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Axion Dark Matter Conversion in Neutron Star Magnetospheres

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Introduction

Compact astronomical objects such as Neutron Stars (NSs) are formed when massive stars undergo a violent transition in the latter stages of their life span. Neutron stars have been ideally recognized as promising astrophysical laboratories for converting dark matter axions into photons. According to several studies of X-ray pulsars and Soft Gamma-Ray repeaters (SGRs), neutron stars are magnetars that exist with high surface and core magnetic fields. In addition to having an intense magnetic field that can reach up to $\sim 10^{17}G$, these are surrounded by electromagnetic plasma that allows resonant axion-photon conversion to occur close to the star's surface. The theory of NS cooling is a vital resource for exploring the properties of the interiors of the superdense matter. After the formation, these stars rapidly cool down by enhanced neutrino & photon emission. Along with the neutrinos and photons, it could also be possible that axions may be produced inside the core of NSs. The cooling rate is controlled by the so-called equation of state (EOS; the relationship between energy density and pressure) superfluidity, particularly the heat blanketing envelopes (HBEs). Axions, WIMPs and MACHOs are only a few dark matter particles postulated in the literature in the past few years. The quantum chromodynamics (QCD) Axions, being low mass and low energy, are motivated by the solution of the strong CP problem. These light pseudo-scalar particles may also explain the abundance of observed unknown forms of matter called dark matter. In this work, we present how modified Tolman Oppenheimer Volkoff system of equations (in the presence of magnetic field) affects the cooling rate and luminosities (photons, neutrinos and axions) within the possible axion mass range. We will also examine the possibility of axion-to-photon conversion in the magnetosphere of neutron stars. We further plan to investigate the impact of the magnetic field on the actual observables, such as energy spectrum and total outcoming flux.

Formalism

We consider the modified TOV equations [1] (in the presence of a strong magnetic field) to generate the profiles using the different equation of states (EoSs). We employed APR and SLY EoSs while solving TOV system of equations for obtaining pressure and mass profiles. The cooling rate and luminosity observables of different particles (photons, neutrinos, and axions) are obtained using NSCool Code. This code is a FORTRAN-based neutron star cooling computational program that solves the heat transport and energy balance equations in full GR using pressure, density, and mass profiles.
The cooling rate equation is:

$$CdT/dt = -L_\nu^\infty - L_\gamma^\infty - L_a^\infty \tag{1}$$

In early times, it was assumed that the neutron stars cool by the dominant neutrino emission process. Axions along with neutrinos and photons may be produced thermally inside the core of NSs.

$$\epsilon_a^s = \left(\frac{59.2}{f_a^2 G_F^2 [\Delta(T)]^2} r(z)\right) \epsilon_\nu^s, \tag{2}$$

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The conversion from axions to photons in the strong magnetic fields of NS magnetospheres depends on the spectrum given by:

$$J_s^{PBF} = \frac{N_s^{PBF}}{2\Delta(T)} \frac{x^3}{\sqrt{x^2-1}} \left[f(x)\right]^2 , \quad (3)$$

where $x = \frac{\omega}{2\delta T}$ and J_s^{PBF} is the energy spectrum [2]. As the axions pass through NS magnetospheres, which hold intense magnetic fields, they can subsequently convert into photons. The axion interaction with photons is given by:

$$L = -\frac{1}{4} g_{a\gamma\gamma} a F \widetilde{F} \quad (4)$$

Results

We have studied the time evolution of axions, neutrinos, and photons luminosities as a function of time in the absence and the presence of a magnetic field for two EoSs. Fig. 1 shows the luminosity as a function of time at axion mass 45 meV for SLY EoS. Here, a considerable departure is seen in the neutrino and axion luminosities in the absence and presence of the magnetic field. This also affects the cooling rates in the presence of magnetic fields, indicating that incomplete modeling of NSs with strong magnetic fields would have an imprint on the magnetic field distribution. Although the qualitative features would remain the same. Fig. 2 depicts the luminosity versus time at axion mass 45 meV for APR EoS. At short times, the incomplete modeling of NSs is also responsible for the lower estimates of photon luminosity. At early times, over the entire time scale, the neutrino luminosity dominates over the axion and photon luminosity. Magnetic fields do not change the qualitative behavior, although there is a significant difference in the neutrino luminosity.

Conclusions

In the presence of the magnetic field, the luminosity of photons, axions, and neutrinos is quite sensitive to the axion mass. It shows a significant departure from without magnetic field counterparts. Thus, all possible sources of magnetic fields should be properly considered before reaching any firm conclusion.

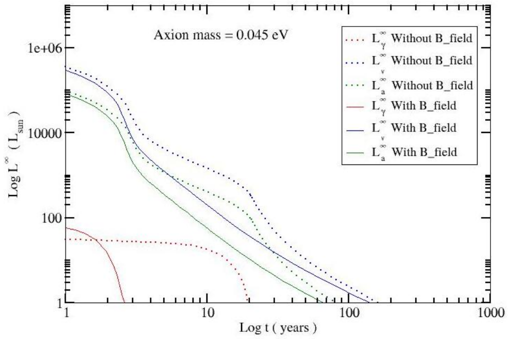

FIG. 1: The variation of luminosity with time for SLY EoS at axion mass 45 meV in the absence and presence of a magnetic field.

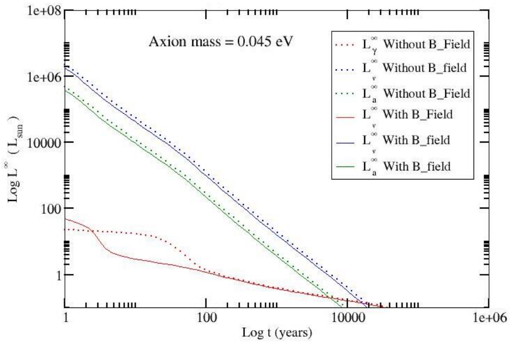

FIG. 2: The variation of luminosity with time for APR EoS at axion mass 45 meV in the absence and presence of a magnetic field.

Acknowledgments

The author acknowledges Birla Institute of Technology and Science, Pilani, Pilani Campus, Rajasthan, for financial support.

References

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