Axion cooling of neutron stars. II. Beyond hadronic axions

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We study the axion cooling of neutron stars within the DFSZ model, which allows for tree-level coupling of electrons to the axion. This extends our previous study [Phys. Rev. D 93, 065044 (2016)] limited to hadronic models of axions. We explore the two-dimensional space of axion parameters within the DFSZ model by comparing the theoretical cooling models with the surface temperatures of a few stars with measured surface temperatures. It is found that axions masses $m_a \geq 0.08$ to 1 eV can be excluded by X-ray observations of thermal emission of neutron stars (in particular by those of Cas A), the precise limiting value depending on the angle parameter of the DFSZ model.

INTRODUCTION

Axions were suggested four decades ago [1, 2] to solve the strong-CP problem in QCD [3]. They are one of the viable candidates for the cold dark matter in cosmology and can play an important role in the stellar astrophysics. Axions are identified with the pseudo-Goldstone bosons which emerge through the spontaneous breaking of the approximate Peccei-Quinn (PQ) global $U(1)_{PQ}$ symmetry [4, 5]. Their coupling to the Standard Model (SM) particles is determined by a decay constant $f_a$ and PQ charges of the SM particles. For reviews of searches of axions in experiments and limits on their properties from astrophysics see Refs. [6–8].

In a previous work [9] (hereafter Paper I) the axion cooling of neutron stars was studied on the basis of numerical simulations, with the aim of placing constraints on the axion coupling (or, equivalently, the mass $m_a$) through comparison of the simulation results for neutron star surface temperatures with the observed surface photon luminosities of a few well-studied objects. As in the case of the Sun, solar-type stars, red giant stars, white dwarfs, and supernovae constraints on axion properties can be obtained by requiring that the coupling of axions to SM particles should not alter significantly the agreement between theoretical models and observations [10, 11]. In Paper I the PQ charges of constituents of neutron star matter were chosen according to the hadronic model of axions, i.e., the Kim-Shifman-Vainshtein-Zakharov (KSVZ) model [12, 13]. In this model protons and neutrons have non-zero PQ-charges and, therefore, couple to the axion at the tree-level. On the contrary, electron’s PQ charge is zero, i.e., the axion does not couple to the electron at the tree-level. In an alternative Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) axion model [14, 15] electrons have non-zero PQ charges, therefore the electronic component of a neutron star can cool by emitting axions. Furthermore, in the DFSZ model the couplings of the SM particles depend only on an angle-parameter and $f_a$, which limits the parameter space of this model to a two-dimensional plane. It is the purpose of this work to adapt and extend the computations reported in Paper I to the DFSZ axion model. An important new aspect of this study is then the additional axion emission through the electronic component of the star, which contributes alongside the axion emission by hadrons studied in detail in Paper I.

This paper is structured as follows: In Sec. we start with a brief review of axion emission processes, discuss the axionic coupling within the DFSZ model and concentrate on the rate of axion emission by electron bremsstrahlung in the neutron star crusts. Sec. discusses the simulation set-up and the resulting cooling tracks for a large array of models of neutron stars. Our conclusions and an outlook are given in Sec. 6. The natural units with $\hbar = c = k_B = 1$, $\alpha = 1/137$ will be used unless stated otherwise.

MICROPHYSICS OF AXION EMISSION IN NEUTRON STARS

Overview

The focus of this work, from the microscopic point of view, is the bremsstrahlung of axions by electrons which are scattered on nuclei in neutron star crusts. This process has been initially studied in Ref. [16]. Improved rates which include many-body correlations were derived later in Refs. [17, 18]. However, these rates have not been implemented in cooling simulations of neutron stars previously; the pioneering simulations of Umeda et al. [19] contain results obtained within the DFSZ model, but the electron bremsstrahlung process has not been mentioned. As indicated above, our simulations in Paper I were limited to hadronic KSVZ model which does not couple the axions to electrons at the tree level. Nevertheless, the electron bremsstrahlung of axions was considered in detail in the context of cooling of white dwarfs [20–23] and appropriate limits on the electron-axion coupling were derived from comparisons of white-dwarf cooling models and their observations. We will discuss the implementation of this process in the following subsection.

A leading axion emission process from the interiors of neutron stars is the nucleon (N) bremsstrahlung $N + N \rightarrow N + N + a$ processes. It was studied in the context of type-II supernovae and the bounds on axion properties were derived by requiring consistency between the explosion energetics as well as energies of neutrinos observed in the 1987A event and energy drained by axion emission [24–28]. More recent work concluded that future supernova observations could
probe axion mass range \( m_a \leq 10^{-2} \) eV [29]. Axions may not free-stream in supernovae if their coupling to matter is large enough, but this is certainly the case for the neutron star cooling problem. Ref. [26] finds that axions are trapped within a newborn neutron star if the axion mass is larger than \( 10^2 \) eV. This implies the existence of an “axion sphere”, i.e., a surface of last interaction of axions with the ambient matter at the initial stage of neutron star evolution. However the physics at the early moments of neutron stars cooling does not affect the following stages of thermal evolution significantly, therefore our simulations are started at a temperature at which axions and neutrinos are untrapped, which is typically \( T \approx 5 \) MeV.

Axion bremsstrahlung via Cooper pair-breaking–formation (PBF) processes sets in after the nucleons undergo a superfluid phase transition [9, 30]. These have been the dominant axion emission processes in the KSVZ model. Our previous limits reflect the efficac y of these processes in cooling neutron stars below the observed temperatures in the neutrino cooling era, which corresponds to the time span \( 0.1 \leq t \leq 100 \) kyr. It is understood that their untrapped counterpart PBF processes [31–35] are sufficient to cool the stars towards their current observational values.

**DFSZ model of axion couplings to SM particles**

The Lagrangian of axion field \( a \) has the form

\[
\mathcal{L}_a = \frac{1}{2} \partial^\mu a \partial^\mu a + \mathcal{L}^{(N)}_{\text{int}} (\partial_\mu a, \psi_N) + \mathcal{L}^{(L)}_{\text{int}} (a, \bar{\psi}_L),
\]

where the second and third terms describe the coupling of the axion to the nucleonic \( (\psi_N) \) and leptonic \( (\bar{\psi}_L) \) fields of the SM. The second term is given explicitly by the interaction Lagrangian

\[
\mathcal{L}^{(N)}_{\text{int}} = \frac{1}{f_a} N^\mu \partial_\mu a, \quad N^\mu = \sum_N \frac{C_N}{2} \bar{\psi}_N \gamma^\mu \gamma_5 \gamma^5 \psi_N ,
\]

where \( N \in n, p \) stands for neutrons and protons, \( N^\mu \) is the baryon current, \( f_a \) is the axion decay constant, and \( C_N \) are the PQ charges of baryons. The coupling of axions to electrons can be written in the pseudo-scalar form

\[
\mathcal{L}^{(e)}_{\text{int}} (a, \psi_e) = \frac{C_e}{2f_a} \bar{\psi}_e \gamma^\mu \gamma_5 \gamma^5 \psi_e \partial_\mu a = -ig_{ae} \bar{\psi}_e \gamma_5 \psi_e a ,
\]

where the Yukawa coupling is given by \( g_{ae} = C_e m_e / f_a \) with \( m_e \) being the electron mass. We will also use a “fine-structure constant” associated with this coupling, which is defined as \( \alpha_{ae} = g_{ae}^2 / 4\pi \).

The PQ charges for the proton and neutron are given by generalized Goldberger-Treiman relations

\[
C_p = (C_u - \eta) \Delta_u + (C_d - \eta z) \Delta_d + (C_s - \eta w) \Delta_s, \quad (4)
\]

\[
C_n = (C_u - \eta) \Delta_u + (C_d - \eta z) \Delta_d + (C_s - \eta w) \Delta_s , \quad (5)
\]

where \( \eta = (1 + z + w)^{-1} \), with \( z = m_u / m_d \), \( w = m_u / m_s \), \( \Delta_u = 0.84 \pm 0.02 \), \( \Delta_d = -0.43 \pm 0.02 \) and \( \Delta_s = -0.09 \pm 0.02 \). The main uncertainty arises from the quark-mass ratios: \( 0.35 \leq z \leq 0.6 \) and \( 17 \leq m_s / m_d \leq 22 \). We adopt below the following mean values: \( z = 0.5 \) and \( w = 0.025 \).

In the DFSZ model, the couplings are given by

\[
C_c = C_d = C_s = \frac{\cos^2 \beta}{3}, \quad C_u = \frac{\sin^2 \beta}{3} ,
\]

where the angle \( \beta \) is a free parameter. Finally, the axion mass is given by

\[
m_a = \frac{z^{1/2} f_a m_\pi}{1 + z} \frac{f_a}{f_{a\gamma}} = 0.6 \text{ eV} \quad (7)
\]

where \( f_{a\gamma} = f_a / (10^7 \text{ GeV}) \), the pion mass \( m_\pi = 135 \text{ MeV} \), its decay constant is \( f_\pi = 92 \text{ MeV} \), and \( z = 0.5 \) as above. Note that Eq. (7) translates a lower bound on \( f_a \) into an upper bound on the axion mass. Table I displays the set of axion-fermion couplings for five values of the parameter \( \cos^2 \beta \) which are used below to cover the relevant range of cooling simulations. In addition, we show in Fig. 1 the same dependence in the full range \( 0 \leq \cos^2 \beta \leq 1 \).

| \( \cos^2 \beta \) | \( C_n \) | \( C_p \) | \( C_c \) |
|----------------|--------|--------|--------|
| 0.0            | -0.14  | -0.13  | 0.00   |
| 0.25           | -0.04  | -0.24  | 0.08   |
| 0.5            | 0.06   | -0.36  | 0.17   |
| 0.75           | 0.16   | -0.47  | 0.25   |
| 1.0            | 0.26   | -0.58  | 0.33   |

**TABLE I.** The values of the axion-nucleon and axion-electron coupling constants for various values of parameter \( \cos^2 \beta \). The first column labels the set of parameters that were used in cooling simulations.

![Fig. 1. Dependence of the magnitudes of the coupling for electrons (e), neutrons (n) and protons (p) on the parameter \( \cos^2 \beta \).](https://example.com/fig1.png)
Axion bremsstrahlung emission in the crust

At temperatures relevant for neutrino cooling era the dominant cooling process associated with the electron component of the star is the electron bremsstrahlung of neutrino-antineutrino pairs or axions when electrons are scattered off the nuclei. For all relevant temperatures and densities, ions are fully ionized and electrons form an ultra-relativistic, weakly interacting gas. The correlations in the ionic component are characterized by the Coulomb plasma parameter

\[ \Gamma = \frac{e^2 Z^2}{T a_i} \approx 22.73 \frac{Z^2}{T_6} \left( \frac{\rho_6}{A} \right)^{1/3}, \tag{8} \]

where \( e \) is the elementary charge, \( A \) and \( Z \) are the mass number and charge of a nucleus, \( T \) is the temperature, \( a_i = (4\pi n_i/3)^{-1/3} \) is the radius of the spherical volume per ion, \( n_i \) the number density of nuclei, \( T_6 \) is the temperature in units of 10^6 K, and \( \rho_6 \) is the density in units of 10^6 g cm\(^{-3}\). The ionic component is in the liquid state for values of \( \Gamma \leq \Gamma_m \approx 180 \). Otherwise, it forms a lattice, i.e., for \( \Gamma > \Gamma_m \) the electrons are scattering on the lattice and phonons. For a recent compilation of the phase diagram of matter in the crust of a neutron star, which requires that the stellar models describing the data are not massive enough to allow for fast cooling processes to occur. This requirement is based on the observation that fast cooling agents appear only above certain density threshold which can be reached only in massive compact stars. The light- to medium-mass neutron stars within the mass range \( 1 \leq M/M_\odot \leq 1.8 \) are good candidates for such cooling. (b) The simulations are compared to observational data for sources with estimated magnetic fields of the order of canonical pulsar fields \( B \approx 10^{12} \) G and below. This ensures that internal heating by strong magnetic fields [37] can be excluded. (c) We continue to use the NSCool code [38] with its specified equations of state and microphysics input to guarantee the easy reproduction of our results and to benchmark the axion cooling of neutron stars (see Paper I for details). The code has been extended to include all the relevant axionic emission processes by hadrons and electrons as discussed above.

Physics input and observational data

The cooling code solves the energy balance and transport equations in spherical symmetry, i.e., rotation and magnetic fields are excluded. We use a generic relationship between the surface temperature \( T_s \) and the temperature of the shell at density \( \rho_6 = 10^{10} \) g cm\(^{-3}\) to avoid the problem of radiative transport in the thin blanket lying below this density. This relation is given by \( T_s^4 = g_s h(T) \), where \( g_s \) is the surface gravity, and \( h \) is some function which depends on the temperature \( T \), the opacity of the blanket, and its equation of state. The surface composition of a neutron star is modeled by the parameter \( \eta \), with \( \eta = 0 \) corresponding to a purely iron surface and \( \eta \rightarrow 1 \) to a light-element surface. Further details of the input physics can be found in Ref. [38] and in Paper I. Throughout a cooling simulation, we extract the neutrino and axion luminosities of our models, as well as the photon luminosity which is given by the Stefan-Boltzmann law \( L_\gamma = 4\pi \sigma R^2 T_4^4 \), where \( \sigma \) is the Stefan-Boltzmann constant, and \( R \) is the radius of the star.

The dataset of surface temperatures considered in Paper I, which we also use here was as follows. The first object - the CXO J232327.9+584842 in Cassiopeia A SNR - is a representative of a group central compact objects (CCOs) - point-like, thermally emitting x-ray sources located close to the geometrical centers of nonplerionic SNRs [39]. These objects have low magnetic fields, which exclude heating processes at this stage of evolution. The value \( T = 2.0 \pm 0.18 \times 10^6 \) K at the age 320 yr was used [40]. In addition three nearby neutron stars which allow spectral fits to their x-ray emission were considered [41]. The fits invoke two black-body temperatures and we identify the lowest one with the surface temperature and quote only this value (see for further details Paper I):

- PSR B0656+14 with fit temperatures \( T_w = (6.5 \pm 0.1) \times 10^5 \) K and characteristic age \( 1.1 \times 10^4 \) kyr.
- PSR B1055-52 with fit temperatures \( T_w = 7.9 \pm 0.3 \times 10^5 \) K and characteristic age \( 5.37 \times 10^2 \) kyr.

Cooling simulations

To make our presentation self-contained we remind here the basic assumptions underlying the strategy adopted in Paper I: (a) the simulations are based on a conservative model of cooling of neutron stars, which requires that the stellar models
FIG. 2. Cooling tracks of neutron star models with mass $M = 1.4M_{\odot}$ for the case of non-accreted iron envelope ($\eta = 0$). The data shows the surface temperatures inferred from the black-body fits to the x-ray emission of CCO in Cas A, PSR B0656+14 and Geminga. Each panel corresponds to fixed value of $f_{\alpha7}$ as indicated. The values of PQ charges are specified in terms of $\cos^2 \beta$ parameter, see Table I.

FIG. 3. Same as in Fig. 2 but for $\eta = 1$. 
FIG. 4. Dependence of the photon $L_\gamma$, neutrino $L_\nu$ and axion $L_a$ luminosities on age for the models of $M = 1.4M_\odot$ stars for indicated values of the axion coupling $f_a\tau$. The PQ charges correspond to $\cos^2 \beta = 0.4$ (light blue) and $\cos^2 \beta = 1$ (violet).

FIG. 5. Same as in Fig. 4 but for $\eta = 1$, in which case the photon luminosity is modified, but the neutrino and axion luminosities are not.
• Geminga, a radio-quiet object, with the $T_w = 5.0 \pm 0.1 \times 10^5$ K and characteristic age $3.4 \times 10^2$ kyr.

The error in the estimate of the ages of these objects from their spin-down age is quantified by varying their age by a factor of 3. As noted in Paper I, the data on PSR B1055-52 are marginally consistent with the cooling curves even in the absence of axions. This can be attributed to (a) larger error in the age of this pulsar than assumed above; (b) internal heating; (c) the modeling of the pairing gaps, which in principle can be tuned to fit the inferred temperature of PSR B1055-52. Given the uncertainties involved we will exclude the data on PSR B1055-52 in the following. We do not attempt to fit the transient behaviour of the Cas A, as has been done in Ref. [42], since the data on rapid cooling is inconclusive [40].

An additional candidate for constraining axion properties is the peculiarly “hot” CCO HESS J1731-347. Ref. [43] derived already limits on $f_a$ from cooling simulations using the data from this object. Since this object challenges our understanding of the cooling of neutron stars even without axionic cooling we will not include it in our data set; see Ref. [43] for an alternative.

Results of simulations

A representative collection of 20 models of cooling neutron stars for four values of the axion decay constant $f_{a7} = 20, 10, 5, 2$ and the PQ changes specified by rows 1 to 5 in Table I were simulated. The mass of each model was kept fixed at $1.4 M_\odot$.

Figures 2 and 3 show the results of cooling simulations of 20 models of $m = M/M_\odot = 1.4$ mass neutron stars defined above with a nonaccreted iron envelope ($\eta = 0$) and a light-element envelope ($\eta = 1$), respectively. Each of the panels corresponds to a value of the axion coupling value $f_{a7} = 20, 10, 5$ and 2; within each panel we vary the PQ charges of neutrons, protons and electrons according to the indicated values of $\cos^2 \beta$ parameter. The dots with error bars show the three test objects quoted above. Quite generally, the temperature of CCO in Cas A is consistent with the cooling curves if one assumes a light-element envelope in the absence of axion cooling; otherwise it theoretical temperatures undershoot the observational value. In the case of older pulsars, the data agrees with the predictions of the theoretical modelling without axion cooling only for an iron envelope.

Consider now switching on the axion production. The additional loss of energy by axion emission decreases the temperatures of our models. For $f_{a7} = 20$ all the five values of PQ charges are consistent with the data; for $f_{a7} = 10$ the value $\cos^2 \beta = 1$ is excluded by the data; for $f_{a7} = 5$ the values $\cos^2 \beta = 0, 0.75$ and 1 are incompatible with the data; finally, for $f_{a7} = 2$ the value $\cos^2 \beta = 0.5$ is excluded by the data as well. Interestingly, because of the non-monotonous dependence of $|C_n|$ on $\cos^2 \beta$ the axion emission rate decreases initially with increasing $\cos^2 \beta$, then increases again to its maximal value for $\cos^2 \beta = 1$, see Fig. 1.

Similar, but not identical, conclusions are reached by examining the data in Fig. 3. One observes that the following combinations are in inconsistent with the Cas A data: $f_{a7} = 5$ and $\cos^2 \beta = 1$; $f_{a7} = 2$ and $\cos^2 \beta = 0$, 0.75 and 1. None of the values of the PQ charges are excluded for $f_{a7} = 10$ and 20 in this case.

Figures 4 and 5 show the neutrino, axion and photon luminosities as a function of time for four values of the axion coupling constant $f_{a7}$ and PQ charges corresponding to $\cos^2 \beta = 0.4$ and $\cos^2 \beta = 1$ (see Table I) in the cases $\eta = 0$ and $\eta = 1$, respectively. Clearly, the figures differ only by the values of the surface photon luminosity, which is larger in the case $\eta = 1$ at early stages of thermal evolution and the opposite is true at later stages of evolution. It is seen that for $f_{a7} = 20$ the axion and neutrino luminosities are comparable. In the remaining cases, the neutrino luminosity is subdominant and the cooling rate is determined by the balance between the axion emission rate and the change in the thermal energy given approximately by $c_V dT/dt$, where $c_V$ is the net specific heat of the star.

To determine the region of parameter-space of the DFSZ model spanned by the values of $f_7$ and $\cos^2 \beta$ which can be excluded using the observational data we have performed additional simulation by varying these parameter within the ranges $0 \leq \cos^2 \beta \leq 1$ and $1 \leq f_7 \leq 20$ on a $10 \times 10$ grid. In the case of Cas A the age of the CCO is known, therefore the cooling curves were required to agree with the observational temperature within the error. Figure 6 shows the exclusion region determined using the above-mentioned criteria, where we have kept only the Cas A data as it provides the most reliable constraint. Note that the shape of the exclusion region corresponds to the dependence of the neutron PQ charges on the $\cos^2 \beta$, which is shown in Fig. 1. It is seen that the values of $f_{a7}$ that can be excluded strongly depend on the value of
$\cos^2 \beta$ parameter and can vary by more than an order of magnitude. Translating these results into mass limits using Eq. (7) we find upper limits on axion masses
\begin{align}
\max [m_a] &\approx 1 \text{ eV}, \quad \cos^2 \beta \approx 0.4, \\
\max [m_a] &\approx 0.075 \text{ eV}, \quad \cos^2 \beta \approx 1.
\end{align}
Thus, the DFSZ axion mass above the quoted values is excluded by numerical simulations of cooling neutron stars and their comparison with the observational data on Cas A.

**DISCUSSION AND CONCLUSIONS**

In this work, we continued our study of cooling of weakly magnetized neutron stars by the emission of axions. The key strategy (see also Paper I) is to assume that the observed objects are not heavy enough to allow for nucleation of new degrees of freedom in their high-density cores. The cooling behavior could be changed significantly in cases of quark matter nucleation [44–47] or hyperonization [48–50]; for reviews see Refs. [51–54]. Even without new degrees of freedom high densities may permit fast (or accelerated) processes involving only neutrons, protons and lepton [55, 56]. For canonical mass stars with masses $M \sim 1.4 M_\odot$, neutrino cooling is slow [38, 57]. Taking the consistency of the neutrino cooling models with the data on three neutron stars with reliable fits to their blackbody emission as a reference point, we explored the modification introduced by switching on the axion emission by electron bremsstrahlung [17, 18].

As a function of the density these are given by simple polynomials
\begin{equation}
\log F_{S/L}(x, \Gamma) = a + bx^2 + cx^4 - [1 - u_{S/L}(\Gamma)],
\end{equation}
with $x \equiv \log \rho$ where
\begin{align}
\Gamma &\approx 0.21946, \quad b = 0.00287263, \quad c = -0.000142016, \\
\Gamma &\leq 11.4, \quad a = -6.47808, \quad b = 0.068645, \quad c = -0.000252677,
\end{align}
for $x \leq x_0 = 11.4$, and
\begin{equation}
\Gamma \geq 0.47804, \quad u_1 = 1.25585, \quad u_2 = -0.743902,
\end{equation}
in the solid phase and
\begin{align}
\Gamma &\approx 0.672409, \quad u_1 = 0.182774, \quad u_2 = 0.144817,
\end{align}
in the liquid phase. Figure 7 shows the dependence of the correlation functions on the density on a log-log plot. The overall accuracy of the fit is below 10%, with some larger deviations $\leq 30\%$ in a narrow range of densities for selected values of $\Gamma$.

**FITS TO THE CORRELATION FUNCTIONS $F_{L/S}$**

The correlation functions $F_{L/S}$ in Eq. (10) have been computed in [17]. We used the following fit formulae for these functions to implement the axion bremsstrahlung by electrons. As a function of the density these are given by simple polynomials
\begin{align}
\Gamma &\approx 0.21946, \quad b = 0.00287263, \quad c = -0.000142016, \\
\Gamma &\leq 11.4, \quad a = -6.47808, \quad b = 0.068645, \quad c = -0.000252677,
\end{align}
for $x \leq x_0 = 11.4$. These fits were carried out for $\Gamma_0 = 10^4$ and then extrapolated to other relevant values of $\Gamma$ using the function
\begin{equation}
\Gamma_{S/L} = u_0 + u_1 (\Gamma/\Gamma_0) + u_2 (\Gamma/\Gamma_0)^2
\end{equation}
where
\begin{align}
u_0 &\approx 0.488049, \quad u_1 = 1.25585, \quad u_2 = -0.743902,
\end{align}
in the solid phase and
\begin{align}
\Gamma &\approx 0.672409, \quad u_1 = 0.182774, \quad u_2 = 0.144817,
\end{align}
in the liquid phase. Figure 7 shows the dependence of the correlation functions on the density on a log-log plot. The overall accuracy of the fit is below 10%, with some larger deviations $\leq 30\%$ in a narrow range of densities for selected values of $\Gamma$.

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FIG. 7. Computations of Ref. [17] (points) are compared with the fits (lines) for the indicated values of the parameter $\Gamma$.

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