate for the energy losses, decreasing the Horizontal Branch time. The Primakoff energy loss rate, in non degenerate conditions, depends on T^7 and ρ and does not affect the previous RGB phase. Ayala et al. (2014) derived, based on the average R parameter obtained from the observations of 39 globular clusters (Salaris et al. 2004), $g_{a\gamma} \leq 0.66 \times 10^{-10}$ GeV^{-1} at 95% CL (Straniero et al. 2015).

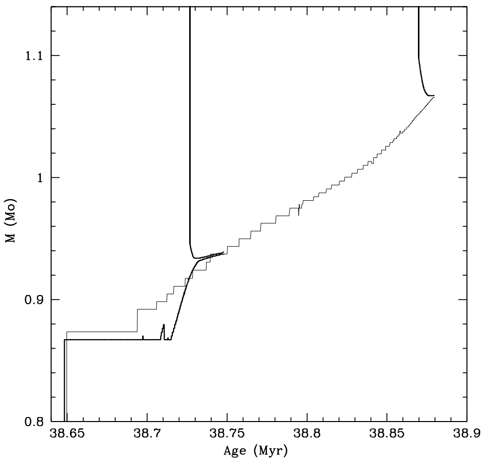

Fig. 1. Evolution along the E-AGB of the location of the He-shell and the bottom of the convective envelope for a 7.5 $M_\odot$ model, including (thick line) and excluding (thin line) axions.

Recently, the CAST collaboration (CAST collaboration et al. 2017) has obtained the experimental upper limit $g_{a\gamma} \leq 0.66 \times 10^{-10}$ GeV^{-1} at 95% CL.

2. Numerical models

Our approach in this work is to assume that DFSZ axions are produced through the mentioned processes (Primakoff, Compton and Bremsstrahlung), adopting for the coupling constants the previous limits, which are the

Table 1. Early-AGB phase

7.5 M⊙	No axions	Axions
M_{CO}	1.07 $M_{\odot}$	0.94 $M_{\odot}$
t_{E-AGB}	222300 yr	77600 yr

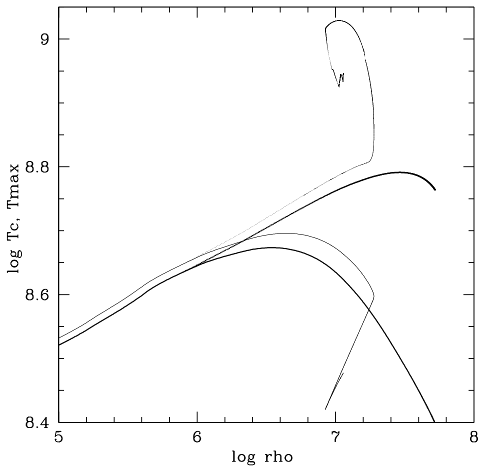

Fig. 2. Evolution of the maximum and central temperatures as a function of the central density (g/cm^3) for models including axions (see text) closed to Mup: the 9.0 $M_{\odot}$ model (thick line) cools down and the 9.2 $M_{\odot}$ model (thin line) experiences carbon burning (Mup). Note that in models without axions, the 7.5 $M_{\odot}$ model experiences carbon burning.

most updated and are also provided with a detailed study of the uncertainties.

The FUNS code (Straniero et al. 2006; Cristallo et al. 2009, 2011), modified to include the corresponding axion processes, is used for all the numerical simulations. The axion energy loss rate for the Primakoff is taken from Raffelt (1990), for the Compton from Raffelt & Weiss (1995), for the non-degenerate Bremstrahlung from Raffelt & Weiss (1995) and for the degenerate Bremsstrahlung from Nakagawa et al. (1987, 1988). Rates and interpolations have been revised by the authors.

All models are computed from the pre-MS to the TP-AGB phase or up to C-burning.

3. Results

First, we identify Mup for the standard, axion free, models with initial chemical composition Y=0.26 and Z=0.013. The obtained Mup, minimum mass that experiences carbon burning, is 7.5 $M_{\odot}$ (0.1 $M_{\odot}$ resolution). Then, we compute models including the axion energy loss rates. Our results show that models in the range 7.5 to 9 $M_{\odot}$ do not ignite carbon. As it is shown in Fig. 1 the main reason for that is the anticipation of the 2nd dredge-up during the early-AGB (E-AGB) phase. In Tab. 1 the corresponding E-AGB times for a 7.5 $M_{\odot}$ model with and without axions are shown. Axions decrease the E-AGB time by nearly a factor of 3, and change the mass of the CO core (M_{CO}) at the end of the E-AGB 0.94 $M_{\odot}$ instead of 1.07 $M_{\odot}$.

The anticipation of the 2nd dredge-up is due to the axion energy losses by Primakoff and Compton within the He-shell. Nuclear energy rates have to compensate the energy carried away by axions. As a consequence, the evolution is faster (Domínguez et al. 1999).

For models including axions, Mup is 9.2 $M_{\odot}$ as it is shown in Fig. 2, to be compared with Mup=7.5 $M_{\odot}$, in models without axions.

There are only two previous works that have analysed the evolution of stars in this mass range including axions, however none of them focus on Mup. One is our previous work (Domínguez et al. 1999), focused on the AGB phase, and in which no change of Mup was identified, and the other is by Friedland et al. (2013) in which they reported blue loops supression for $g_{a\gamma} = 0.88 \times 10^{-10}$ GeV^{-1}. Assuming the same $g_{a\gamma}$ and mass range we do not obtain any change in the blue loops.

4. Conclusions

When DFSZ axions, with the current coupling constants, are included in stellar models, Mup is shifted up by nearly 2 $M_{\odot}$, with respect to models without axions. This is mainly due to the anticipation of the second dredged-up caused by Primakoff and Compton energy loss rates operating within the He-shell.

Stars with masses smaller than Mup, 9.2 $M_{\odot}$ in models with axions, produce CO WDs, potential progenitors of Type Ia Supernovae (SNIa). Thus, axions may increase the number of systems contributing to SNIa and help explainin the observed rates of SNIa. For the same reason, the minimum mass for CCSNe progenitors would be greater than 9.2 $M_{\odot}$, in conflict with the observed progenitor masses of CCSNe (Smartt 2015). Considering also that a mass interval over Mup is expected to produce ONe WDs and electron capture SNe, the minimum mass for CCSNe progenitor would be even greater.

Note that uncertainties in the ^{12}C + ^{12}C nuclear reaction rate (Straniero et al. 2016) would also shift Mup.

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