

Impact of Axions on the Minimum Mass of Core Collapse Supernova Progenitors

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In this study we include axions in stellar evolution models adopting the current stringest constraints for their coupling to photons and electrons. We obtain that the minimum stellar mass of Core Collapse Supernova (CCSN) progenitors is shifted up by nearly $2 M_{\odot}$. This result seems to be in tension with the observationally derived minimum mass of CCSN progenitors.

1 Introduction

Stars are known to be good laboratories for particle physics. Axions and Axions Like Particles (ALPs) may be produced in stellar interiors and freely escape, carrying energy out and thus, modifying stellar evolution.

Axions are weakly interactive particles that were introduced to explain the absence of CP violation in the strong interactions [1, 2, 3]. Later on, these particles and, in general, ALPs were proposed as dark matter candidates [4]. In well motivated axion models, like the DFSZ [5, 6], 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 rates in these interactions proportional to the square of the coupling constants. In stellar interiors, ALPs 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 [7]).

The ALP stellar approach consists of constraining the coupling strengths in order to avoid conflicts with astronomical observations. Moreover, there are also astronomical observations that could be better explained considering an extra-energy sink (see i.e. [8]). Among them, the observed decrease of the pulsational period of some white dwarfs [9, 10] and the shape of the observed WD luminosity function [11, 12]. In both cases the derived limits are for g_{ae} .

In this work we study the influence of axions on the value of the minimum stellar mass that experiences central carbon burning, M_{up} ([13]) and so, the minimum possible stellar mass that may produce a CCSN. Among CCSNe, type II-P are those expected to come from the evolution of single stars. Their bright supergiant progenitors are identified on the corresponding images taken at the SN locations before the explosion, and the progenitor masses estimated from the

luminosities of these supergiants. Masses in the range 7-10 $M_{\odot}$ have been estimated for the type II-P SNe 2003gd, 2005cs, 2009md, 2006my, 2012A and 2013ej (see [14]), while theoretical predictions for the minimum masses of CCSNe are above 9-10 $M_{\odot}$. As we will show, the presence of axions coupled to photons and electrons would increase the progenitor mass expected by these current prediction, possibly beyond observational constraints.

2 Numerical simulations & Results

We consider DFSZ axions produced through the mentioned processes (Primakoff, Compton and Bremsstrahlung), adopting for the coupling constants the most updated limits that are also provided with corresponding uncertainties:

- $g_{ae} \leq 4.3 \times 10^{-13}$ at 95% CL [15], based on the luminosity of the RGB tip derived from globular clusters (GCs).
- $g_{a\gamma} \leq 0.66 \times 10^{-10} \text{ GeV}^{-1}$ at 95% CL, based on the R parameter derived for GCs [16, 17], and being also the the experimental upper limit obtained by the CAST collaboration [18].

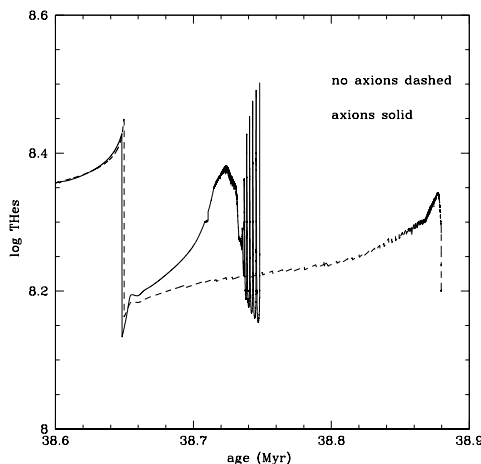


Figure 1: Evolution in time of the maximum temperature within the He-shell for the reference model of 7.5 $M_{\odot}$, without axions (dotted line), and for a model with the same mass, including axions (solid line).

The FUNS code [19, 20, 21], 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 [7], for the Compton from [22], for the non-degenerate Bremsstrahlung from [22] and for the degenerate Bremsstrahlung from [23, 24]. Rates and interpolations have been revised by the authors.

We compute models in the mass range 7 to 11 $M_{\odot}$, with a resolution of 0.2 $M_{\odot}$, and assuming solar initial chemical composition, $Z = 0.013$ & $Y = 0.26$. All models are computed from the pre-MS to central C-burning, or alternatively, to CO core cooling (along the AGB phase).

We have first identified, as a reference, the minimum initial stellar mass needed for central C-burning, M_{up} , without axions, and it turns out to be $7.5 M_{\odot}$. Then, we compute models including the previous axion energy loss rates and we find that models in the mass range 7.5 to $9.1 M_{\odot}$ do not ignite carbon, being M_{up} $9.2 M_{\odot}$.

The main reason of this shift of M_{up} by $1.7 M_{\odot}$ is the smaller CO core developed, for the same initial stellar mass, by models that include axions. The growth of the CO core, during the so called early-AGB phase, is halted earlier because the evolution is faster: nuclear energy has to compensate the axion energy losses within the He-shell. This effect was discussed by some of us, in another context, some years ago ([25]). The different time-scales are clearly seen in Fig. 1. The early-AGB time is reduced by the axion effect, from 2.223×10^5 yrs to 7.76×10^4 yrs which results in final CO core masses of $1.066 M_{\odot}$ for the reference model, and $0.937 M_{\odot}$ for the model with axions.

We identify both, Compton and Primakoff, as being the most important processes and equally relevant. For example, when only Primakoff is included M_{up} is $8.4 M_{\odot}$, so M_{up} is shifted up, with respect to models without axions by $0.9 M_{\odot}$ instead of by $1.7 M_{\odot}$ when Compton is also included.

However, the change in the CO core mass for a given total stellar mass is not the only factor that influences M_{up} . We find that an increase of the final CO core mass by $0.113 M_{\odot}$, with respect to that of the reference model, is needed for C-burning. Axions cool the degenerate inner part of the CO core and this is due the Bremsstrahlung process. In fact, when Compton and Primakoff are included but Bremsstrahlung is not included, M_{up} is $9.0 M_{\odot}$ instead of $9.2 M_{\odot}$.

3 Conclusions

The production of DFSZ axions in stellar interior, assuming the current stringest upper limits for the coupling constant values, represents an important energy sink. In this work we have focused on the evolution of stellar masses that are close to the observed minimum progenitor mass for CCSNe. Assumed values for g_{ae} and $g_{a\gamma}$ are 4.3×10^{-13} and $0.66 \times 10^{-10} \text{ GeV}^{-1}$, respectively. Our main result is that the minimum stellar mass that experiences central carbon burning, M_{up} , is shifted up by $1.7 M_{\odot}$, from $7.5 M_{\odot}$ for the reference model to $9.2 M_{\odot}$ when axions are included, implying that:

- Stars with masses smaller than $9.2 M_{\odot}$, would produce CO WDs, potential progenitors of Type Ia Supernovae (SNIa). This may help to solve the problem related with the predicted low theoretical SNIa rates as compare with the rates derived from observations (see [26] for a review).
- CCSNe would only be produced by stars with masses greater than $9.2 M_{\odot}$. In fact, considering that a mass interval over M_{up} is expected to produce ONe WDs and electron capture SNe, the minimum mass for CCSNe progenitor would be even greater. This would be in conflict with the observationally derived minimum progenitor masses of CCSNe, $7\text{-}10 M_{\odot}$ [14], .

It is remarkable that the next generation of dedicated axion experiments, like ALPSII [27] and IAXO [28], will focus on the range of parameters that is being tested by stellar models, like those considered in this work.

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