Mem. S.A.It. Vol. 93, 11

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Stars and physics beyond the Standard Model

Axions and Axion Like Particles

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Received: 16 January 2022; Accepted: 30 May 2022

Abstract. Weak interactive particles with mass up to a few hundreds of keV may be produced through thermal processes occurring in hot stellar interiors. We investigate the effects of the production of axion-like-particles, on the observable properties of stars, and we show how these effects may be exploited to infer the existence and eventually to understand the physics of feebly interactive particles which are not accessible in laboratory experiments.

Key words. Astroparticle physics – Stars: interiors – Stars: supernovae progenitors – Galaxy: globular clusters

1. Introduction

Axions and, more in general, axion-like-particles (ALPs) emerge in different extension of the *Standard Model* as Pseudo-Goldstone bosons of some broken global symmetry. Originally, axions were proposed as a solution of the so-called strong CP problem, i.e., the absence of CP violation in the strong interactions (Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978). The existence of such particles could also account for most or all of the dark matter in the Universe. In particular, axions with masses of a few μeV would be good cold dark matter candidates (Sikivie 2008; Kawasaki & Nakayama 2013), while for masses larger than 60 meV they would attain thermal equilibrium at the QCD phase transition, or later, thus contributing to the cosmic radiation density (Turner 1987; Massó et al. 2002; Archidiacono et al. 2013).

Axions or ALPs interactions with standard model particles allow their production in stellar interior. For $m_a \lesssim 100$ keV, their mean-free-path is larger than typical stellar radii, so that once released near the center they freely escape from the star. In such a case, ALPs production in stellar interiors acts as an energy sink mechanism. Although ALPs belong to a more general class of pseudoscalar particles, their cooling effects in stellar interiors are indistinguishable from those caused by the production of QCD axions.

The coupling with photons is a general property of ALPs. In hot stellar cores, the Primakoff process, that is, the conversion of a photon into an ALP in the electromagnetic field of an ion, $\gamma + Ze \rightarrow a + Ze$, is the major consequence of the ALP-photon coupling. The stellar energy-loss rate due to this process depends on the square of $g_{a\gamma}$, a quantity representing the strength of the ALP-photon coupling. This rate increases as T^4, but it is suppressed at high density because of the electron screening that reduces the effective charge of the ions. The coupling with electrons is also a potential ALP-production channel in stellar interior. In that case, these particles can be produced by various processes. Compton scattering, $\gamma + e \rightarrow \gamma + e + a$, is the most important production channel, while electron-positron pair annihilation, $e^- + e^+ \rightarrow 2a$, may be relevant in very massive stars approaching the final core collapse. As for the Primakoff, the associated energy-loss rate is larger at higher temperature, but both the Compton and the pair processes are suppressed when electron degeneracy develops. This is a consequence of the well-known Pauli blocking. High electron degeneracy develops in the cores of RGB and AGB stars, as well as in white dwarf interiors. In these cases, however, Bremsstrahlung, $e + Ze \rightarrow e + Ze + a$, may become an important source of ALPs. In general the energy-loss rates due to Compton, pair and Bremsstrahlung scale as the square of g_{ae}, a quantity representing the strength of the ALP-electron coupling. Note that in case of QCD axions, both mass and coupling strengths are inversely proportional to the energy scale at which the Peccei-Quinn symmetry was broken in the early Universe. Thus, the higher this energy scale, the weaker the coupling with Standard Model particles. This mass-coupling relation is not necessarily satisfied in the more general case of ALPs.

In this paper, we summarize the results of our studies on the modification of the macroscopic stellar properties caused by the possible ALP production occurring during the advanced phases of the evolution of low and massive stars. In particular, we present the hints about ALP physics we get from the comparison of the theoretical expectations with the observations of different Milky Way stars. In this work, an extensive use of data from space-based-astronomical observatories has been done. In particular, we have used data from HST, GAIA and NuSTAR.

2. Globular Clusters Stars

Globular Clusters (GC) are ideal sites to test fundamental physics. They are found in spirals, ellipticals as well as in Dwarfs or irregular galaxies. The Milky Way hosts hundreds of GCs, preferentially located in its halo and bulge. A typical GC contains between 10^5 and 10^7 almost coeval stars, as old as 13 Gyr. It is the presence of such a large number of stars with similar properties that makes these objects a good laboratory to investigate new physics. The thermal production of weak interactive particles, such as neutrinos, starts to affect the evolution of GC stars after their departure from the main sequence, when they enter the RGB and the temperature within the core attains a few 10^8 K. Figure 1 show an image of the GC M3 and its color-magnitude diagram. Bremsstrahlung ALPs may be efficiently produced during the RGB phase and, later on, during the AGB phase, while Primakoff and Compton are active during the HB phase. Finally, Bremsstrahlung ALPs may accelerate the cooling of the brightest white dwarfs. Several observable properties of these stars may provide hints on the coupling of ALPs with Standard Model particles. For instance:

- RGB-tip luminosity (ALP-electron coupling)
- RGB Luminosity Function (ALP-electron coupling)
- ZAHB luminosity (ALP-electron coupling)
- RR-Lyrae mass (ALP-electron coupling)
- R=number of HB stars/number of RGB stars (ALP-photon and ALP-electron coupings)
- R2=number of AGBstars/number of HB stars (ALP-photon and ALP-electron coupings)

2.1. RGB tip

When the central H is almost fully consumed, GC stars leave the main sequence and move

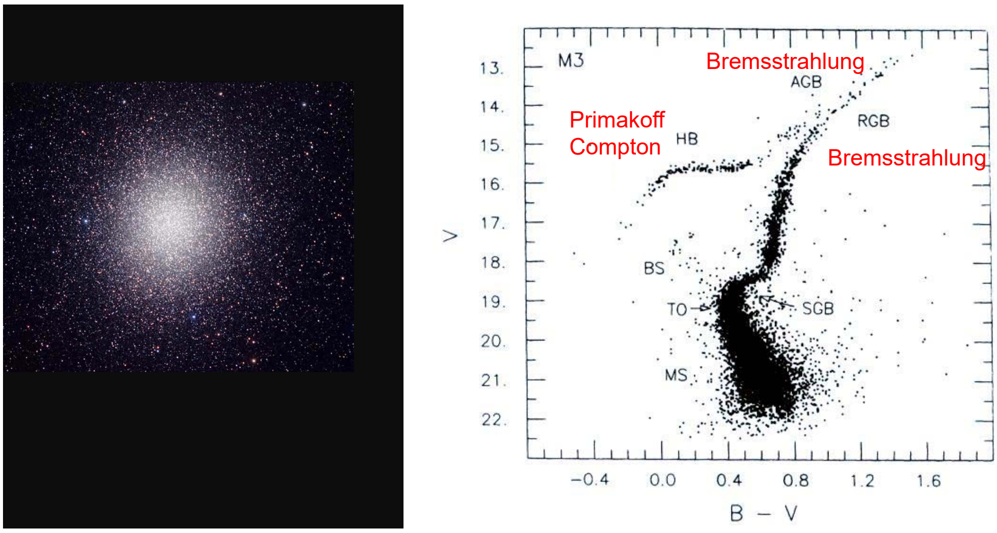

Fig. 1. An image of the globular cluster M3 (left) and the corresponding color-magnitude diagram (right). Labels indicate the evolutionary phases during which an effective ALP production may take place, as driven by different thermal processes.

toward the RGB. In this phase, the He-rich core contracts, while the external H-rich envelope expands. Then, the luminosity of the stars, which is sustained by an efficient shell-H burning, progressively increases. Indeed, the luminosity of a RGB star depends on the mass of the He-rich core that increases because of the H into He conversion. Later on, as also the central density increases, the condition for the development of electron degeneracy are attained. Thus, the production of neutrinos by plasma oscillations becomes an important energy sink process. In this conditions, the pressure by degenerate electrons counterbalances the gravitational contraction of the core, while plasma-neutrinos emission causes an energy loss. In practice, both these processes limit the increase of the core temperature and, in turn, the moment at which the He burning starts. This occurrence coincides with the tip of the RGB, whose luminosity is extensively used as calibrated standard candle in several cosmological studies. However, an additional energy-loss process would increase the He-core mass at the He ignition and, in turn, the RGB-tip luminosity.

In Straniero et al. (2020), we studied the possible activation of additional energy sink mechanisms in RGB stars, as predicted by many extensions of the Standard Model. In particular, we studied the possible production of ALPs, mainly through their coupling with electrons (Bremsstrahlung). Then, by combining Hubble Space Telescope (HST) and ground based optical and near-infrared photometric samples, we derived the RGB tip absolute magnitude of 22 galactic globular clusters (GGCs). Different distance scales have been adopted, among which those based on the astrometric measurements obtained by GAIA. Then we compared the observed tip luminosities with those predicted by state-of-the-art stellar models that include the energy-loss due to the ALP production in the degenerate core of red giant stars.

We found that theoretical predictions including only the energy-loss by plasma neutrinos are, in general, in good agreement with the observed tip bolometric magnitudes, even though the latter are $\sim$ 0.04 mag brighter, on the average (see Figure 2). This small shift may be the result of systematic errors affecting the evaluation of the RGB tip bolomet-

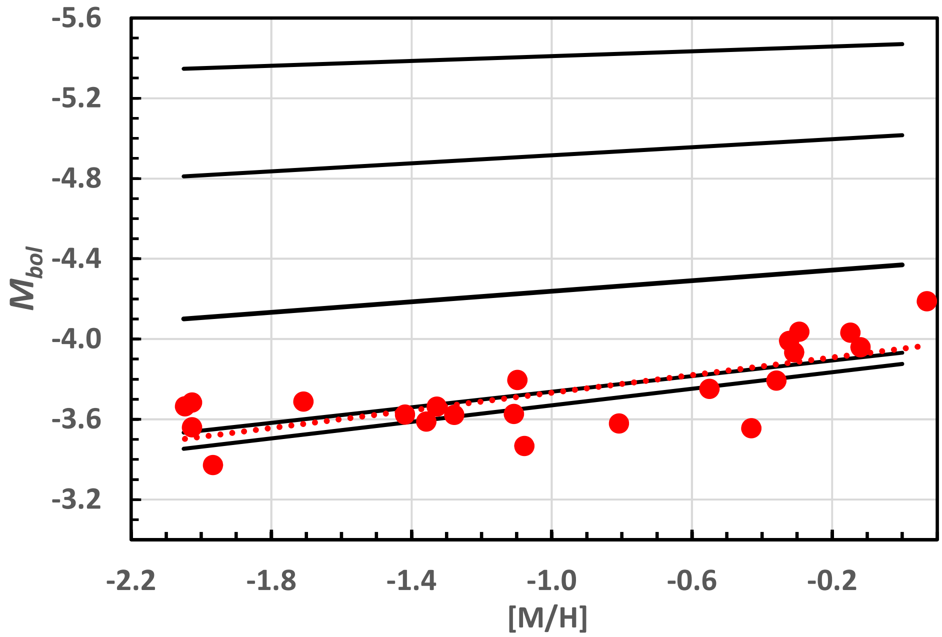

Fig. 2. The RGB tip bolometric magnitude vs cluster metallicity. The red dots represent the observed values for 22 GCs, and the red-dashed line is a least square fit of these data. The black-solid lines are the theoretical predictions as obtained under different assumptions for the ALP-electron coupling, namely, $g_{ae}/10^{-13} = 0, 1, 4, 10$ and 20. Note that the larger the coupling the brightest the RGB tip. The observed values are well reproduced for $g_{ae}/10^{-13} \sim 1$. If the signal seen by the XENON1T collaboration (Aprile et al. 2020) was due to solar axions, the coupling would be as large as $g_{ae}/10^{-13} \sim 20$, a value clearly excluded by our analysis.

ric magnitudes or, alternatively, it could be ascribed to an ALP-electron coupling causing a non-negligible thermal production of ALPs. In order to estimate the strength of this possible ALP sink, we performed a cumulative likelihood analysis using the RGB tips of the whole set of 22 GGCs. All the possible source of uncertainties affecting both the measured bolometric magnitudes and the corresponding theoretical predictions have been carefully considered. As a result, we found that the value of the ALP-electron coupling parameter that maximizes the likelihood probability is $g_{ae}/10^{-13} \sim 0.60^{+0.32}_{-0.58}$. This hint is valid, however, if the dominant energy sinks operating in the core of red giant stars are standard neutrinos (0 magnetic dipole moment) and ALPs coupled with electrons. Any additional energy-loss process, not included in the stellar models, would reduce such a hint. Nevertheless, we found that values $g_{ae}/10^{-13} > 1.48$ can be excluded with a 95% of confidence.

This new bound represents the most stringent constraint for the ALP-electron coupling available so far. The new scenario that emerges after our work represents a great challenge for future experimental ALP search. For instance, we can exclude that the signal recently seen by the XENON1T experiment was due to solar axions (Aprile et al. 2020).

3. Massive stars

During the most advanced phases of the evolution of a massive stars (M> 10 $M_{\odot}$), the core temperature rises above 1 GK, so that the thermal production of small and weakly interac-

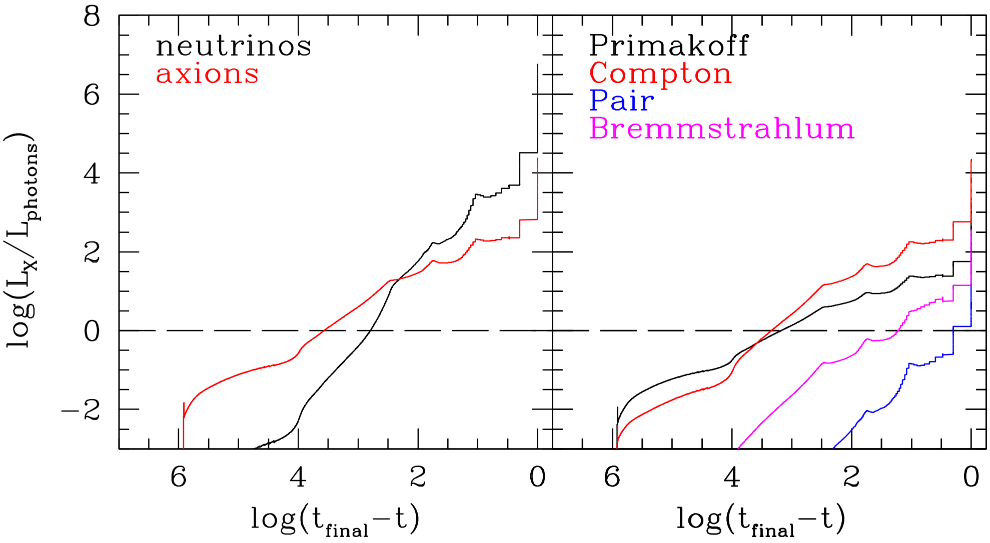

Fig. 3. Left panel: the expected ALP luminosity is compared to the neutrino luminosity for a 20 $M_\odot$ stellar model (from Straniero et al. (2019)). Note that during the advanced phases of the evolution, the luminosity of these weak interactive particles largely overcomes the photon luminosity. Right panel: contributions to the total ALP luminosity from different thermal processes.

tive particles becomes very efficient. Actually, from the C-burning phase up to the final core collapse and beyond, the production of thermal neutrinos is the major energy-loss mechanism that largely overcomes the energy loss due to the electromagnetic radiation (see Figure 3). The possible additional contribution by ALPs to this energy sink has been investigated in Straniero et al. (2019) and Xiao et al. (2021). In the first paper, in particular, we found that the activation of an ALP production may modify the pre-explosive luminosity of a core-collapse supernova progenitor. As a result, we found that the estimation of the progenitor masses based on pre-explosive images should be revised, and that the discrepancy between these masses and those estimated from the explosive yields is reduced.

3.1. ALPs from Betelgeuse

Betelgeuse is a nearby red supergiant of about 20 $M_\odot$. The precise evolutionary stage is uncertain. Comparing the luminosity and the effective temperature of Betelgeuse with extant stellar models we can only conclude that the time to the core collapse is less than a few 10^4 yr. As shown in Figure 3, in this interval of time the ALP luminosity, mainly from Compton scattering, can grow up, from $\sim 10^{38}$ erg/s (He-burning pase) up to 10^{42} erg/s (just before the core collapse). Can this ALP flux be detected at a distance of less than 200 pc? Obviously the answer depends on the strength of the ALP interaction used by a specific detector. However, passing through an external magnetic field, ALPs emitted by the star can be efficiently converted into photons (inverse Promakof). Therefore, if the electromagnetic spectrum from Betelgeuse, or any other nearby red supergiant, would show a clear signature of this ALP-photon conversion, we could be able to measure the corresponding intensity of the ALP flux and, in turn, we could determine the time left to the final core collapse.

In Xiao et al. (2021) we used observation of Betelgeuse in hard x rays to constrain the coupling between ALP and photons. Note that Betelgeuse is not expected to be a standard source of x rays, but light ALPs produced in the stellar core could be converted back into photons in the galactic magnetic field, producing a detectable flux that peaks in the hard x-ray band ($E_\gamma > 10$ keV). Using a 50 ks observation of Betelgeuse by the NuSTAR satellite telescope, we found no significant excess of events above the expected background. Then, using models of the galactic magnetic field in the direction of this red supergiant, we obtained a 95% C.L. upper bound for the ALP-photon coupling of $g_{a\gamma} < (0.5 - 1.8) \times 10^{-11}$ GeV^{-1} (depending on magnetic field model) for ALP masses $m_a < (5.5 - 3.5) \times 10^{-11}$ eV. We have estimated that this promising search for detectable ALPs from stars can be extended to about 20-30 red supergiant in the galactic neighborhood.

Acknowledgements. The study here reported is part of the project "Stars as astroparticle laboratories" funded by the Agenzia Spaziale Italiana (ASI) and the Instituto Nazionale di Astrofsica (INAF) under the agreement n. 2017-14-H.0 - attivitá di studio per la comunitá scientifica di Astrofisica delle Alte Energie e Fisica Astroparticellare.

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