A new Constraint on the Axion-Photon Coupling

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2013-04/giannotti_maurizio

We show that the emission of axions coupled to photons with $g_{a\gamma} \geq 0.8 \times 10^{-10}\text{GeV}^{-1}$ would eliminate the blue loop stage for stars in the mass window $\sim 8 - 12\ M_{\odot}$. This is excluded by observations of the blue sequences and of Cepheid stars.

1 Introduction

Stars are efficient laboratories to study the properties of *light, weakly interacting* particles. Observations require, in fact, that the energy drain cannot be too different from the Standard Model (SM) predictions [1]. This has provided a great deal of understanding in different sectors of particle physics beyond the standard model, including nonstandard neutrino properties [2, 3, 4], majorons [5], novel baryonic or leptonic forces [6], and more recently unparticles [7] and extra-dimensional photons [8].

An interesting example of light, weakly interacting particle is the axion [9, 10, 11, 12] and, more generally, Axion Like Particles (ALPs). These are pseudoscalar particles coupled to photons through the interaction term

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} aF\tilde{F}\,. \tag{1}$$

Current experiments are probing the region of $g_{a\gamma} \sim 10^{-10}\text{GeV}^{-1}$ and it is common to measure the coupling strength in terms of the dimensionless parameter $g_{10} = g_{a\gamma}/(10^{-10}\text{GeV}^{-1})$.

Astronomical observations can provide very useful insights in our knowledge of this coupling. In particular, the analysis of globular cluster stars in the Horizontal Brunch (HB) in comparison with the number of stars in the Red Giant (RG) phase leads to the strong bound $g_{10} \leq 1$, valid for masses below a few 10 GeV, that is for axions light enough to be efficiently produced in the stellar core [13, 14].

A slightly stronger bound, valid however in a quite smaller ALP mass range, is derived from the terrestrial experiment CAST (Cern Axion Solar Telescope) [15], which has excluded the region $g_{10} \geq 0.88$ for an ALP mass below 0.02 eV.

The strongest bound to date, however, is derived by the analysis of the evolution of massive stars [16, 17]. These stars, while burning helium in their core, evolve into a stage called the *blue loop* during which they contract and expand again. In the Hertzsprung-Russell (HR) diagram, this appears as a loop which extends toward the left (see Figure 1), in the region of higher surface temperature (*blue*) before turning back in the colder (*red*) region to the right side of the diagram.

The existence of the loop is corroborated by astronomical observations. In particular, the loop is essential to account for the observed Cepheid stars.

In [16] it was shown that the additional cooling induced by axions coupled to photons would eliminate this evolutionary stage for stars of mass between 8 and 12 $M_\odot$, unless $g_{10} < 0.8$.

Here we will discuss this new constraint on the axion-photon coupling and provide some insight on how the blue loop stage can be used as a sensitive probe for exotic processes and weakly interacting particles.

2 Blue loop and particle physics

At the end of the H-burning stage (main sequence) stars expand and cool down. During the following stage the star burns helium in the core and hydrogen in a shell.

Figure 2 (top curve) shows the surface temperature evolution of a $9.5M_\odot$ star from the main sequence to the end of the He-burning stage. The transition from H- to He- burning happens at $t_{\rm MS} \simeq 23.8$ Myr and corresponds to the (relatively fast) migration toward the right of the HR diagram shown in Fig. 1 (pre-blue loop stage).

As shown in Fig. 2, at $t_{\rm BL} \simeq 25.4$ Myr the surface temperature rapidly increases and the star contracts. This is the start of the blue loop stage, a migration toward the left of the HR diagram. Simulations have shown that this happens when the hydrogen has burned enough in the shell and the H fraction has reached an *almost step-like profile* [18, 19, 20].

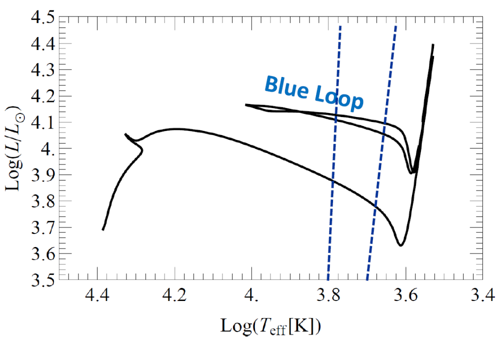

Figure 1: Evolution in the HR diagram of a 9.5 $M_\odot$ star. The region between the two dashed lines is the instability strip, where the Cepheid variables are found.

Finally, after another 1 Myr or so, the surface temperature begins to decrease again and the star starts its journey back to the right of the HR diagram. Physically, the end of the stellar contraction and the *turning back* in the HR diagram, say at $t = t_{\rm back}$, is caused by the dropping of the helium content in the core below some threshold value [18].

It is quite remarkable, for our analysis, that the set and the end of the blue loop stage are determined by the physics of the shell and of the core respectively. Consequently, an exotic process which is efficiently produced in the core but not in the shell would cause a shortening of the blue loop stage without significantly changing $t_{\rm BL}$ (see Fig. 2).

Observationally, the shortening of the blue loop stage corresponds to a reduction of the number of *blue* with respect to *red* stars of a given luminosity (see [21] for a recent analysis of the observations).

More significantly, if the ratio of the time scales of the core and shell burning changes enough, the blue loop stage may disappear altogether [22] and that would have the additional consequence of leaving us without an explanation for the observed Cepheid stars at that particular luminosity. Given the good level at which the Cepheid stars are known, the complete disappearance of the blue loop stage, even for a small range of luminosities, is observationally forbidden.

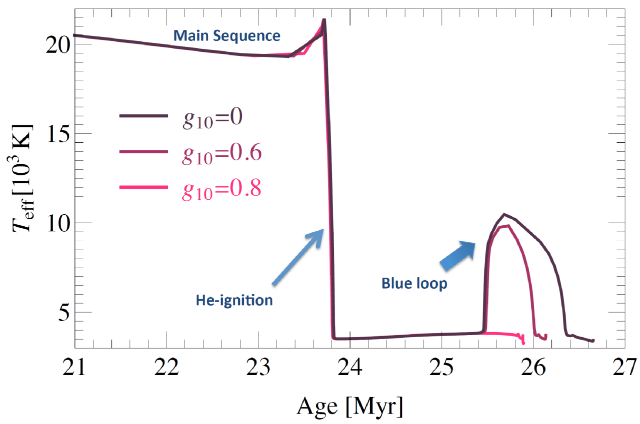

Figure 2: Surface temperature evolution of a 9.5 $M_\odot$ star for three different values of the axion-photon coupling.

This fact can be used to constraint new physics, in particular novel cooling mechanisms which are strongly dependent on the temperature and efficient at relatively low densities.

As a simple criteria, we require that an additional cooling mechanism must always satisfy $t_{\rm back} \geq t_{\rm BL}$ to guaranty the existence of the blue loop. This may be more conveniently restated in terms of the He-burning stage lifetime as follows: an additional cooling is phenomenologically forbidden if

$$t'_{\rm He}/t_{\rm He} \leq (t_{\rm BL} - t_{\rm MS})/(t_{\rm back} - t_{\rm MS})\,. \tag{2}$$

The exact value for the right hand side should be determined by numerical simulations and depends on the star mass and, possibly, other stellar parameters. Our simulations with the publicly available stellar evolution code MESA [23] show that a value of 0.8 is a fairly conservative choice for stars of initial mass around 10 $M_\odot$. A more detailed analysis is in preparation.

3 Discussion and conclusion

The blue loop criteria described above is very efficient in constraining the axion-photon coupling [16].

Axions (and, more generally, ALPs) can be produced in stars through the Primakoff process, $\gamma + Ze \to a + Ze$, which is efficient at relatively low densities and high temperatures, that is, in an environment typical of the core He-burning stars. After being produced, they freely stream out of the star carrying energy away and providing, therefore, a very efficient cooling mechanism. This results in a shortening of the He-burning stage.

In the case of low mass HB stars, it is possible to show that, under reasonable assumptions, $t'_{\rm He}/t_{\rm He} \simeq 1/(1 + 0.4g_{10}^2)$ [1]. Preliminary simulations indicate that the above scaling formula is reasonably correct also in the case of more massive stars.

From the discussion in the previous section we know that a 20 % reduction of the (central) He-burning time would eliminate the blue loop stage for stars in the 10 $M_\odot$ mass range and is, therefore, observationally forbidden. This corresponds to the requirement that $g_{10} \geq 0.8$, a result confirmed by the numerical simulation shown in Fig. 2.

This bound is somewhat more stringent than the one from HB stars. In addition, since the core temperature of more massive stars is higher than that in low mass stars, the bound extends to higher ALP masses.

Only recently massive stars have been considered to study particle physics [24]. This work shows that they may be quite efficient laboratories.

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