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PAPER

Impact of axions on the Cassiopea A neutron star cooling

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Impact of axions on the Cassiopea A neutron star cooling

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Abstract. The observed anomalous steady decrease in surface temperature of the supernova remnant Cassiopeia A (Cas A), which was reported about ten years ago, has generated much debate. Several exotic cooling scenarios have been proposed using non-standard assumptions about the physics and evolution of this neutron star (NS). At present, significant corrections have been made to the observational data, which make it possible to numerically simulate the Cas A NS cooling process in the framework of the scenario of minimal neutrino cooling. If there is an additional source of cooling, such as axion emission, the steepness of the Cas A NS surface temperature drop will increase with the growth of the axion-nucleon interaction strength. This makes it possible to limit the minimum value of the axion decay constant f_a using the condition that the NS surface temperature should be within the 99% confidence interval obtained from the observational data. Two types of axion models are considered: the Kim-Shifman-Weinstein-Zakharov — KSVZ model and the Dean-Fischler-Srednitsky-Zhitnitsky –DFSZ model. The above criterion gives a lower limit on the axion decay constant, $f_a > 3 \times 10^7$ GeV and $f_a > 4.5 \times 10^8$ GeV for KSVZ and DFSZ axions, respectively.

Keywords: axions, dark matter theory, neutron stars, supernova neutrinos

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1 Introduction

Cooling isolated neutron stars are of exceptional interest to astrophysicists, because these extremely dense compact objects in the Universe serve as a kind of laboratory for the study of matter, which cannot be reproduced in laboratory conditions. Studying thermal evolution of isolated neutron stars in X-rays is of a great importance for better understanding the evolution of such objects and provides a possibility to investigate their composition and structure (see e.g., [1–3]). However, it is difficult to determine the actual thermal radiation from the surface, since the magnetosphere can emit non-thermal X-rays. Therefore, it seems to be a great success if, among the many observed neutron stars, an object is found whose X-ray radiation can be unambiguously associated with the temperature of its surface.

In this regard, over the past two decades, much attention has been paid to the thermal X-ray emission of a neutron star (NS) at the center of the Cassiopeia A (Cas A) supernova remnant.[1] About ten years ago, [6, 7] analyzed data from Chandra's observations over a decade and reported an anomalous steady decrease in surface temperature T_s by about 4%, which they interpreted as a direct observation of the cooling of NS Cas A, a phenomenon that had never been observed for any isolated NS.

We shall discuss later the current state of these observations, at the moment we note that although the real cooling rate is under debate one can not exclude that the Cas A NS cooling is extraordinarily fast. Such a rapid drop in surface temperature (if it occurs) is in conflict with standard cooling scenarios based on the efficient modified Urca process. If the NS in Cas A underwent standard cooling (through neutrino emission from the core due to the modified Urca process) its surface temperature decline in 10 years would be $0.2\% - 0.3\%$ [8, 9].

A rapid decrease, but a relatively high surface temperature (about 2×10^6 K) requires a sharp change in the properties of neutrino emission from NS. Some exotic cooling scenarios have been proposed using non-standard assumptions about the physics and evolution of NS, including softened pion modes [10], quarks [11, 12] or cooling after heating process in r-mode [13]. The existence of softened pions or quarks in the NS core depends mainly on the density of the substance, but not on the temperature. If this rapid cooling were constant since the birth of the NS, the current temperature would have to be much lower than currently measured.

It is reasonable to assume [14, 15] that the cooling was initially slow, but that it later accelerated significantly. In this case, the rapid decrease in temperature can naturally be explained in terms of the minimal cooling paradigm [1, 2], which assumes that the rapid

[1]The supernova remnant in Cassiopeia A contains a young ($\approx$ 340 yr old [4]) neutron star which was discovered by Chandra satellite [5] in 1999.

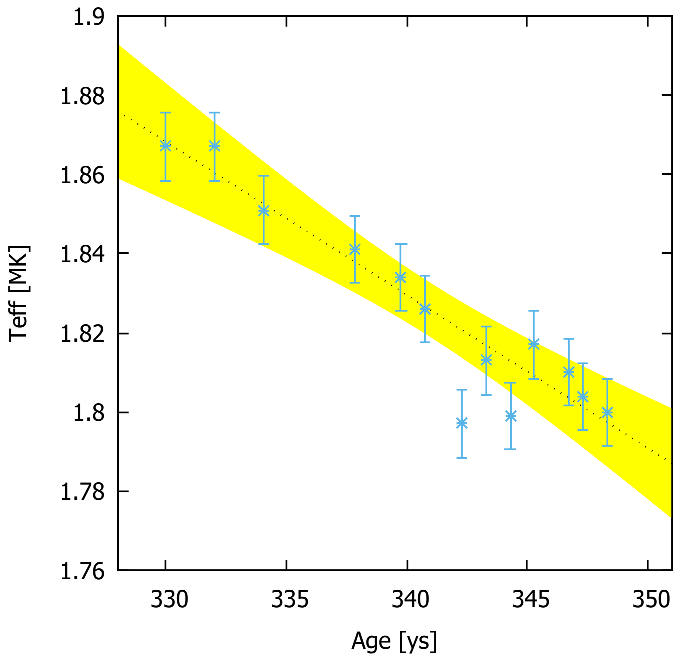

Figure 1. Surface temperature of the neutron star in the Cassiopeia A supernova remnant over the past 18 years. Error bars are 1σ. Dotted line shows linear fit to the set of T_s. Yellow area shows 99% confidence interval for the surface temperature.

cooling of a neutron star is caused by neutron superfluidity in the core. This scenario assumes that neutrons have recently become superfluid (in the $^3\mathrm{P}_2$ triplet state) in the NS core, causing a huge neutrino flux as a result of thermal Cooper pair breaking and formation (PBF) processes that accelerates the cooling of [14, 15], while the protons were already in the superconducting singlet state $^1\mathrm{S}_0$ with a higher critical temperature. Although this mechanism is consistent with the generally accepted cooling paradigm, theoretical simulations have shown [15, 16] that PBF processes in neutron triplet condensate are not efficient enough to explain the rapid temperature drop. This stimulated the work of [17], where axion emission was added to compensate for the deficit of neutrino energy losses from the Cas A NS and reproduce the seeming rapid cooling of this object reported in [6, 7].

The next 10 years made significant adjustments to the observational data. The new work [16, 18] on the observation of Cas A showed that the above-mentioned rapid cooling of NS Cas A is not so obvious due to systematic errors inherent in observations and associated with the problems of calibrating the detectors of the Chandra satellite telescope. Modern analysis [19, 20] yields upper limits corresponding to 3.3% or 2.4% temperature decreases in 10 years depending on values of the absorbing hydrogen column density. Although the stellar cooling rate remains high, it turns out to be significantly less than the previously declared one and fits well into the scenario described above of neutrino cooling due to PBF processes. Figure 1 depicts the surface temperature of a neutron star in a supernova remnant Cassiopeia A over the past 18 years, as reported in [20]. The dotted line represents standard least square linear fit showing an average yearly temperature change rate and yellow area shows 99% confidence interval for the Cas A surface temperature.[2]

[2]The 99% confidence interval is constructed under the assumption of a linear time-dependence of the temperature, which approximately takes place on the considered part of the NS cooling curve.

It can be argued that during the observation period, the effective surface temperature of CasA should be within the yellow shaded area shown in the figure 1 with a 99% probability. This conclusion can be used to revise the previous estimate of the strength of the axion-nucleon interaction, taking into account the new analysis of observational data. Indeed, the observed rapid cooling of the Cassiopeia A neutron star is caused by powerful neutrino losses due to PBF processes in the superfluid neutron core. The more powerfull energy losses from the PBF processes the more steep decline of the cooling curve. If now, in addition to the neutrino losses, we take into account the emission of axions in the same PBF processes, the decline steepness of the cooling curve will depend on the intensity of the axion emission, that is, on the axion decay constant, which we are interested in. Since the axion-neutron coupling is inversely proportional to the axion decay constant f_a, its lower value should be limited by the condition that the cooling curve is still in the yellow region.

In this paper, we study the cooling of NS Cas A due to simultaneous neutrino and axion energy losses in order to estimate the limit on the axion decay constant based on the above criterion.

Let us remind that axions are hypothetical Nambu-Goldstone-bosons associated with the spontaneously broken Peccei-Quinn symmetry that have been suggested as a solution to the strong-CP violation problem in QCD [21–23] but the scale of symmetry-breaking, which is also called the axion decay constant f_a, is left undetermined in the theory.

Axions are a plausible candidate for the cold dark matter of the universe, and a reasonable estimate of the axion decay constant represents much interest. 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 inverse proportional to the scale of symmetry-breaking [24–27]:

$$m_a = 0.60\,\mathrm{eV}\,\frac{10^7\mathrm{GeV}}{f_a}. \tag{1.1}$$

We use natural units, $\hbar = c = k_B = 1$.

Numerous laboratory experiments, as well as astrophysical arguments, were used to constrain the permissible range of the axion mass m_a (see e.g. [28–31]). Currently [32, 33], cosmological arguments give the lower limit $m_a > 10^{-5}\,\mathrm{eV}$ in order to avoid an "overclosed universe". The most stringent upper limits on the axion mass derive from astrophysics. The strength of axion coupling with normal matter and radiation is limited by the condition that the lifetime of stellar evolution or the rate of energy loss do not contradict observations. In the physics of supernova explosions, where the dominant process of energy loss is the emission of pairs of neutrinos and axions in nucleon bremsstrahlung [34–37], the requirement that stars do not lose too much energy due to the emission of axions leads to a lower limit for the Peccei-Quinn scale f_a or, which is the same, to the upper limit of the axion mass m_a. The limit from Supernova 1987A gives $m_a < 0.01\,\mathrm{eV}$ [38, 39]. The thermal evolution of cooling neutron stars including the axion emission in addition to neutrino energy losses was studied in refs. [40–43]. The authors propose upper limits for the axion mass of the order of $m_a < 0.06 - 0.3\,\mathrm{eV}$, comparing the theoretical curves with the ROSAT observational data for three pulsars: PSR 1055-52, Geminga, and PSR 0656 + 14. A similar analysis of the time evolution of the hot young neutron star in supernova remnant HESS J1731-347 was carried out in works [44, 45].[3] Recently, an estimate of the limit on the decay constant of an axion

[3] One should remark that the analysis in refs. [44, 45] was based on a wrong age estimate for the supernova

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from the cooling neutron star in Cassiopeia A was reported in [50]. We will later compare the results of this work with our estimate.

Two types of axion models are known: the Kim-Shifman-Weinstein-Zakharov (hadronic) — KSVZ model [51, 52], where the axion interacts only with photons and hadrons, and the Dean-Fischler-Srednitsky-Zhitnitsky — DFSZ model [53, 54] involving the additional axion coupling to the charged leptons. For a general review on axion physics see, e.g., [55, 56]. The axion phenomenology, in particular in relation with the astrophysical processes, is largely discussed in [57–61].

2 Energy losses

Numerical simulations of the Cas A NS cooling are based on the public code NSCool [62, 63] which I have modified to include additional energy losses via the axion emission. I have also introduced important corrections taking into account the axial anomalous contribution to the neutrino emissivity caused by the pair breaking and formation (PBF) processes in the neutron triplet superfluid. Recall that the current version of the NSCool code incorporates all the corresponding neutrino cooling reactions: DU, MU, PBF, and bremsstrahlung, but the emissivity of the neutron $^3\mathrm{P}_2$ superfluid requires serious correction. Namely, the NSCool code includes only complete collective suppression of neutrino emission in the vector channel,[4] as was proved in [64, 65]. However, the public version of the code does not includes the collective correction due to anomalous terms in the axial channel[5] which additionally significantly reduces the PBF neutrino emissivity [66] (for recent review see [67]). Recall that PBF processes in a superfluid medium include, in addition to the usual terms due to the production and absorption of particle-hole pairs, also anomalous terms describing neutrino emission caused by the production and absorption of two particles or two holes. This is a very important correction that, as will be seen later, makes it possible to correctly describe the observed rate of change in the Cas A NS temperature.

Since the neutrino emission occurs mainly owing to neutron spin fluctuations, the part of the interaction Hamiltonian relevant for PBF processes is:

$$\mathcal{H}_{\nu n} = -\frac{G_F C_A}{2\sqrt{2}} \delta_{\mu i} \left(\Psi^+ \hat{\sigma}_i \Psi \right) l^\mu, \tag{2.1}$$

Here $l^\mu = \bar{\nu}\gamma^\mu (1-\gamma_5)\, \nu$ is the neutrino current, $G_F = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$ is the Fermi coupling constant, $C_\mathsf{A} = 1.26$ is the axial-vector coupling constant of neutrons, and $\hat{\sigma}_i$ are the Pauli spin matrices.

The correct form of the PBF neutrino emissivity of the $^3\mathrm{P}_2$ superfluid neutrons, as derived in [66], reads

$$Q^{\mathrm{PBF}}_{\bar{\nu}\nu} \simeq \frac{2}{15\pi^5} G_F^2 C_\mathsf{A}^2 p_{Fn} m_n^* \mathcal{N}_\nu T^7 F_4 \left(T/T_c \right), \tag{2.2}$$

remnant from [46]: the authors assumed an age a neutron star in SNR HESS J1731-347 of 27 kyr, but recent studies have revealed that it should be almost an order of magnitude younger [47–49].

[4]Dipole radiation in the vector channel of weak interactions is absent in a collision of identical particles.

[5]As reported in [68], the axial anomalous contribution from ref. [66] is included to the PBF emissivity in the modern (not public) version of the code.

where p_{Fn} is the Fermi momentum of neutrons, $m_n^* \equiv p_{Fn}/V_{Fn}$ is the neutron effective mass, and $\mathcal{N}_\nu = 3$ is the number of neutrino flavors; the function F_l is given by

$$F_l\left(T/T_c\right) = \int \frac{d\mathbf{n}}{4\pi} \frac{\Delta_{\mathbf{n}}^2}{T^2} \int_0^\infty dx \frac{z^l}{\left(\exp z + 1\right)^2}, \tag{2.3}$$

with $z = \sqrt{x^2 + \Delta_{\mathbf{n}}^2/T^2}$. The superfluid energy gap[6]

$$\Delta_{\mathbf{n}}\left(\theta, T\right) = \ \Delta\left(T\right)\sqrt{1 + 3\cos^2\theta}, \tag{2.4}$$

is anisotropic. It depends on polar angle θ of the quasiparticle momentum and temperature T.

In standard physical units eq. (2.2) takes the form

$$\begin{aligned} Q_{n\nu}^{\mathrm{PBF}} &= \frac{4G_F^2 p_{Fn} m_n^*}{15\pi^5\hbar^{10}c^6}\left(k_B T\right)^7 \mathcal{N}_\nu \frac{C_{\mathrm{A}}^2}{2} F_4\left(\frac{T}{T_c}\right) \\ &= 1.170\ \times 10^{21} \frac{m_n^*}{m_n}\frac{p_{Fn}}{m_n c} T_9^7 \mathcal{N}_\nu \frac{C_{\mathrm{A}}^2}{2} F_4\left(\frac{T}{T_c}\right)\ \ \frac{\mathrm{erg}}{\mathrm{cm}^3\mathrm{s}} \end{aligned} \tag{2.5}$$

with $T_9 = T/10^9\mathrm{K}$ and m_n being the bare neutron mass. Notice, the neutrino emissivity, as indicated in eq. (2.2), is 4 times less than that implemented in the public NSCool code.

The axion interaction with fermions j has a derivative structure. We will focus in the axion interaction with non-relativistic nucleons. The corresponding Hamiltonian density can be written in the form:

$$\mathcal{H}_{an} = \frac{c_N}{2f_a}\delta_{\mu i}\left(\Psi^+\hat{\sigma}_i\Psi\right)\partial^\mu a, \tag{2.6}$$

where Ψ is a nucleon field, c_N is a model dependent numerical coefficient. For nucleons, the dimensionless couplings c_N are related by generalized Goldberger-Treiman relations to nucleon axial-vector current matrix elements. A recent determination using lattice QCD finds [69, 70]:

$$\begin{aligned} c_n^{\mathrm{KSVZ}} &= -0.02(3), \qquad c_p^{\mathrm{KSVZ}} = -0.47\,(3)\,, \\ c_n^{\mathrm{DFSZ}} &= 0.254 - 0.414\sin^2\beta \pm 0.025, \\ c_p^{\mathrm{DFSZ}} &= -0.617 + 0.435\sin^2\beta \pm 0.025, \end{aligned} \tag{2.7}$$

where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs fields in the DFSZ model. Note, a cancellation in the coupling to neutrons is still possible for special values of $\tan\beta$. In numerical simulations, the value $\tan\beta = 10$ will be used.

A comparison of eqs. (2.1) and (2.6) shows that both the emission of neutrino pairs and axions are caused by fluctuations of the spin density in the medium. The axion emissivity due to the PBF processes in neutron spin-triplet superfluid has been derived in ref. [17] in the form

$$Q_{na}^{\mathrm{PBF}} = g_{\mathrm{ann}}^2 \frac{2}{3\pi^3}\frac{p_{Fn}}{m_n}\frac{m_n^*}{m_n} T^5 F_2\left(\frac{T}{T_c}\right), \tag{2.8}$$

where the function $F_2\left(T/T_c\right)$ is defined in eq. (2.3). The combination

$$g_{\mathrm{ann}} = \frac{\mathfrak{c}_N m_N}{f_a} \tag{2.9}$$

[6]Note that the definition of the gap amplitude in eq. (2.4) matches what is implemented in the NSCool code and differs from the gap definition used in refs. [66, 67] by $1/\sqrt{2}$ times.

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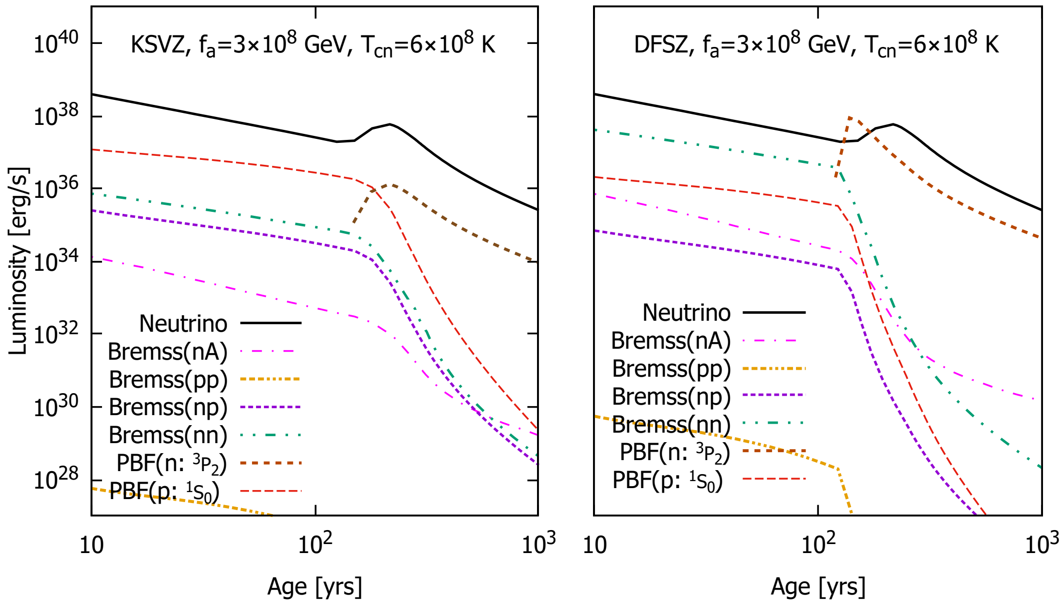

Figure 2. Luminosity of each axion emission and the total neutrino emission processes as a function of time. Dimensionless coupling constants c_N are as indicated in eqs. (2.7) and $\tan\beta = 10$.

with m_N being the nucleon mass, plays a role of a Yukawa coupling. In standard physical units, it turns out

$$Q_{na}^{\rm PBF} = 3.24 \times 10^{40} g_{\rm ann}^2 \frac{p_{Fn}}{m_n^* c}\left(\frac{m_n^*}{m_n}\right)^2 T_9^5 F_2\left(\frac{T}{T_c}\right)\ \frac{\rm erg}{\rm cm^3 s} \tag{2.10}$$

The axion emissivity of the PBF processes in superconducting proton component is given by

$$Q_{pa}^{\rm PBF} = 1.55 \times 10^{40} g_{app}^2 \left(\frac{m_p^*}{m_p}\right)^2 T_9^5 \left(\frac{p_{Fp}}{m_p c}\right)^3 \frac{6}{7} F_2\left(\frac{T}{T_{cp}}\right)\ \frac{\rm erg}{\rm cm^3 s} \tag{2.11}$$

It differs from the proton PBF emission of neutrino pairs in the axial channel (see e.g. [71]) only in the coupling constant and phase volum of freely escaping particles resulting in the weaker temperature dependence.

Axion-nucleon couplings also cause the emission of axions through NN bremsstrahlung processes and modified urca processes, which have so far been studied in the literature (see, for example, [8, 37, 40, 44, 72, 73] and references therein). We omit explicit expressions for these processes for brevity. In figure 2, we show luminosities of various axion emission processes in the KSVZ and DFSZ models with $f_a = 3 \times 10^8$ GeV as functions of time. For comparison, we also show the total luminosity of neutrino emission.

It is instructive to compare this figure with figure 1 of ref. [50] where the same calculation was carried out. In the graphs presented in this work, the surprisingly small contribution of the PBF processes in the neutron spin-triplet superfluid to axion losses immediately catches the eye, while these processes dominate in neutrino losses after the neutron superfluidity onset in the NS core. The authors do not provide an explicit analytical expression for the corresponding axion emissivity, only referring to the work [17]. Let me remind you that in this work the same equation (2.8) is derived which is used in the present work (but see footnote 6).

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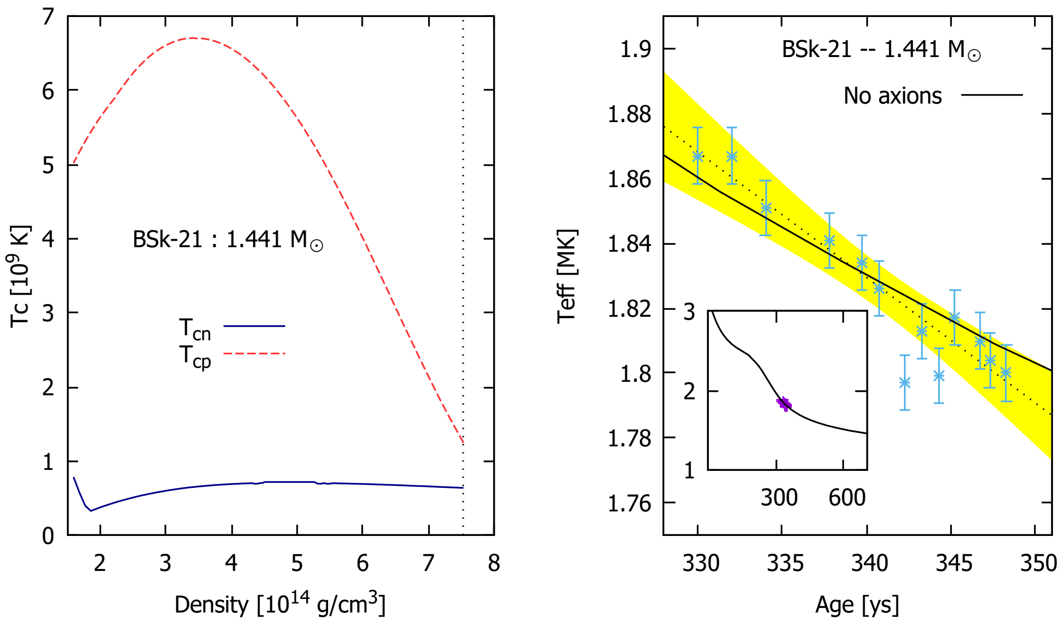

Figure 3. Left panel: critical temperatures T_c for proton singlet superfluidity and for triplet superfluidity of neutrons in the NS core as a function of a mass density constructed using the BSk21 ($M_{NS} = 1.441 M_\odot$, $R = 12.6$ km). Right panel: surface temperature T_s without redshift as a function of age for $1.441 M_\odot$ BSk21 NS with an iron envelope. The black line shows the temperature change obtained in the minimum cooling scenario. The inset shows the same NS cooling trajectory for a longer time.

3 Cooling simulation

Following [74] I consider a non-rotating neutron star of a mass $M_{NS} = 1.441 M_\odot$ with Fe envelope. The equilibrium structure of the star was obtained as a solution to the relativistic Tolman-Oppenheimer-Volkov equations supplemented by the BSk21 equation of state [75, 76].

As was found in ref. [14, 15] the minimal cooling scenario puts stringent constraints on the temperature T_{cn} for the onset of neutron superfluidity in the Cas A NS. Namely, the transition temperature dependence on the density should have a wide peak with maximum $T_{cn}(\rho) \approx (5-8) \times 10^8$ K. For the NS cooling simulations, I use the widely adopted CCDK model [77, 78] for the proton gap and the TToa model [79] for the neutron gap in the NS core. For singlet pairing of neutrons I have chosen the "SFB" model [80]. The choice of other models for the singlet pairing of neutrons slightly affects the result, since the $^1S_0$ pairing of neutrons occurs only in the inner NS crust. Critical temperatures for proton singlet superfluidity and for triplet superfluidity of neutrons in the NS core vs a mass density are shown in the left panel of figure 3. The accepted model of proton superfluidity assumes a sufficiently high critical temperature, which is necessary for sufficient suppression of modified Urca processes prior to the current era of rapid cooling.

Let us first consider NS cooling without axion emission. The corresponding cooling trajectory obtained as a result of numerical simulation is shown in right panel of figure 3 with a black line. The line demonstrates temporal behavior the NS surface temperature. The cooling curve describes the observed decrease in temperature and is within the confidence interval.

Let us now investigate the influence of axion emission processes on the evolution of the NS temperature by adding axion energy losses. Taking the dimensionless coupling constants

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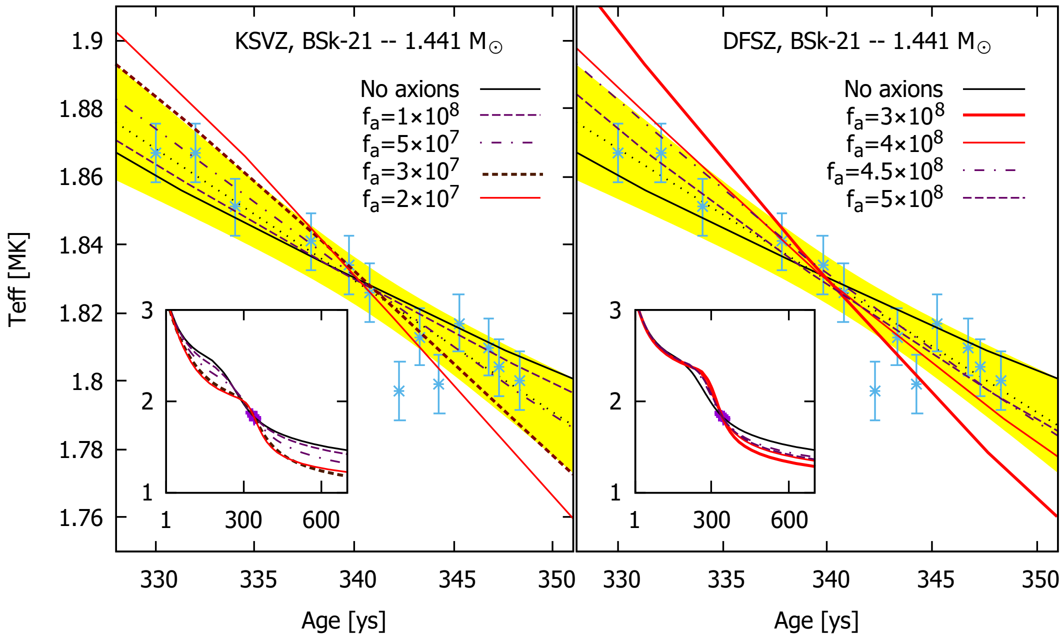

Figure 4. Cooling curves compared to observed data. The inset shows the same NS cooling trajectories for a longer time.

c_N given in eq. (2.7) with $\tan\beta = 10$, I will use the axion decay constant f_a as a parameter. The best-fit curves of the surface temperature T_s for several values of f_a are shown in figure 4 for the KSVZ and DFSZ models together with the trajectory obtained of the minimal neutrino cooling scenario.

For each curve, I vary the neutron triplet gap parameters and the amount of light elements in the NS envelope (the envelope parameter η) to fit the observed data. As one can see, as f_a decreases, the NS surface temperature falls steeper during the observation period, and, finally, below a certain critical value f_a^{cr}, it goes beyond the 99% confidence interval. With the baseline scenario of Cas A NS cooling, we can now definitely constrain the emission of axions by the condition that the cooling curve should be localized in the yellow region. The KSVZ axion model yields $f_{a\mathrm{KSVZ}}^{\mathrm{cr}} = 3 \times 10^7$ GeV, while in the DFSZ model one gets $f_{a\mathrm{DFSZ}}^{\mathrm{cr}} = 4.5 \times 10^8$ GeV.

4 Discussion and conclusion

The influence of emission of axions by nucleons on the steepness of the temperature decline of the NS surface is investigated. Additional axion radiation accompanying the PBF neutrino emission of nucleons in the NS core significantly increases the NS cooling rate, making the cooling trajectory steeper. At some critical value of the axion decay constant, the best fit cooling trajectory goes beyond the 99% confidence interval obtained from the observational data. This condition is used to restrict the minimum value of the axion decay constant to obtain $f_{a\mathrm{KSVZ}} > 3 \times 10^7$ GeV and $f_{a\mathrm{DFSZ}} > 4.5 \times 10^8$ GeV.

Note that in the case of the KSVZ model, the above estimate contradicts the result obtained in [50], and agrees well with the estimates obtained in [17, 42, 44]. Remind that ref. [17] sets a restriction $f_{a\mathrm{KSVZ}} \gtrsim 5 \times 10^7$ GeV for $c_n = -0.02$, while ref. [42] sets $f_{a\mathrm{KSVZ}} \gtrsim (5 \div 10) \times 10^7$ GeV for the KSVZ model. A similar estimate was obtained in [44]: $f_{a\mathrm{KSVZ}} >$

6.7×10^7 GeV. For the DFSZ model, the authors of [44] state: $g^2_{\rm ann} = 7.7 \times 10^{-20}$. If one replaces c_n in this ratio with the value specified in the formula (2.7) with $\tan\beta = 10$, as I use in my calculations, it is easy to find that $f_{a\rm DFSZ} > 5.2 \times 10^8$ GeV, in good agreement with the result obtained in the present work.

Unfortunately, the coupling constants c_N depend on the axion model. Given the QCD uncertainties of the hadronic axion models [81–83], the dimensionless constant c_n could range from -0.05 to 0.14. While the canonical value $c_n^{\rm KSVZ} = -0.02$ is often used as generic examples, in general a strong cancelation of $c_n^{\rm KSVZ}$ below $c_n^{\rm KSVZ} = -0.02$ is also allowed. In case of $c_n^{\rm KSVZ} \to 0$ a powerfull PBF emission of KSVZ axions from $^3\mathrm{P}_2$ neutron pairing is impossible.

A few comments should also be made regarding the observed cooling rate of Cassiopea A remnant, which is still controversial. In works [18, 19] the authors state that the previously described rapid cooling of NS Cas A is probably a systematic artifact, and they cannot rule out the standard slow cooling for this NS. Their results (2006-2012) are consistent with no temperature drop at all, or less temperature drop than previously reported, although the associated uncertainties are too large to firmly rule out the previously reported rapid cooling. Further observations are needed to more accurately estimate the rate of temperature drop. Note, however, that the theoretical cooling trajectory shown in figure 3 is in even better agreement with slower cooling. In this case the linear regression fit (dotted line) would be closer to the theoretical neutrino cooling trajectory which should result to a more strong restrictions to the axion decay constant.

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