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Studies on Axions as the Energy Source in Magnetar

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Abstract. Highly magnetized neutron stars known as magnetars are some of the most interesting objects in the Universe. Non-baryonic dark matter candidate axions are produced in the highly magnetized neutron star via Bremsstrahlung process in the highly dense medium. These axions thus produced are then converted into photons in the strong magnetic field via Primakoff effect giving rise to the observed X-ray luminosity level of these objects. Our results are found within observational limit of SGRs(1806-20, 1900+14,0526-66 and 1627-41) and AXPs(4U0142+61,1E1048-5937,RXS1708-4009 and 1E1841-045).

Keywords. Dark matter—axion—magnetar—SGRs—AXPs

1. Introduction

Magnetar is known as the highly magnetised neutron star. The Anomalous X-ray Pulsars (AXPs) and the Soft Gamma Repeaters (SGRs) are considered as the two classes of magnetars (Kouveliotou 1999) which emit X-rays of the order of 10^{33}–10^{35} erg s^{-1}. Mikheev *et al.* (2010) first studied the resonant production of axions in magnetar magnetosphere. Axions are pseudoscalar bosons proposed by Peccei and Quinn (1977) to solve the strong CP problem. In the early Universe, axions are produced by both thermal and non-thermal processes. Axions can be detected through their weak interaction with matter. They have the characteristic property of being converted into photons and also known for their roles in the form of both hot dark matter (HDM) and cold dark matter (CDM) particles (Jeong *et al.* 2014). Large magnetic field of some astrophysical objects like magnetars can convert photons to axions and vice versa known as the Primakoff effect. Therefore, magnetar would be good location for the search for axions. In case of magnetar the density of the electron component in the region of closed field lines exceeds Goldreich-Julian density by several orders of magnitude.

The dominant axion emission processes in neutron star core is nucleon–nucleon axion bremsstrahlung (NNAB). The emission rate of the process $n + n \rightarrow n + n + a$ in degenerate limit have been calculated by Iwamoto (1984). Later, numerically the emission rate was calculated by Brinkmann and Turner (1988) in arbitrary nucleon degeneracy.

The axion–nucleon interaction Lagrangian density is given by (Iwamoto 1989)

$$\mathcal{L}_{aNN} = i g_{aNN} \bar{\psi}_n \gamma_5 \psi_n \phi_a \ . \quad (1)$$

The axion–nucleon coupling constant (Kolb & Turner 1990) is

$$g_{aNN} = \frac{0.5 m_N}{f_{PQ}/N} \simeq 7.8 \times 10^{-8} \left(\frac{m_a}{\text{eV}}\right) , \quad (2)$$

where m_a is the axion mass (Brinkmann & Turner 1988) and is given by

$$m_a \simeq 0.62 \ \text{eV}[10^7 \ \text{GeV}/(f_{PQ}/N)] \ . \quad (3)$$

Here, m_N ($\simeq$0.94 GeV) is the nucleon mass, N is the color anomaly of the PQ symmetry and f_{PQ} is the Peccei-Quinn symmetry breaking scale.

Hanhart *et al.* (2001) showed that axion production in neutron stars occurs mainly as bremsstrahlung from nucleon–nucleon scattering. This process has the same degree of relevance in the production of X-rays via axion–nucleon scattering in the core of neutron stars. Friedman (1973) estimated the differential energy spectrum of various galactic X-ray sources showing that most of the energy range is in keV range due to bremsstrahlung process. The diffuse X-ray between 10 keV and 100 keV are found to be isotropic to better than five per cent over angular sizes of ten degrees (Schwartz 1970). Morris (1986) suggested that a comparatively low mass axion (10^{-3} eV) can escape the core of the neutron star and conversion to X-rays can effectively take place in the magnetosphere. The neutrinos and axions are produced in the core of the magnetar. Neutrinos can effectively lose energy and so the temperature is not expected to rise in the magnetosphere (Phillips 1999). Therefore the rise in temperature in magnetosphere will not cause X-rays. Axion emitted from highly magnetized neutron star decays into X-rays in the magnetosphere of the star. Das *et al.* (2012) have studied soft gamma ray (hard X-ray) emission in magnetar with non-baryonic dark matter-axion and neutrino.

In this work we have computed axion production by NNAB process in magnetar and the conversion of these axions to photons is then calculated via Primakoff effect.

2. Calculation

The axion emission rate by the bremsstrahlung process (NNAB) (Kolb & Turner 1990) is estimated to be

$$\dot{\epsilon} \simeq 1.59 \times 10^{39} \mathrm{erg\, g^{-1}\, s^{-1}} g^2_{aNN} \left(\frac{\rho}{8\times 10^{14}\,\mathrm{g\,cm^3}}\right) \times \left(\frac{T_1}{3.5\times 10^{11}\,\mathrm{K}}\right)^{3.5}. \quad (4)$$

Thus the axion luminosity can be calculated as $L_a = 1.4 M_{\odot}\dot{\epsilon}$ gives

$$L_a = 3.7\times 10^{57} \mathrm{erg\, s^{-1}} \left(\frac{m_a}{\mathrm{eV}}\right)^2, \quad (5)$$

for temperature T_1 is of the order of 10^8 K and density ρ in the 10^{14} g /cm^3 range. For an axion mass $m_a > 0.02$ eV, the interaction rates get strong. In this case, the mean free path for the axion is smaller than the neutron star radius and the axions produced in the core are absorbed before it can escape (Kolb & Turner 1990). So we consider mass of axion in the range of $\leq 10^{-3}$ eV so that it can escape the core and their conversion into photons may take place in the magnetosphere. Primakoff effect is an important process in the photon-axion conversion. In presence of external electromagnetic field, the axion couples into virtual photon and produces a real photon.

$$a + \gamma_{\mathrm{virtual}} \rightleftharpoons \gamma. \quad (6)$$

The newly produced high energy photon lies in the range of X-ray frequency. The axion photon coupling is given by

$$L_{\gamma\phi} = -\frac{1}{4M} F^{\mu\nu}\tilde{F}_{\mu\nu}\phi, \quad (7)$$

where $\frac{1}{4M}$ is the coupling constant, ϕ is the axion field strength and $F^{\mu\nu}$, $\tilde{F}_{\mu\nu}$ are tensor of the electromagnetic field and its dual tensor respectively. The conversion probability of axion to photon in transverse magnetic field (Pshirkov & Popov 2009) is given by

$$P_{a\rightarrow\gamma}(L) = 2\left(\frac{B}{2M}\right)^2 \left[\frac{1-cosqL}{q^2}\right], \quad (8)$$

where

$$q = \frac{\left|m^2_{\gamma} - m^2_a\right|}{2E_a} \quad (9)$$

is known as the axion-photon momentum difference, L is the axions path length, m_a and E_a are the rest mass and the energy of the axion respectively and m_{γ} is the plasma mass of a photon and this is given by

$$m_{\gamma} = 0.37\sqrt{n/10^8\,\mathrm{cm^{-3}}}\,\mu\mathrm{eV}. \quad (10)$$

The plasma density in the region of closed field lines is then

$$n(r) \simeq \alpha_1 \left(\frac{0.1\,\mathrm{rad/s}}{\Omega}\right) B_0 r_0^3 r^{-3} T^{-1}. \quad (11)$$

Here r_0 is magnetar radius, T is the spin period of the magnetar in second, $\alpha_1 = 21\times 10^3\,\mathrm{s\,cm^{-3}\,G^{-1}}$ and B is the magnetic field in Gauss. The magnetic field of the magnetar as a function of r is $B(r) = B_0(r_0^3/r^3)$. So the photon plasma mass as a function of r is given by

$$m_{\gamma}(r) = \alpha_1^{1/2}\alpha_2 \left(\frac{0.1\,\mathrm{rad/s}}{\Omega}\right)^{1/2} B_0^{1/2} r_0^{3/2} r^{-3/2} T^{-1/2}, \quad (12)$$

where $\alpha_2 = 3.7\times 10^{-11}\,\mathrm{cm^{3/2}\,eV}$.

The conversion of axion takes place (Pshirkov & Popov 2009) when $m_{\gamma} = m_a$.

From the above condition, the crtical radius and critical magnetic field can be derived:

$$r_c = \alpha_1^{1/3}\alpha_2^{2/3} \left(\frac{0.1\,\mathrm{rad/s}}{\Omega}\right)^{1/3} B_0^{1/3} T^{-1/3} m_a^{-2/3} r_0, \quad (13)$$

$$B_c = \alpha_1^{-1}\alpha_2^{-2} \left(\frac{0.1\,\mathrm{rad/s}}{\Omega}\right)^{-1} \left(\frac{10\,\mathrm{km}}{r_0}\right)^{-1} m_a^2 T. \quad (14)$$

In this case $E_a \gg m_a$. From the condition of maximum probability $qL = \pi$, the axion-photon momentum can be written as

$$q^2 = \frac{3\pi m_a^2}{2E_a r_c}. \quad (15)$$

Using equations (13), (14) and condition of maximum probability, the expression for probability of conversion can be written as

$$P_{a\rightarrow\gamma} = 20\,\mathrm{G}^{-2}\,\mathrm{cm}^{-1}\,\mathrm{eV}^3 \frac{2E_a}{3\pi}\alpha_1^{-5/3}\alpha_2^{-10/3} \times \left(\frac{0.1\,\mathrm{rad/s}}{\Omega}\right)^{-5/3} B_0^{1/3} T^{5/3} r_0 m_a^{4/3} M^{-2}\,. \quad (16)$$

Table 1. Emission of axion and X-rays as function of axion mass in nucleon-nucleon axion bremsstrahlung process.

m_a (eV)	L_a (erg/s)	$P_{a\rightarrow\gamma}$	L_X (erg/s)
5×10^{-4}	2.99×10^{40}	2.40×10^{-6}	7.20×10^{34}
10^{-3}	1.19×10^{41}	6.06×10^{-6}	7.26×10^{35}
5×10^{-3}	2.99×10^{42}	5.18×10^{-5}	1.55×10^{38}

The X-ray emission from the axion conversion per second in strong magnetic field is then estimated from

$$L_X = P_{a\rightarrow\gamma} L_a\,. \quad (17)$$

To estimate the energy per second in magnetar we have assumed $B_0 = 10^{15}$ G, $T = 10$ s, $r_0 = 10$ km. The axion luminosity, conversion probability and X-ray

Table 2. Observational data of some known soft gamma repeaters.

Name	$B(10^{15})$ G	L_x (erg/s)	References
SGR1900 + 14	1.51	$1.5\pm0.3\times10^{36}$	Zhang *et al.* (2003), Esposito *et al.* (2007)
SGR0526 − 66	1.47	2×10^{35}	Zhang *et al.* (2003), Kulkarni *et al.* (2003)
SGR1806 − 20	0.924	$1.2\pm0.1\times10^{36}$	Zhang *et al.* (2003), Esposito *et al.* (2007)
SGR1627 − 41	0.2	3.5×10^{33}	Mereghetti *et al.* (2006)

Table 3. Observational data of some known AXPs.

Name	$B(10^{14})$ G	L_x (erg/s)	References
4U0142 + 61	1.3	3.3×10^{34}	Kaspi & Gavril (2004)
1E1048 − 5937	5	3.4×10^{34}	Kaspi & Gavril (2004)
RXS1708 − 4009	4.6	6.8×10^{35}	Kaspi & Gavril (2004)
1E1841 − 045	7.1	2.3×10^{35}	Kaspi & Gavril (2004)

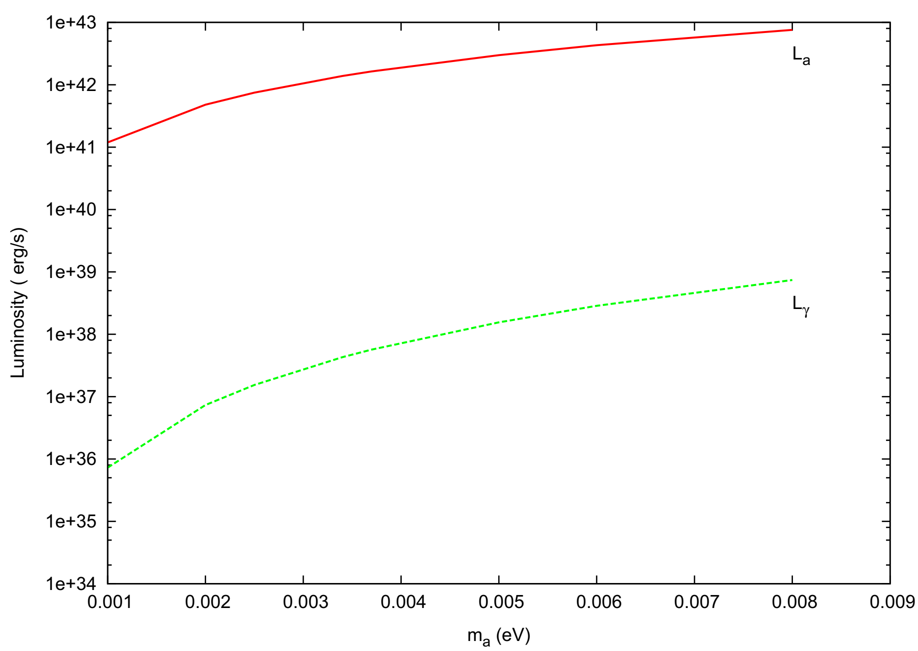

Figure 1. Axion and X-ray luminosity as a function of axion mass.

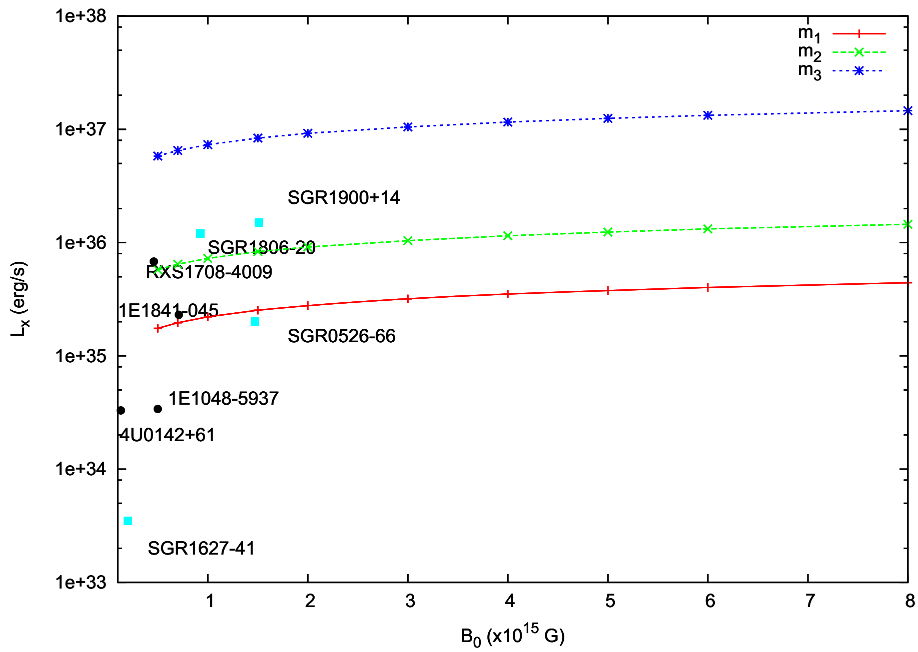

Figure 2. Luminosity as a function of magnetic field for different axion masses. Energy emission from some SGRs and AXPs are also shown in the plot for comparison with the observation. The curves, m_1, m_2 and m_3 represent axion masses 7×10^{-4} eV, 10^{-3} eV and 2×10^{-3} eV respectively.

luminosity determined are shown in Table 1 for different axion masses. Energy emission and magnetic field of some SGRs(1806-20, 1900+14,0526-66 and 1627-41) and AXPs(4U0142+61,1E1048-5937,RXS1708-4009 and 1E1841-045) are given in Tables 2 and 3 respectively.

The axion luminosity as well as X-ray luminosity are calculated and are plotted as a function of axion mass in Fig. 1. It is seen that the luminosity due to axion always exceeds that of the X-ray luminosity. The energy emission from the axion conversion for different values of axion masses and magnetic filed is shown in Fig. 2. The observed X-ray emission rate of some known SGRs(1806-20, 1900+14,0526-66 and 1627-41) and AXPs(4U0142+61,1E1048-5937,RXS1708-4009 and 1E1841-045) are also shown in Fig. 2 for comparison.

3. Conclusion

Here we have calculated the X-ray emission L_X as a function of axion mass for the nucleon bremsstrahlung process in magnetar. Lower mass axions emit energy at lower rate which does not comply with the observation of X-ray emitting sources. The axion production rate and conversion probability both increase with axion mass. The calculated X-ray emission is close to the observed estimate (Tables 2 and 3). As temperature increases, production of axion and its conversion to photons both increases. Thus it can be said that axion plays a major role in the production of X-ray in magnetar. One interesting thing emerges in theses calculations, the axion mass is constrained within the axion mass value between 7×10^{-4} eV and 2×10^{-3} eV which could explain the X-ray luminosities of the SGR's and AXPs considered. This mass range may be universal for this non-baryonic dark matter particle in the universe and other astronomical objects.

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