Axion mass limit from observations of the neutron star in Cassiopeia A

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Abstract. Direct Chandra observations of a surface temperature of isolated neutron star in Cassiopeia A (Cas A NS) and its cooling scenario which has been recently simultaneously suggested by several scientific teams put stringent constraints on poorly known properties of the superfluid neutron star core. It was found also that the thermal energy losses from Cas A NS are approximately twice more intensive than it can be explained by the neutrino emission. We use these unique data and well-defined cooling scenario to estimate the strength of KSVZ axion interactions with neutrons. We speculate that enlarged energy losses occur owing to emission of axions from superfluid core of the neutron star. If the axion and neutrino losses are comparable we find $c_n^2 m_a^2 \sim 5.7 \times 10^{-6} \text{eV}^2$, where $m_a$ is the axion mass, and $c_n$ is the effective Peccei-Quinn charge of the neutron. (Given the QCD uncertainties of the hadronic axion models, the dimensionless constant $c_n$ could range from $-0.05$ to $0.14$.)

Keywords: axions, neutron stars, supernova neutrinos

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1 Introduction

Axions are hypothetical pseudoscalar particles that have been suggested as a solution of the CP-violation problem in the strong interactions [1–3]. Though axions arise as Nambu-Goldstone bosons and thus must be fundamentally massless their interaction with gluons induces their mixing with neutral pions. Axions thereby acquire a small mass which is approximately given by [4–7]:

$$m_a = 0.60 \text{eV} \frac{10^7 \text{GeV}}{f_a},$$

where the unknown constant $f_a$ with the dimension of an energy is the axion decay constant. For a general review on axion physics see, e.g., [8–13]. The axion phenomenology, in particular in relation with the astrophysical processes, is largely discussed in [14–19].

Axions are a plausible candidate for the cold dark matter of the universe, and a reasonable estimate of the axion mass (or, equivalently, the axion decay constant) represents much interest. Over the years, various laboratory experiments as well as astrophysical arguments have been used to constrain the allowed range for $f_a$ or, equivalently, for the axion mass $m_a$. Currently [20, 21], cosmological arguments give $m_a > 10^{-5} \text{eV}$. The most stringent upper limits on the axion mass derive from astrophysics.

Axions produced in hot astrophysical plasma can transport energy out of stars. Strength of the axion coupling with normal matter and radiation is bounded by the condition that stellar-evolution lifetimes or energy-loss rates not conflict with observation. Such arguments are normally applied to the physics of supernova explosions, where the dominant energy loss process is the emission of neutrino pairs and axions in the nucleon bremsstrahlung [22–25]. The limit from Supernova 1987A gives $m_a < 0.01 \text{eV}$ [26, 27]. In works [28, 29] the thermal evolution of a cooling neutron star was studied by including the axion emission in addition to neutrino energy losses. The authors suggest the upper limits on the axion mass of order $m_a < 0.06 – 0.3 \text{eV}$ by comparing the theoretical curves with the ROSAT observational data for three pulsars: PSR 1055-52, Geminga and PSR 0656+14. Accuracy of such estimates substantially depends on the assumptions of the matter equation of state and of the effects of nucleon superfluidity which should be properly taken into account. In the most cases the cooling scenario involves many parameters which are poorly known.

The possibility of a more correct estimate has appeared following a publication of analysed Chandra observations of the neutron star in Cassiopeia A (Cas A NS) during 10 years [30, 31]. The authors found a steady decline of the surface temperature, $T_s$, by about 4% which they interpret as a direct observation of Cas A NS cooling, the phenomenon which has never been observed before for any isolated NS. The decline is naturally explained if
neutrons have recently become superfluid (in \(^3\text{P}_2\) triplet-state) in the NS core, producing a splash of neutrino from pair breaking and formation (PBF) processes\(^1\) that currently accelerates the cooling [32, 33]. The observed rapidity of the Cas A NS cooling implies that protons were already in a superconducting \(^1\text{S}_0\) singlet-state with a larger critical temperature. This scenario puts stringent constraints on poorly known properties of NS cores. In particular, the density dependence of the temperature for the onset of neutron superfluidity should have a wide peak with maximum \(T_c(\rho) \approx (7–9) \times 10^8\) K.

2 Neutrino and axion energy losses from superfluid NS core

The neutrino pair emission caused by recombination of thermally broken Cooper pairs [34, 35] occurs through neutral weak currents generated by spin fluctuations of the nucleons [36, 37]. Since the proton condensation occurs with a zeroth total spin of a Cooper pair the spin fluctuations of the proton condensate are strongly suppressed in the non-relativistic system [34]. As a result, the dominating energy losses occur owing to the PBF neutrino radiation from triplet pairing of neutrons, while the proton superfluidity quenches the other neutrino reactions which efficiently operate in normal (nonsuperfluid) nucleonic systems (\(\bar{\nu}\nu\) bremsstrahlung, murca processes etc.)

Since the neutrino emission occurs mainly owing to neutron spin fluctuations, the part of the interaction Hamiltonian relevant for PBF processes is (we use natural units, \(\hbar = c = k_B = 1\)):

\[
H_{\nu n} = -\frac{G_F C_A}{2\sqrt{2}} \delta_{\mu i} (\Psi^+ \hat{\sigma}_i \Psi) l^\mu, \tag{2.1}
\]

where \(l^\mu = \bar{\nu} \gamma^\mu (1 - \gamma_5) \nu\) is the neutrino current, \(G_F = 1.166 \times 10^{-5}\) GeV\(^{-2}\) is the Fermi coupling constant, \(\Psi\) is the nucleon field, \(C_A \approx 1.26\) is the neutral-current axial-vector coupling constant of neutrons, and \(\hat{\sigma}_i\) are the Pauli spin matrices.

The dominant axion emission from a hot neutron star core is also caused by spin fluctuations of non-relativistic neutrons. The corresponding Hamiltonian density can be written in the form of derivative coupling:

\[
H_{\alpha n} = \frac{c_n}{2f_a} \delta_{\mu i} (\Psi^+ \hat{\sigma}_i \Psi) \partial^\mu a, \tag{2.2}
\]

where \(c_n\) is the effective Peccei-Quinn charge of the neutron. This dimensionless, model-dependent coupling constant could range from \(-0.05\) to 0.14 [38, 39].

The emission of neutrino pairs is kinematically possible owing to the existence of a superfluid energy gap, which admits the quasiparticle transitions with time-like momentum transfer \(K = (\omega, \textbf{k})\), as required by the final neutrino pair: \(K = K_1 + K_2\). The energy-loss rate by \(\bar{\nu}\nu\) emission caused by the neutron PBF processes is given by the phase-space integral

\[
Q_{\bar{\nu}\nu} \simeq N_\nu \frac{G_F^2 C_A^2}{8} \int \frac{\omega}{1 - \exp \frac{-\omega}{T}} 2 \text{Im} \Pi_A^{\mu\nu}(\omega) \frac{\text{Tr} (l^\mu l^\nu)}{2\omega_1 (2\pi)^3} \frac{d^3k_1}{2\omega_1} \frac{d^3k_2}{2\omega_2}, \tag{2.3}
\]

where \(N_\nu = 3\) is the number of neutrino flavors, and \(\Pi_A^{\mu\nu}\) is the retarded axial polarization tensor which describes spin fluctuations in the neutron superfluid at temperature \(T\). The Fermi velocity is small in the nonrelativistic system, \(V_F \ll 1\), and we can study the neutrino

\(^1\)In ref. [32] the authors use the term Cooper pair formation (CPF).
energy losses in the lowest order over this small parameter. Since the transferred space momentum comes in the polarization functions in a combination $k V F \ll \omega, \Delta$, one can evaluate $\Pi^\mu\nu_A$ in the limit $k = 0$.

After integration over the phase space of escaping neutrinos and antineutrinos the total energy which is emitted into neutrino pairs per unit volume and time is given by the following formula (see details, e.g., in ref. [40]):

$$Q_{\bar{\nu} \nu} = \frac{G^2_F C_A^2}{64\pi^5} \int_0^\infty d\omega \int_{k < \omega} d^3q \frac{\omega}{1 - \exp\left(-\frac{\omega}{T}\right)} \text{Im} \Pi^\mu\nu_A(\omega) \left(K_\mu K_\nu - K^2 g_{\mu\nu}\right),$$  

(2.4)

where we use a shortened notation $\Pi^\mu\nu_A(\omega) \equiv \Pi^\mu\nu_A(\omega, k = 0)$.

If now $K = (k, k)$ denotes the axion four-momentum (we ignore a small axion mass), the energy radiated per unit volume and time in axions is given by the following phase-space integral

$$Q_a = \frac{1}{4} \frac{c^2}{f^2} \int \frac{k}{1 - \exp\left(-\frac{k}{T}\right)} 2 \text{Im} \Pi^\mu\nu_A(k) K_\mu K_\nu \frac{d^3k}{2k(2\pi)^3}. $$  

(2.5)

In the above, it was assumed that both axions and neutrinos can escape freely from the medium so that final-state Pauli blocking factors can be ignored.

The medium properties are embodied in a common function $\text{Im} \Pi^\mu\nu_A$ which is exactly the same for axion or neutrino interactions because in eqs. (2.4) and (2.5) the global coupling constants are explicitly pulled out. For the $3P_2(m_j = 0)$ pairing of neutrons this function is calculated in ref. [37] with taking into account of the ordinary and anomalous axial-vector vertices. According to eq. (93) of this work:

$$\text{Im} \Pi^\mu\nu_A(\omega) = -\delta^{ij}\delta^{\nu\rho} p_F M^* \int dn \left( \delta_{ij} - \frac{\vec{b}_i \vec{b}_j}{k^2} - \frac{3}{4} (\delta_{ij} - \delta_{i3}\delta_{j3}) \right) \times \Delta_n^2 \Theta \left(\omega^2 - 4\Delta_n^2\right) \text{tanh} \frac{\omega}{4T},$$  

(2.6)

where $p_F$ is the Fermi momentum of neutrons, $M^* \equiv p_F/V_F$ is the neutron effective mass, and $\Theta (x)$ is the Heaviside step-function. For the $3P_2(m_j = 0)$ pairing the normalised vector $\vec{b}(n)$ is defined as

$$\vec{b}(n) \equiv \sqrt{1/2} (-n_1, -n_2, 2n_3).$$  

(2.7)

Its angular dependence is represented by the unit vector $n = p/p$ which defines the polar angles $(\theta, \varphi)$ on the Fermi surface:

$$n = (\sin \theta \cos \varphi, \sin \theta \sin \varphi, \cos \theta).$$  

(2.8)

The superfluid energy gap, generally defined by the relation

$$\Delta_n^2 = \vec{b}^2(n) \Delta^2(\tau),$$  

(2.9)

is anisotropic. It depends on the polar angle $\theta$ and on the relative temperature $\tau \equiv T/T_c$. For the one component state $m_j = 0$ one has

$$\Delta_n = \frac{1}{\sqrt{2}} \sqrt{1 + 3 \cos^2 \theta} \Delta(\tau).$$  

(2.10)
Insertion of eq. (2.6) into eqs. (2.4) and (2.5) yields the neutrino emissivity as given by eq. (96) of ref. [37]:

\[ Q_\nu(m_j = 0) \simeq \frac{2}{5\pi^2} G_F C_A^2 p_F M^* T^7 F_4 \left( \frac{T}{T_c} \right), \]  

(2.11)

and the axion emissivity

\[ Q_a(m_j = 0) = \frac{c_2^2}{f_a^2} \frac{2}{3\pi^3} p_F M^* T^5 F_2 \left( \frac{T}{T_c} \right), \]

(2.12)

where

\[ F_l(\tau) = \int \frac{dn}{4\pi} \frac{\Delta_{n}^2}{T^2} \int_0^\infty dx \frac{z^l}{(\exp z + 1)^2} \]

(2.13)

with \( z = \sqrt{x^2 + \Delta_{n}^2/T^2} \). Details of the numerical evaluation of this integral can be found in [35, 37].

### 3 Mixed cooling by emission of axions and neutrino pairs

Before proceeding to estimates of the axion radiation, let us note a few important details of theoretical simulation of the CAS A NS neutrino cooling. The authors of ref. [32] have reported that our eq. (2.11) gives too slow cooling. To achieve a better quantitative agreement of their simulation to the observed data the neutrino energy losses were artificially enlarged in approximately two times. This indicates that the thermal energy losses of Cas A NS are approximately twice more intensive than neutrino losses given in eq. (2.11). Since currently there is no definitive explanation for this increase, we can speculate that the additional energy losses from the superfluid core of the Cas A NS are caused by axion emission, as described in eq. (2.12).

To get an idea of a compatibility of the axion emission with the CAS A NS observation data let us consider a simple model of cooling of the superfluid neutron core enclosed in a thin envelope as typical for the NS. We assume that the bulk matter consists mostly of \( ^3P_2 \) superfluid neutrons with \( m_j = 0 \). In the temperature range which we are interested in, the thermal luminosity of the surface is negligible in comparison to neutrino and axion luminosities of the PBF processes in the NS core. In this case the equation of global thermal balance [41] reduces to

\[ C(\tilde{T}) \frac{d\tilde{T}}{dt} = -L(\tilde{T}). \]

(3.1)

Here \( L(\tilde{T}) \) is the total PBF luminosity of the star (redshifted to a distant observer), while \( C(\tilde{T}) \) is the stellar heat capacity. These quantities are given by (see details in refs. [42]):

\[ L(\tilde{T}) = \int dV Q(T, \rho) \exp(2\Phi(r)), \]

(3.2)

\[ C(\tilde{T}) = \int dV C_V(T, \rho), \]

(3.3)

where \( Q(T, \rho) \) is the total (neutrino + axion) emissivity, \( C_V(T, \rho) \) is the specific heat capacity, \( dV \) is the element of proper volume determined by the appropriate metric function, and \( \Phi(r) \) is the metric function that determines gravitational redshift. A thermally relaxed star has an
isothermal interior which extends from the center to the heat blanketing envelope. Taking into account the effects of General Relativity (e.g., [43]), isothermality means spatially constant redshifted internal temperature

\[ \bar{T}(t) = T(r, t) \exp(\Phi(r)), \]  

(3.4)

while the local internal temperature \( T(r, t) \), depends on the radial coordinate \( r \).

Given the strong dependence of the PBF processes on the temperature and the density, the overall effect of simultaneous emission of neutrino pairs and axions can only be assessed by complete calculations of the neutron star cooling which are beyond the scope of this paper. A rough estimate can be made in a simplified model, where the superfluid transition temperature \( T_c \) is constant over the core.

In the temperature range of our interest, the specific heat is governed by the neutron component (the contribution of electrons and strongly superfluid protons is negligibly small) and can be described as

\[ C \simeq \frac{1}{3} T R_B(T/T_c) \int dV p_F M^*, \]  

(3.5)

where \( R_B(T/T_c) \) is the superfluid reduction factor, as given in eq. (18) of ref. [44].

Making use of eqs. (2.11) and (2.12) we obtain the PBF luminosity in the form

\[ L = \left[ \frac{2}{5\pi^5} G_F C_A T^7 F_4(T/T_c) + \frac{c_n^2}{f_a^2} \frac{2}{3\pi^3} T^5 F_2(T/T_c) \right] \int dV p_F M^* e^{2\Phi(r)}. \]  

(3.6)

Insertion of eqs. (3.4), (3.5) and (3.6) into eq. (3.1) allows to obtain the following equation for the non-redshifted temperature \( T_b(t) \equiv T(r_b, t) \) at the edge of the core or, equivalently, at the bottom of the envelope at \( r = r_b \):

\[ \frac{dT_b}{dt} = \frac{3\alpha}{R_B(T_b/T_c)} \left[ \frac{2}{5\pi^5} G_F C_A T_b^7 F_4(T_b/T_c) + \frac{c_n^2}{f_a^2} \frac{2}{3\pi^3} T_b^5 F_2(T_b/T_c) \right], \]  

(3.7)

where the constant \( \alpha \equiv \alpha(r_b) \) is defined as

\[ \alpha \equiv \frac{\int dV p_F M^* e^{2\Phi(r)} \exp \Phi(r_b)}{\int dV p_F M^*}, \]  

(3.8)

and can be found from the CAS A NS observation data.

We convert the internal \( T_b \) to the observed effective surface temperature \( T_s \) using (see, e.g., [45, 46])

\[ T_s/10^6 \text{ K} \simeq (T_b/10^8 \text{ K})^{0.55}. \]  

(3.9)

This allows to compare the computed results with the observed (non-redshifted) CAS A NS surface temperatures which are cataloged in table 1 of ref. [32].

4 Results and discussion

For numerical estimate of the axion coupling strength to neutrons we designate

\[ g = \frac{c_n^2}{f_a^2}. \]  

(4.1)
\begin{figure}[ht]
\centering
\includegraphics[width=0.8\textwidth]{cooling_curves.png}
\caption{(Color on line) Cooling curves for a simulated CAS A NS consisting of a superfluid neutron core and a low-mass blanketing envelope. $T_c$ is taken constant over the core. Four curves correspond to the mixed (neutrino + axion) cooling at four values $g = 0$ ($T_c = 7.55 \times 10^8$ K), $g = 0.1$, $0.16$ and $0.22$ ($T_c = 7.2 \times 10^8$ K). The points with error bars demonstrate the observed surface temperatures cataloged in table 1 of ref. [32]. The inset shows the cooling curves but over a larger range of ages. The lower curve corresponds to the mixed cooling at $g = 0.16$ while the upper curve demonstrates cooling due to only neutrino emission artificially enhanced 2.1 times as suggested in ref. [32].}
\end{figure}

with $f_g = f_a / (10^9 \text{GeV})$, and consider $g$ as a free parameter. Figure 1 demonstrates the effect of mixed cooling of superfluid neutron star with a constant $T_c$ over the core. Two solid lines are the cooling curves for the simulated NS calculated at $g = 0.0$ and $g = 0.16$. The case $g = 0$ describes the cooling caused by only the PBF neutrino emission given in eq. (2.11), with constant $T_c = 7.55 \times 10^8$ K. This curve demonstrates too slow cooling and cannot explain the data. The case $g = 0.16$ agrees with the observations. This corresponds to the mixed neutrino + axion radiation, as described by eqs. (2.11) and (2.12), with $T_c = 7.2 \times 10^8$ K. The two dashed curves calculated at $g = 0.1$ and $g = 0.22$ demonstrate that even a relatively
small deviation off the value \( g = 0.16 \) results in substantial modification of the temperature profile and does not allow to reproduce the observed cooling rate of the Cas A NS.

Thus we obtain \( g \simeq 0.16 \) or, equivalently,

\[
\frac{c_n^2}{f_a^2} \simeq 1.6 \times 10^{-19} \text{GeV}^{-2}. \tag{4.2}
\]

The same estimate immediately follows from a simple comparison of eqs. (2.11) and (2.12) if one assumes that the axionic emissivity is approximately equal to the neutrino emissivity. This gives

\[
\frac{c_n^2}{f_a^2} \sim \frac{3}{5\pi^4} G_F^4 C_A^2 T^2 \frac{F_2(\tau)}{F_2(\tau)} \tag{4.3}
\]

Inserting the typical values, \( T_c \simeq 7.2 \times 10^8 \text{K} \) and \( T \simeq 3.8 \times 10^8 \text{K} \), we find \( \tau \equiv T/T_c \simeq 0.53 \) and \( F_2(\tau) / F_2(\tau) \simeq 10.4 \). Insertion of the above parameters into Eq. (4.3) results in the estimate given in eq. (4.2).

One can use eq. (1.1) to convert the decay constant \( f_a \) to the axion mass \( m_a \). This yields

\[
c_n^2 m_a^2 \sim 5.7 \times 10^{-6} \text{eV}^2. \tag{4.4}
\]

Unfortunately, the coupling constant \( c_n \) depends on the axion model. Given the QCD uncertainties of the hadronic axion models [47–49], the dimensionless constant \( c_n \) could range from \(-0.05\) to \(0.14\). While the canonical value \( c_n = 0.044 \) is often used as generic examples, in general \( c_n \) is not known so that for fixed \( c_n^2 m_a^2 \) a broad range of \( m_a \) values is possible.

One should keep in mind that a strong cancelation of \( c_n \) below \( c_n = 0.044 \) is also allowed. In case of \( c_n \to 0 \) a powerful PBF emission of axions is impossible. This would mean that our assumption of the mixed cooling is invalid, and the PBF neutrino losses are indeed at least two times larger than is predicted in eq. (2.11). Then the axion energy losses produce no noticeable modification of the temperature profile of the CAS A NS, and one has to replace the eq. (4.4) by the inequality

\[
c_n^2 m_a^2 \ll 5.7 \times 10^{-6} \text{eV}^2. \tag{4.5}
\]

Can we discriminate the two cases from observations of the NS surface temperature? As demonstrated in the insert in figure 1, the difference between the corresponding theoretical cooling curves becomes discernable only after about 1000 years of cooling. Perhaps future observation of the surface temperature of old neutron stars will help to clarify the cooling mechanism.

Finally let us notice that our estimate of interaction of the hadronic axions with neutrons has no analogies for a comparison. Previous astrophysical constraints was derived basically for axions interacting simultaneously with neutrons and protons. In our case the proton contribution is turned off due to large superfluid energy gap.

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