X-ray Emission spectrum from strongly magnetized neutron stars due to axion to photon conversion

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Outline

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- Theoretical formalism;

  TOV equations,

  NS Cooling via axion emission from its core,

  Conversion into photons via magnetosphere magnetic field of NS
- Results and comparison with the data
- Summary and future Outlook

Motivation

- Several observations such as; Galaxy rotation curve, Star rotation curve, Gravitational lensing, Galaxy cluster formation etc. cannot be explained without considering extra matter called Dark Matter.
- Modified Gravity is another approach to explain the above mysterious observations.
- Even after working for so many years, we are still far from the exact properties of the dark matter.
- Many Dark matter candidates (WIMPs, Axions, MACHOs) have been proposed so far.

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- Properties of the dark matter can be determined using observations pertaining to the various compact objects in the Universe; such as NSs.
- They should have core magnetic field that goes to 10^{17} Gauss. The exact origin of such high magnetic fields in different astrophysical objects is still an open area of research.
- This magnetic field may significantly modify the emission of high-energy electromagnetic radiation from these objects, affecting their cooling properties.
- There is also a renewed interest in studying NSs since they have been proposed to be the source of axionic DM particles.

Introduction

- Emission properties of compact astrophysical objects such as Neutron stars (NSs) is an important area to study physics of DM and normal high density matter.
- Recent observations of gravitational wave events involving mergers of NSs and BHs have opened up new frontiers in astronomy and astrophysics.
- Future Compressed baryonic matter experiment (CBM) involving matter at very high density and low temperatures may be an important facility to study physics of high density matter.
- Despite of several successes of Standard model of Particle Physics, it does not account for any dark matter. So DM physics lies under BSM Physics.

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- Observations associated with NSs (with high magnetic field; Magnetars) can be used here to find out the properties of the dark matter.

- Earlier, it was assumed that as NSs cool primarily through the neutrino & photon cooling mechanism.

- Neutrino cooling predominates for an initial thousand years, and then eventually, photon emission surpasses neutrinos during the later ages of NSs.

- Here it has been assumed (based on recent work by Buschman et al.,) that as NSs cools down it emits axions (QCD axions or ALPs) too in addition to usually assumed photons and neutrinos.

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- Not only NSs but also other events happening deep inside space include; Supernovae Explosion, Gamma ray Burst, Emission of various charged Particles and rays from Galaxy Clusters etc. can be used to find the properties of the DM.
- Humans can only build their detectors in the forms of various Telescopes, Satellite missions etc. located on earth.
- Here we will concentrate on the impact of magnetic field on emission properties of the magnetized NSs under the scenario of formation of axionic DM from its core and its subsequent conversion into photons in the magnetosphere of magnetized NSs.

Axionic Dark Matter

- Axion: Originally proposed to solve strong CP problem of QCD.
- Axions are hypothetical, pseudoscalar particles.
- The QCD axion and axion-like particles (ALPs) are anticipated to pair derivatively to fermionic matter and electromagnetism, thus enabling their production inside the heated cores of NSs.

  The effective Lagrangian of axions-fermion is given by:

$$\mathcal{L} = -\frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{int}(\partial_\mu a, \psi_f) \tag{1}$$

  The second term in the expression denotes axion coupling to a fermionic field ψ_f
- The axions may be produced inside the cores of NSs thermally by Cooper pair breaking formation and the N-N Bremsstrahlung process.

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- These axions can convert into photons due to high magnetic field present inside magnetosphere of NSs.
- Such a conversion mechanism has been proposed to explain hard X-ray excess from nearby NSs.
- Also considered a compelling candidate for the search of the mysterious DM.
- Along with neutrinos & photon, a popular dark matter candidate, axions may also be emitted from the cores of NSs.

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- The production rate of axions depends on their emissivity, critical temperature profiles of the NSs, and proton & neutron Fermi's momenta profiles.
- In the presence of strong magnetic fields surrounding the NSs, these produced axions (in the core) may be converted into X-rays due to their weak interaction with the matter. The axions mixing with photons is based on the axion-photon coupling term given by the Lagrangian:

$$\mathcal{L}_{conv} = -\frac{1}{4} g_{a\gamma\gamma} a F \widetilde{F}. \quad (2)$$

Here, F & $\widetilde{F}$ corresponds to an electromagnetic field strength tensor and corresponding dual tensor, respectively, $g_{a\gamma\gamma}$ is axion-photon coupling parameter

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- Here we will concentrate on Dark Matter issues based on axion emission.
- In the current work, we will attempt to explain hard X-ray emission observed from a group of Stars [M7] under the assumption of emission of of axions from the core of NSs.

Tolman Oppenheimer Volkoff (TOV) equations

- In Schwarzschild coordinates, the space-time metric inside the spherically symmetric star is given by:

$$ds^2 = -\exp(2\phi)c^2 dt^2 + \frac{dr^2}{1 - \frac{2G\, m(r)}{rc^2}} + r^2 d\Omega, \quad (3)$$

where, $\exp(2\phi(r)) = 1 - \frac{2Gm(r)}{r\, c^2}$.

- The interior solution of Einstein's equation of GTR for this metric yields the following first-order differential equations (TOV):

$$\frac{dm}{dr} = 4\pi r^2 \epsilon(r) \quad (4)$$

$$\frac{dP}{dr} = -c^2 \frac{G\left(\epsilon + \frac{P}{c^2}\right)\left(m(r) + 4\pi r^3 P/c^2\right)}{r\left(r\, c^2 - 2G\, m(r)\right)} \quad (5)$$

Modified TOV Equations (In the presence of magnetic field)

- TOV Equations (In Presence of magnetic field)[1].

$$\frac{dm}{dr} = 4\pi r^2 \left(\epsilon + \frac{B^2}{2\mu_0 c^2}\right) \tag{6}$$

$$\frac{d\phi}{dr} = \frac{G\left(m(r) + 4\pi r^3 P/c^2\right)}{r\left(r\,c^2 - 2G\,m(r)\right)} \tag{7}$$

$$\frac{dP}{dr} = -c^2 \left(\epsilon + \frac{B^2}{2\mu_0 c^2} + \frac{P}{c^2}\right)\left(\frac{d\phi}{dr} - \mathcal{L}(r)\right) \tag{8}$$

$$\mathcal{L}(r) = -B_c^2 \left[3.8\left(\frac{r}{\bar{r}}\right) - 8.1\left(\frac{r}{\bar{r}}\right)^3 + 1.6\left(\frac{r}{\bar{r}}\right)^5 + 2.3\left(\frac{r}{\bar{r}}\right)^7\right] \times 10^{-41} \tag{9}$$

[1] Chatterjee et al, PhysRevC.99.055811,99,055811(2021)

Neutron Star Cooling: PBF Process (NS Core)

- Pair breaking formation process (PBF) [2].
- **Neutrino emission** is the dominant process at early times. [3].
- Substantial cooling of superfluid by emitting neutrinos through (PBF) process.
- Both spin 0 s-wave and spin 1 p-wave nucleon could exist in the NS cores.

$$X + X \rightarrow [XX] + \nu + \overline{\nu} \tag{10}$$

- Neutrino emission rate [4] for s-wave superfluid:

$$\epsilon_{\nu}^{s} = \frac{5G_F^2}{14\pi^3} v_N(0)\, v_F(N)^2\, T^7 I_{\nu}^{s} \tag{11}$$

[2] Page et al., PhysRevC.99.055811,777,497–530(2006)
[3] Bushmann et al. Phys. Rev. Lett,126,021102(2021)
[4] Keller et al., Elsevier,897,62–69(2013)

Continued

- **Axion production mechanism** occur in NS core through (PBF)
- Interaction Lagrangian given by: $\mathcal{L}_{int} = (C_f/2\, f_a)\bar{\psi}_f \gamma^\mu \gamma_5 \psi_f \partial_\mu a$
- Axion emission rate [5] for the s-wave pairing given by :

$$\epsilon_a^s = \frac{8}{3\pi f_a^2} v_N(0) v_f(N)^2 T^5 I_a^s \tag{12}$$

$$v_N(0) = \frac{m_N p_F(N)}{\pi^2} \tag{13}$$

$$z = \frac{\Delta T}{T} \tag{14}$$

$$f_F(x) = [e^x + 1]^{-1} \tag{15}$$

[5] Keller et al., Elsevier,897,62–69(2013)

Energy Spectrum of Axions (PBF)

The local energy spectrum of axions follows the modified thermal distribution given [6]:

$$\frac{dF}{dE} \propto \frac{(E/T)^3\ (E/T)^2 + 4\pi^2}{e^{E/T} - 1}, \tag{16}$$

where, E is local axion energy and F is the axion-converted-photon flux. The energy spectrum of axions due to the spin-0 S-wave process is given as:

$$J_a^{s,PBF} = \frac{d\epsilon_a^{s,PBF}}{d\omega_a}, \tag{17}$$

$$J_a^{s,PBF} = \frac{N_a^{s,PBF}}{2\Delta T} \frac{\left(\frac{\omega_a}{2\Delta T}\right)^3}{\sqrt{\left(\frac{\omega_a}{2\Delta T}\right)^2 - 1}} \left[f_F(\frac{\omega_a}{2T})\right]^2, \tag{18}$$

[6] Buschmann, Phys. Rev. Lett., 126,021102,(2021)

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where,

$$N_a^{s,PBF} = \epsilon_a^s \; z_n^5 / I_a^s$$

is the normalization constant derived from the expression $\int_{2\Delta T}^{\infty} J_a^s d\omega_a = \epsilon_a^s$ and $2y\Delta T$ is an axion energy.

T corresponds to a locally measurable quantity at some radius within the interiors of NSs.

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The axion emissivity due to the P-wave paired neutron superfluid is given by [7]:

$$\epsilon_a^P = \frac{2\,C_n^2}{3\pi f_a^2}\, v_n(0)\, T^5\, I_a^p, \tag{19}$$

where C_n is the axion model dependent constant. The integral I_a^p is expressed as:

$$I_a^p = z_n^5 \left(\int_1^{\infty} \frac{y^3}{\sqrt{y^2 - 1}} [f_F\,(z_n y)]^2 dy \right), \tag{20}$$

where $z_n = \Delta_q(T, \theta)/T$ with θ is the angle quantization axis and momentum of the neutron.

[7] Buschmann, Phys. Rev. Lett., 126,021102,(2021)

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Two states of P-wave superfluid pairing exist, denoted as A and B.

The $^3P_2$ pairing is denoted by types A and B, where $m_J = 0$ and 2 represent the total projection of the momentum of Cooper-pair over the z-axis.

Here Δ_q corresponds Δ_A or Δ_B,

The superfluid gaps is expressed as [8]:

$$\Delta_A = \Delta_0^A \sqrt{1 + 3\cos^2\theta}. \tag{21}$$

$$\Delta_B = \Delta_0^B \sin\theta. \tag{22}$$

[8] Sedrakian, Phys. Rev. D, 93,065044,(2016)

Neutron Star Cooling : N-N Bremsstrahlung process (NS Core)

- The axions and neutrinos are expected to emit during the nucleon collisions by the bremsstrahlung process.
- To calculate the production rates in the core, the prerequisites are the processes involving protons, neutrons, and electrons.
- In the current analysis, the axion production occurs in the fully degenerate nucleon-nucleon bremsstrahlung process, $N + N \to N + N + a$, where N can be either a neutron or a proton, and a is the emitted axion.
- The current process involves the emission of radiation (in this case, axions) during the interaction of charged particles[9].

[9] Sedrakian, Phys. Rev. D, 93,065044,(2016)

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The expression for axion emission rate is given by:

$$\epsilon_a^{brem} = \frac{\alpha_a n_B \Gamma_\sigma T^3}{4\pi m_N^2} I_a^{brem} \tag{23}$$

The axion integral is expressed as:

$$I_a^{brem} = \int_0^\infty s(x) x^2 e^{-x} \, dx, \tag{24}$$

where, Γ_σ means the spin rate (nucleon) changes under collisions with the other nucleon.

For the degenerate limit:

$$\Gamma_\sigma = \frac{4\alpha_\pi^2 p_F T^3}{3\pi n_B} \tag{25}$$

$$s(x) = \frac{\left(x^2 + 4\pi^2\right)|x|}{4\pi^2\left(1 - e^{-|x|}\right)}. \tag{26}$$

Here p_F is the fermi momentum of the nucleon.

Energy Spectrum of Axions (Bremsstrahlung)

The energy spectrum of axions due to the N-N bremsstrahlung process is given by:

$$J_a^{brem} = \frac{d\epsilon_a^{brem}}{d\omega_a} = \frac{N_a^{brem}\omega_a^5}{e^x T^6}, \tag{27}$$

where, $N_a^{brem} = \frac{\epsilon_a^{brem}}{4\pi^2 I_a^{brem}}$ is the normalization constant derived from the expression $\int_0^\infty J_a^{brem} d\omega_a = \epsilon_a^{brem}$ and $x \times T$ is an axion energy.

Here, $x = \frac{\omega_a}{T}$ is the dimensionless quantity and ω_a (equivalently $x \times T$) is the axion energy.

Conversion Probability and Axion-converted-Photon Flux

The axions mixing with photons is based on the axion-photon coupling term given by the Lagrangian [10]:

$$\mathcal{L}_{conv} = -\frac{1}{4} g_{a\gamma\gamma} a F \widetilde{F}. \tag{28}$$

Here, F & $\widetilde{F}$ corresponds to an electromagnetic field strength tensor and corresponding dual tensor, respectively, $g_{a\gamma\gamma}$ is axion-photon coupling parameter given as:

$$g_{a\gamma\gamma} = \frac{C_\gamma \alpha}{2\pi f_a}, \tag{29}$$

where, C_γ is a axion model dependent factor and $\alpha = 1/137$ is QED fine structure constant.

[10] Buschmann, Phys. Rev. Lett., 126,021102,(2021)

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The following expression provides an approximate relationship for conversion probability [11]:

$$P_{a\to\gamma} \approx 1.5 \times 10^{-4} \left(\frac{g_{a\gamma\gamma}}{10^{-11}\ GeV^{-1}}\right)^2 \left(\frac{1\ keV}{\omega}\right)^{0.8} \times \left(\frac{B_0}{10^{13}\ G}\right)^{0.4} \left(\frac{R_{NS}}{10\ km}\right)^{1.2} \sin^{0.4}\theta, \quad (30)$$

where, ω is the axion energy and R_{NS} is radius of NS (in km). B_0 is the strength of the surface magnetic field at the pole, and θ is the magnetic axis polar angle.

We have multiplied the axion-photon conversion probability with the axion energy spectrum and obtain the final axion-converted-photon flux at the different values of axion energy.

[11] Buschmann, Phys. Rev. Lett., 126,021102,(2021)

Results: Energy spectrum of axions with axion energies

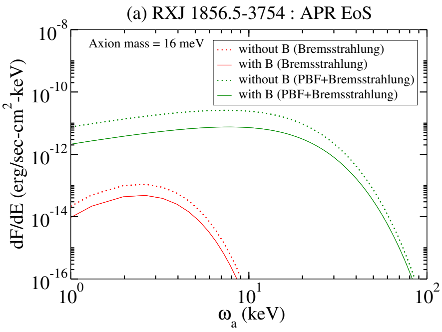

Figure: The variation of the energy spectrum of axions with the axion energy for APR EoS in the presence and absence of magnetic field

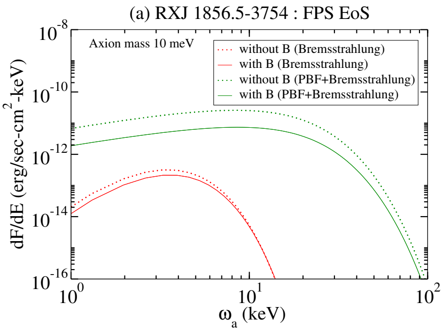

Figure: The variation of the energy spectrum of axions with the axion energy for FPS EoS in the presence and absence of magnetic field

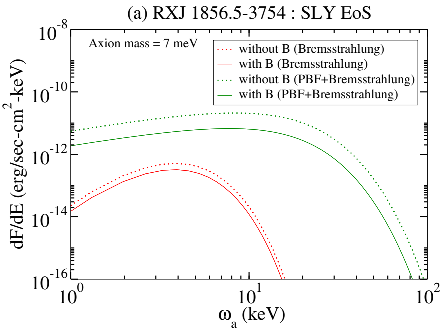

Figure: The variation of the energy spectrum of axions with the axion energy for SLY EoS in the presence and absence of magnetic field

Results: Axion-converted-photon flux with axion energies

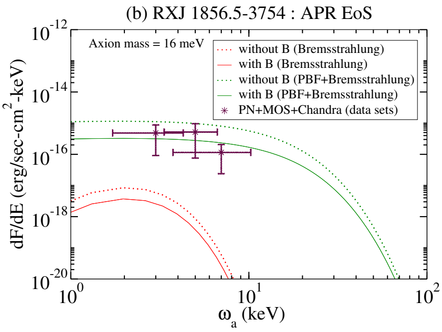

Figure: The variation of the axion-converted photon flux with the axion energy for APR EoS and FPS EoS in the presence and absence of magnetic field

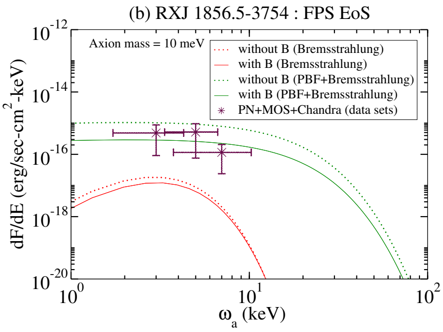

Figure: The variation of the axion-converted-photon flux with the axion energy for FPS EoS in the presence and absence of magnetic field

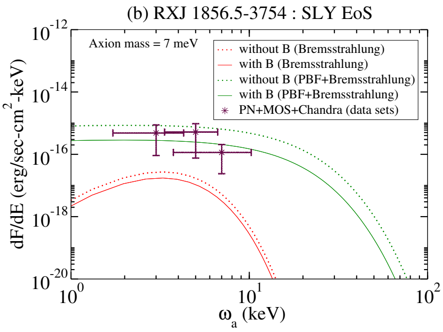

Figure: The variation of axion-converted-photon flux with the axion energy for SLY EoS in the presence and absence of magnetic field

Summary and Future Outlook

- Missing matter issue is a very Challenging Task. It may be solved in the coming future or may give another mystery!! Nobody knows!
- We study how the presence of a strong magnetic field affects the energy spectrum of axions and axion-converted-photon flux.
- Current work is based on the hypothesis that the axions are produced in the core of NSs by the Cooper pair breaking and formation process and the Bremsstrahlung process, then converted into X-rays due to a strong magnetic field in NSs magnetospheres.
- We have also explored the effect of the magnetic field by comparing our numerically computed results with the available archival data of PN+MOS+Chandra for Magnificient seven (M7) star RXJ 1856.5-3754 (M7).

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- Our investigation reports that the influence of a the strong magnetic field on the observables depends on the employed EoS.
- We find the axion mass bounds that describe the photon flux data from NSs for the mentioned three EOSs, namely APR, FPS, and SLY, as 16 meV, 10 meV, and 7 meV, respectively.
- Further extension of work is being done to incorporate other effects, such as rotation of the NSs (called Pulsars!)

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