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Axion mass limits may be improved by pulsar x-ray measurements

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Axions thermally emitted by a neutron star would be converted into x rays in the strong magnetic field surrounding the star. The present observational limit of pulsed x rays from the Vela pulsar (PSR 0833−45) is not small enough to bound the axion mass. An increase in x-ray sensitivity by a factor of 10^4 would constrain the axion mass $M_a < 3\times10^{-3}$ eV if the core is nonsuperfluid and at temperature $T_c \sim 2\times10^8$ K. This would improve the limits $M_a \lesssim 4\times10^{-2}$ eV from neutron-star cooling and $M_a < 1\times10^{-2}$ eV from red-giant evolution. If the core is superfluid throughout, a factor of 10^5 in sensitivity would be needed. A search for modulated hard x rays from PSR 1509−58 or other young pulsars is suggested. A limit on pulsed hard x rays $<5\times10^{-7}$ photons/cm^2 sec from a very young hot ($T_c \sim 7\times10^8$ K) pulsar within the Galaxy could set a firm bound on the axion mass, since neutron superfluidity is not expected above this temperature.

INTRODUCTION

A natural explanation of the observed *CP* conservation in strong interactions was given by Peccei and Quinn[1] (PQ) which resulted in the introduction of the axion,[2] a light pseudoscalar boson. The scheme was extended to grand-unification scale.[3,4] This led to the "invisible" axion with mass $M_a \sim 3.7\times10^{16}$ eV$^2/F < 1$ eV, where F is the energy scale at which the postulated PQ symmetry is spontaneously broken. Detection of the axion and determination of its mass is important for cosmology as well as elementary-particle physics.

Axion emission of stars is proportional to $M_a{}^2$, as long as the axions do not interact or decay before escaping the star. The axion luminosity would provide an additional cooling mechanism and accelerate stellar evolution.[5] The limit from the sun[6,7] is $M_a < 1.7$ eV, while red giants give a limit $M_a < 0.07$ eV so that axion luminosity will not dominate.[6] Detailed stellar-evolution calculations of red giants[8] give a limit $M_a < 10^{-2}$ eV in order that helium ignition will take place, so that the maximum luminosity of red giants in clusters will be consistent with observation.

A cosmological lower bound to $M_a \gtrsim 10^{-5}$ eV arises from the contribution of relic axions to the energy density of the Universe.[9] Axions with mass near this lower limit would provide a large fraction of the energy density of the Universe in the form of cold dark matter,[10] which could provide the closure density, explain the formation of galaxies, and provide the material of galactic halos,[11] and explain the observed large-scale structure in the distribution of visible matter.[12]

Sikivie[13] pointed out the electromagnetic interaction of axions and suggested laboratory detectors for solar axions of mass near 10^{-1} eV and for galactic-halo axions of mass near 10^{-5} eV. Improved detectors for galactic axions in the range $2\times10^{-6} < M_a < 4\times10^{-4}$ eV have been proposed.[14] Moody and Wilczek[15] have proposed measurement of the extremely weak long-range axionic force.[5]

Iwamoto[16] considered axion emission from neutron stars. He compared the axion luminosity with neutrino and surface thermal photon luminosities in the standard cooling scheme (no pion condensate or quark matter). He found that the axion luminosity will significantly shorten the time for cooling to $T \sim T_1 \equiv 2\times10^8$ K unless $M_a \lesssim 4\times10^{-2}$ eV. We will see that this limit is insensitive to the neutron-star equation of state and the presence or absence of nuclear superfluidity.

AXION-TO-X-RAY CONVERSION BY NEUTRON STAR

In this paper we point out that axions emitted by a neutron star will be converted into x-ray photons in the magnetosphere of the star (see inset of Fig. 1). The enormous magnetic field and the interaction distance of several kilometers can result in efficient conversion of axions into photons, despite the extremely weak coupling of the "invisible" axion.

Observational limits on the modulated flux of x rays from pulsars can provide an upper bound on the axion mass. The bound depends on the temperature and possible superfluidity of the neutron star. The axions will have a thermal distribution[16] at the temperature of the core of the star, $T_c \sim T_1 \equiv 2\times10^8$ K, and are red-shifted as they travel out to the surface. The axions convert into x rays which are further red-shifted as they leave the star.[17,18]

From the astrophysical limits given earlier, $M_a < 1$ eV $\ll kT_c$, so the emitted axions will be highly relativistic. The very small difference between the momentum of the axion and that of the photon is provided by the spatial variation of the magnetic field of the star. For efficient conversion, the field must have significant Fourier components with wave numbers in the range required for momentum conservation. An axion traveling radially outward through the magnetosphere can only convert into an x ray traveling in the same direction, since the momentum available from the magnetic field is insignificant compared to the axion momentum.

The axion-to-x-ray conversion depends on the transverse component of the magnetic field, since the coupling is proportional[13] to $\mathbf{E}_x\cdot\mathbf{B}_*$ where $\mathbf{E}_x$ is the E field of the

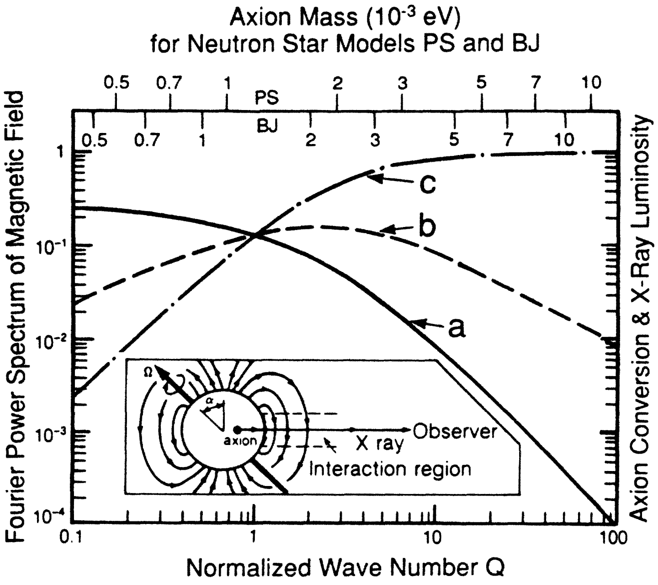

FIG. 1. Axion-to-x-ray conversion at a neutron star. Dependence on normalized wave number Q of the magnetic field $Q=R_*q=R_*M_a{}^2c^3/2\hbar E_a$. The corresponding axion mass M_a for models BJ and PS at $T_c \simeq 2\times 10^8$ K is indicated. a, the Fourier power spectrum of the normalized magnetic field. b, dependence on Q of the cross section for a $a \rightarrow \gamma$ conversion (arbitrary units). c, the normalized x-ray luminosity from axion conversion. Inset: Axion-to-x-ray conversion at a neutron star (see text).

x-ray photon, and $\mathbf{B}_*$ is the B field of the star. The conversion x rays will be polarized, and conversion will be most efficient at the magnetic equator of the neutron star where the field is entirely transverse. The x rays reaching the solar system will be modulated as the neutron star rotates. If radio or optical pulsed emission comes from the polar regions, the modulation will be out of phase.

AXION EMISSION FROM A NEUTRON STAR WITH NONSUPERFLUID CORE

We first calculate the axion luminosity. The result, which is model dependent, will be used in our calculations relating the axion mass to x-ray luminosity. Iwamoto[16] found that the most important process for axion emission from the isothermal core is axion bremsstrahlung from neutron-neutron collisions: $n+n \rightarrow n+n+a$, with an energy-loss rate

$$\epsilon_{ann} \propto M_a{}^2 T^6 \tag{1}$$

from his Eq. (5), correcting his expression for M_a which should read $M_a = 3.7\times 10^{-5}(10^{12}\ \text{GeV}/F)$ eV.

Iwamoto compared the axion luminosity L_a with the neutrino luminosity L_ν and with the luminosity from surface-thermal-photon emission L_s under various conditions, but did not give numerical estimates for L_a. He considered two equations of state: a medium-soft equation of state by Bethe and Johnson[21] (BJ), and a stiff equation of state by Pandharipande and Smith[22] (PS). The neutrino luminosity had previously been calculated by Soyeur and Brown[23] using these two equations of state. Calculations for L from the modified URCA process in the core[23,24] give $L_\nu \approx (10^{34}\ \text{erg/sec})(T/T_1)^8$. Iwamoto found that in the absence of nucleon superfluidity, axion emission will dominate the energy loss from neutron stars at $T_c \sim T_1$, if $M_a \sim 1.1\times 10^{-2}$ eV; so, from (1) and the value of L_ν at T_1, we find

$$L_a \simeq (8\times 10^{31}\ \text{erg/sec})(M_a/10^{-3}\ \text{eV})^2(T/T_1)^6 . \tag{2}$$

AXION EMISSION FROM A NEUTRON STAR WITH SUPERFLUID CORE

In the case of nucleon superfluidity[19,20] the above process is strongly suppressed as a result of the energy gap below the critical temperature $T \sim 7\times 10^8$ K where $^3P_2$ neutron superfluidity sets in at core densities between 2 and 8×10^{14} g/cm^3 (Ref. 19).

Iwamoto found that if the neutrons and protons are superfluid *throughout* the core, the dominant process is axion bremsstrahlung by electrons in the crust: $e^- + (Z,A) \rightarrow e^- + (Z,A) + a$, with an energy-loss rate

$$\epsilon_{aee} \propto M_a{}^2 T^4 \tag{3}$$

from Eq. (8) of Ref. 16.

At $T = 3\times 10^8$ K (BJ) or 2×10^8 K (PS) the axion luminosity L_a will be equal to L_s, the photon luminosity for thermal emission from the surface, if $F = 6\times 10^8$ GeV (BJ) or 9×10^8 GeV (PS), that is, if $M_a = 6\times 10^{-2}$ eV (BJ) or 4×10^{-2} eV (PS). To find the photon luminosity, Soyeur and Brown[23] used the blackbody formula $L_s = 4\pi\sigma R_*{}^2 T_s{}^4$, with $R_* = 11$ km (BJ) or 16 km (PS) from their Table I, and with effective surface temperature T_s ($\sim T_c/125$) taken from Fig. 2 of Tsuruta.[25] The numerical values are $L_s = 3\times 10^{34}$ erg/sec at $T_c = 3\times 10^8$ K (BJ) or 1×10^{34} erg/sec at $T_c = 2\times 10^8$ K (PS). Then, from relation (3),

$$L_a \simeq (1.6\times 10^{30}\ \text{erg/sec})(M_a/10^{-3}\ \text{eV})^2(T/T_1)^4 \tag{4}$$

for BJ, or 4× higher for PS, which has a thicker crust.

AXION MASS LIMITS FROM NEUTRON-STAR COOLING

We find the bound on M_a from neutron-star cooling to be the same for superfluid as for nonsuperfluid models. Although axion emission will dominate the energy loss[16] near T_1 if $M_a > 1.2\times 10^{-2}$ in the absence of nucleon superfluidity in the core, inspection of the cooling curves calculated by several authors[26–29] for a range of nonsuperfluid models (see Table I) indicates that a moderate increase in the cooling rate would lead to a temperature at a given age which is still within the range of uncertainty of the cooling calculations, and so observations of the surface temperature would not confirm or contradict axion emission.

For example, let $M_a = 4\times 10^{-2}$ eV, then from (2), and the expression for L_ν, at $T = 7\times 10^8$ K, $L_a \simeq L_\nu = 2\times 10^{38}$

erg/sec, while at $T=T_1=2\times10^8$ K, $L_a=10^{35}$ erg/sec$\simeq13L_\nu$. Consider model V$_\gamma$II (nonsuperfluid) of Ref. 26, temperatures for this model are given in Table I. The calculated increase of the cooling rate caused by axion emission below $T=7\times10^8$ K would lead to $T=T_1$ at $t\simeq10^4$ yr, instead of at $t\simeq10^5$ yr, giving a corresponding $T_s\simeq1.6\times10^6$ K, which is quite consistent with observation (see the following section).

Similarly, in the superfluid case, although axion emission would dominate[16] for 10^9 K $>T>3\times10^8$ K (BJ) or 4×10^9 K$>T>2\times10^8$ K (PS) the total luminosity would increase by a factor less than 10 for $M_a<4\times10^{-2}$ eV. This would still permit surface temperatures compatible with observation at ages of 10^3 and 10^4 yr. We conclude that the limit on axion mass placed by cooling of neutron stars is $M_a\lesssim4\times10^{-2}$ eV for both superfluid and nonsuperfluid models.

NEUTRON-STAR CORE TEMPERATURES

The emission of axions from neutron stars is strongly temperature dependent. However, cooling calculations for different neutron-star models all give core temperatures between 1.5 and 4×10^8 K at age $t\simeq10^4$ yr even though the models differ in their assumptions of the equation of state, core superfluidity and magnetic field strength (see Table I). The dependence of thermal conductivity of the crust on magnetic field is very weak, and does not affect the core temperature significantly.[30]

It is interesting to note that the predicted surface temperature as seen by a distant observer $T_s^\infty\sim(1.2\text{–}3)\times10^6$ K at age 10^4 yr, quite consistent with the value $T_s^\infty\sim1.5\times10^6$ K from observation of nonpulsed soft-x-ray luminosity from the Vela pulsar,[31] although the observations did not have sufficient spectral resolution to show that the emission has a thermal distribution. The predicted $T_s^\infty\simeq(1.8\text{–}6)\times10^6$ K, for age $t\simeq10^3$ yr, is comparable to $T_s^\infty\simeq2\times10^6$ K from observation of the Crab pulsar.[32]

Alternately, we may instead estimate the core temperature T_c from the observed surface temperature T_s^∞. Then, following the most recent analysis[17] relating T_c and T_s^∞ we expect $T_c\simeq(2.8\text{–}3.6)\times10^8$ K for an observed $T_s^\infty\sim1.5\times10^6$ K (Vela pulsar) and $T_c\sim(4.5\text{–}6)\times10^8$ K for an observed $T_s^\infty\sim2\times10^6$ K (Crab pulsar). [A much lower estimate for the Vela pulsar of $T_c\sim(0.5\text{–}2.5)\times10^7$ K has been made from analysis of postglitch relaxation in terms of vortex creep in the superfluid core,[33] although a similar analysis for the Crab pulsar[34] gave $T_c\sim3\times10^8$ K which is consistent with the other estimates.]

EFFICIENCY OF CONVERSION INTO X RAYS

A general expression for the axion-to-x-ray conversion cross section σ is given by Sikivie in Eq. (6) of Ref. 13. A simple method to calculate σ is to use the results of Ref. 13 for solar axion conversion in a laboratory detector. We divide the number of x rays/sec produced in a laboratory detector by conversion of solar axions:

$$6\times10^{-3}SL^2(10^8\ \text{GeV}/v)^4(B/10T)^2N^2(8\pi R/E_aL)\ \text{sec}^{-1}$$

TABLE I. Neutron-star cooling: summary of theoretical core and surface temperatures.

							Core temperature T_c (10^8 K) vs					Surface temperature T_e (10^6 K) vs			
							Neutron-star age					Neutron-star age			
Ref.[a]	Model	Equation of state	M_* ($M_\odot$)	R_* (km)	ρ_c (10^{14} g/cm^3)	Superfluid core	10^0 yr	10^1 yr	10^2 yr	10^3 yr	10^4 yr	10^5 yr	10^2 yr	10^3 yr	10^4 yr	10^5 yr
26	V$_\gamma$II	Medium	1.07	12.3	7.4	Yes	20	14	9	5.6	1.6	0.1	5	3	1.25	0.17
26	V$_\gamma$II	Medium	1.07	12.3	7.3	No	16	14	8	5.6	4	2.5	4.4	3	2.3	1.6
27	A[b]	Soft	1.32	8	35	Yes	28	16	10	8	3	0.22	8	6	3	0.25
27	A[b]	Soft	1.32	8	35	No	10	8	5.2	3.5	2.7		4.7	3.5	2.7	0.7
28	PS	Stiff	1.3	16.1	4	Yes	16	13	9	5.2	3					
28	PS	Stiff	1.3	16.1	4	No	10	7.4	5.1	3.5	2.2					
29	I	Stiff	0.253	13	4.1	Yes	19	13.5	7.2	3.8	2.1		2.7	1.8	1.2	
29	IIA	Medium	0.822	10.7	9.1	Yes	23	17	8.7	3.8	1.9	0.5	4.4	2.5	1.6	0.7
29	IIB	Medium	0.822	10.7	9.1	No	11	7.2	5	3.4	2.2		3	2.3	1.7	
29	III	Soft	1.54	9.5	18.9	Yes	10	8	5.6	3.7	1.9		3.5	2.6	1.7	

[a] Other authors (Ref. 51) have used low values of opacity (Ref. 17) or have given only surface temperatures (Ref. 52).

[b] Equation of state: "ST" model from Ref. 26, based on Reid potential, with $B\sim5\times10^8$ T; all others for $B=0$.

[Eq. (13) of Ref. 13], by the solar axion flux: $0.8\times10^{17}(10^8\text{ GeV}/v)^2\ m^{-2}\text{sec}^{-1}$ [Eq. (3) of Ref. 13]. The result requires correction by factors $(4\pi)^{-1}(8\sqrt{2})^{-2}\cong(1600)^{-1}$. The factor $(1/4\pi)$ is a correction required because of the use of practical units of magnetic field,[35] while Kaplan[36] showed that the coupling was taken too large in Ref. 13 by a factor of $8\sqrt{2}$. Sikivie[37] has also given corrected detection rates for solar axions.

With the corrections given above, we find

$$\sigma=1.1\times10^{-25}SL^2(M_a/10^{-3}\text{ eV})^2(B/10T)^2R'\ , \qquad (5)$$

where L is the length of the detector in meters, S is its area in square meters, and the result is expressed in terms of M_a by Eq. (2) of Ref. 13: $M_a=1.24\times10^{-3}$ eV$(10^{10}$ GeV$/v)(N/6)$. The response function R' of the detector is equal to the square of the relevant Fourier component of the normalized magnetic field inside the detection region, with wave number

$$q=k_x-k_a=(M_ac^2)^2/2\hbar cE_a \qquad (6)$$

as required for momentum conservation, since the axions are highly relativistic.[13] $E_a\simeq3.3kT_c$ at the peak of the thermal distribution.[38] In terms of R of Eq. (12) of Ref. 13, $R'=8\pi R/E_aL$.

To evaluate σ at the neutron star, we must substitute the square of the Fourier transform of the normalized magnetic field in the magnetosphere outside of the star for the expression given in Ref. 13. We find the required Fourier transform below.

The field distribution may be approximated by a dipole field:

$$\mathbf{B}(r)=(B_0/2)(R_*/r)^3(\hat{\boldsymbol\theta}\sin\theta+2\hat{\mathbf{r}}\cos\theta)\quad\text{for } r>R_*\ ,$$

where r is the radial distance from the center, R_* is the radius of the star, θ is the polar angle from the magnetic field axis, and B_0 is the (radial) field at the pole of the star. We note that the magnetic field at the equator $B_R=B_0/2$. For an oblique rotator with magnetic axis at an angle α to the rotation axis, B_0 may be determined[39] from the pulsar braking:

$$B_0=(3Ic^3P\dot{P}/8\pi^2)^{1/2}R_*{}^3(\sin\alpha)^{-1}\ .$$

We will take $I\cong10^{45}(R_*/10\text{ km})^2$ g cm^2.

Since an axion will convert into an x-ray photon traveling in the same direction, we will treat the magnetic field and its transform in one dimension. Axions are emitted throughout the core (in the crust in case of superfluidity), so we should integrate σ over all parallel axion-photon paths through the magnetosphere which originate inside the core (crust) of the star. The spatial variation of the transverse magnetic field along such paths will be similar, yielding similar spatial frequency distributions. For simplicity we will consider only a central path passing radially through the magnetic equator, where

$$\mathbf{B}(r)=(B_0/2)b(r)\hat{\boldsymbol\theta}\ ,\quad\text{with } b(r)=(R_*/r)^3\ .$$

The Fourier transform of $b(r)$ over the range $R_*<r<\infty$ has been approximated by a discrete Fourier transform $\tilde{b}(Q)$, where $Q=R_*q$. The spectral power distribution $\tilde{b}^2(Q)$ is shown in Fig. 1, curve a. [We note that to a good approximation $\tilde{b}^2(Q)\simeq(2.3+Q^{1.2})^{-5/3}$.] The integral of $B(r)$ over $R_*<r<\infty$ is equal to $R_*B_0/4$, while in the limit $Q\to0$, $|\tilde{b}(Q)|\to0.5$ so that $\tilde{b}^2(Q)\to0.25$ (see Fig. 1). Therefore we set $L=R_*$ in Eq. (13) of Ref. 13, to be consistent with the normalization of $\tilde{b}^2(Q)$. The magnetic field of the neutron star may contain higher multipole components,[40] which do not contribute to the braking since they fall off rapidly with distance from the star. This would increase $\tilde{b}^2(Q)$ for $Q>2\pi$, so we can consider the curves in Fig. 1 as giving lower limits at large Q. The possible existence of very large magnetic fields inside the star[41] would not cause the conversion of axions because the very short photon mean free path $(\ll R_*)$ inside the star would suppress the coherent conversion of axions into photons.

Substituting in (5) and dividing by the area S, we find the fraction σ/S of the incident axions which will convert into x rays in the magnetosphere of the star:

$$\sigma/S=2.7\times10^{-4}\tilde{b}^2(Q)(M_a/10^{-3}\text{ eV})^2\times(B_0/10^8\text{ T})^2(R_*/10\text{ km})^2\ . \qquad (7)$$

The dependence of σ/S on Q is indicated by curve b of Fig. 1 [$\sigma/S\propto\tilde{b}^2(Q)M_a{}^2$ from (7) and $M_a{}^2\propto q\propto Q$ from (5)]. The axion luminosity $L_a\propto M_a{}^2\propto Q$ from (2), (4), and (6), so the x-ray luminosity from axion conversion $L_x=(\sigma/S)L_a\propto Q^2\tilde{b}^2(Q)$, which is plotted in Fig. 1, curve c. This function indicates the dependence of the expected x-ray luminosity on axion mass. It is nearly constant above $Q=10$ (where $M_a=4\times10^{-3}$ eV if $T\simeq T_1$), but decreases rapidly for smaller Q (and M_a). An observational limit on L_x lower than the maximum approached for $M_a\gtrsim10^{-2}$ eV would be needed to place any bound on M_a by this method.

COMPARISON WITH OBSERVATIONS

The present observational limits on the modulated x-ray flux from pulsars are not sufficient to place any upper limit on axion mass. However, we can determine the degree of improvement in existing observations which will be needed to place a bound on M_a. Our conclusions will be model dependent because axion emission is suppressed when the neutrons are superfluid throughout the core.

The Vela pulsar (PSR 0833−45): The best limit to modulated x-ray emission of a reasonably young neutron star is for the Vela pulsar (PSR 0833−45) by Knight, Matteson, Peterson, and Rothschild,[42] who found that the pulsed flux is less than 5×10^{-6} photons/keV cm^{2}sec(3σ) over the range 15−175 keV, i.e., $<5\times10^{-4}$ photons/cm^{2}sec (95% C.L.). For $T=T_1$ and a gravitational potential ϕ/c^2 of -0.16, the energy of observable x-ray photons from axion conversion would be 3.3 $kT_1\times0.86\simeq50$ keV. With this average photon energy, and the Vela pulsar distance of $\simeq500$ parsec, the corresponding (95% C.L.) upper limit on modulated x-ray luminosity is $L_x^\infty<1.2\times10^{33}$ erg/sec.

This may be compared with the calculated x-ray luminosity from axion conversion given in Table II. The calculations are for models BJ and PS with $M_*=1.3M_\odot$ and

TABLE II. Calculated hard-x-ray luminosity of the Vela pulsar from axion conversion in various models for core temperature $T_c = 2\times 10^8$ K and axion mass $M_a = 3\times 10^{-3}$ eV.

Core	Nonsuperfluid		Superfluid	
model	BJ	PS	BJ	PS
R_* (km)	11	16	11	16
Gravitational potential ϕ/c^2	-0.2	-0.12	-0.2	-0.12
B_0 (10^8 T)	2.8	1.33	2.8	1.33
Q (see text)	4.4	6.4	4.4	6.4
$\tilde{b}^2(Q)$ (10^{-2})	3.0	1.7	3.0	1.7
σ/S (10^{-4})	7.0	1.9	7.0	1.9
L_a (10^{32} erg/sec)	7.4	7.4	0.15	0.56
L_x (10^{28} erg/sec)	51	13	1.0	1.1
L_x^∞ (10^{28} erg/sec)[a]	35	11	0.7	0.8
Fraction of present limit (10^{-4})	3	0.9	0.06	0.07

[a] $L_x^\infty = e^{2\phi/c^2} L_x$ from Ref. 17.

$T = T_1$. For the nonsuperfluid models we see that to constrain the axion mass to $M_a < 3\times 10^{-3}$ eV, improvement in the present observational limit by a factor of 3.5×10^3 (BJ) or 1.1×10^4 (PS) is needed.

If the neutrons and protons are superfluid throughout the core axion emission is considerably reduced, so that to set a limit of $M_a < 3\times 10^{-3}$ eV, we require improvement of the present observational limit by a factor of 1.5×10^5.

The core neutrons may be nonsuperfluid in part of the star[19] between the density ranges for ${}^1S_0$ superfluidity (1×10^{11}–1.5×10^{14} g/cm^3) and ${}^3P_2$ superfluidity (2×10^{14}–8×10^{14} g/cm^3). Also, the core neutrons may be nonsuperfluid at densities above 8×10^{14} g/cm^3 which are reached in models with softer equations of state such as BJ (Ref. 43). In that case axion emission would take place by neutron-neutron axion bremsstrahlung from the nonsuperfluid region, and the analysis for nonsuperfluid models would apply.

The Crab Pulsar (PSR 0531+21): The pulsed x-ray emission over the range 45–110 keV is $(2.1\pm 0.7)\times 10^{-4}$ photons/keV cm^{2}sec (Ref. 44). If $T_c \simeq 4\times 10^8$ K, $E_a \simeq 110$ keV, the corresponding energy flux is 1.4×10^{-9} erg/cm^{2}sec. The distance $d \simeq 2\times 10^3$ parsecs, so the luminosity is 7×10^{35} erg/sec. From Fig. 2(b) of Ref. 44 the sinusoidal part of the pulsed flux $\simeq 40\%$, so $L_x^\infty \simeq 3\times 10^{35}$ erg/sec.

The predicted core temperature from Table I is $T_c \sim (3.5$–$8)\times 10^8$ K. We take $T_c = 4\times 10^8$ K, $B_0 = 3.1$ (1.5) $\times 10^8$ T for BJ (PS), and neglect superfluidity. Then we find $L_a \simeq 5\times 10^{34}$ erg/sec for $M_a = 3\times 10^{-3}$ eV from (2) and the calculated L_x^∞ from axion conversion is 6.7 (2.4) $\times 10^{31}$ erg/sec for BJ (PS). Even for a larger axion mass the calculated x-ray flux from axion conversion is much smaller than the measured pulsed x-ray flux, so observation of the Crab pulsar cannot set any axion mass limit.

PSR 1509−58: This pulsar has a spin-down age similar to the Crab, and a distance of about 4.2×10^3 parsecs. It was recently discovered as a soft-x-ray[45] and radio[46] pulsar. The soft x-ray data has been summarized and evaluated.[47] The increase of calculated axion emission at the (presumed) high temperature of this young neutron star can offset the reduction in x-ray flux at the solar system due to the large distance. Also this pulsar has a large $\dot{P}$ which gives $B_0 = 12\times 10^8$ T for model BJ, or $B_0 = 6\times 10^8$ T for model PS. We take $T_c \simeq 4\times 10^8$ K, as for the Crab pulsar, and $M_a = 3\times 10^{-3}$ eV, then $L_a \sim 5\times 10^{34}$ erg/sec and $Q = 2.2$ (3.2) for BJ (PS). From (7), $\sigma/S = 3$ (1) $\times 10^{-2}$ for BJ (PS). The resulting x-ray flux at the solar system is 3 (1) $\times 10^{-6}$ photons/cm^{2}sec for BJ (PS) if the pulsar core is not superfluid. This requires improvement of measurement sensitivity by a factor of 500 compared with the existing Vela observations. No search for pulsed hard x rays from this pulsar has yet been made to the author's knowledge. A good upper limit on modulated x-ray luminosity from this or other[48] young pulsars could set an axion mass limit.

Very young pulsars: The rate of pulsar formation in the galaxy may be $\frac{1}{20}$ to $\frac{1}{80}$ per yr (Ref. 49). Very young pulsars would have hot cores; at $t \sim 10^2$ yr the expected $T_c \sim (6$–$10)\times 10^8$ K (Table I). This may be sufficient to extinguish any ${}^3P_2$ superfluidity of the core neutrons and eliminate suppression of axion emission caused by superfluidity. For $T_c \sim 7\times 10^8$ K and $M_a = 3\times 10^{-3}$ eV, $L_a \simeq 1\times 10^{36}$ erg/sec and $E_a \simeq 200$ keV. The hard x rays from axion conversion could reach the solar system from any part of the Galaxy. We will assume that the pulsar magnetic field (which can be determined from $P\dot{P}$) has reached at least 3×10^8 T within that time. Then for model BJ (PS), $Q = 1.3$ (1.8), and $L_x^\infty \simeq 3$ (5) $\times 10^{33}$ erg/sec. For a typical distance $d \sim 1.3\times 10^4$ parsecs we find the modulated flux at the solar system measured would be 5 (9) $\times 10^{-7}$ photons/cm^{2}sec. A young pulsar, if found, could be very useful in setting an improved axion mass limit without the uncertainty of core superfluidity. There exist strong galactic x-ray sources[50] of uncertain nature with flux of about 5×10^{-5} photons/keV cm^{2}sec. A search for periodicity in these sources would be necessary to confirm that they are pulsars, evaluate their magnetic field strength, and set a limit on modulated x-ray flux.

CONCLUSIONS

Axion emission by neutron stars can be detected by observation, unlike neutrino emission, since axions are converted into x rays in the magnetosphere of the star. The production of axions in neutron stars and the conversion efficiency both increase with axion mass, so upper limits could be placed on the axion mass M_a from a sufficiently good observational limit on modulated x ray flux from a pulsar.

Improvement in observational limits on modulated x-ray emission from the Vela Pulsar appears to offer the best prospects for limiting the axion mass to below 3×10^{-3} eV. In the absence of nucleon superfluidity in the core, and assuming standard cooling which gives a core temperature $T_c \simeq 2\times 10^8$ K for the Vela pulsar (no pion condensation or quark matter), an improvement in the present observational limit on the modulated x-ray flux by a factor of 10^4 can limit the axion mass to less than 3×10^{-3} eV *if* pulsed x-ray emission of nonaxion origin from the pulsar magnetosphere does not interfere. Measurements of modulated x-ray emission from PSR 1509−58 or a still younger pulsar could also provide a limit on the axion mass. A bound from a very young hot pulsar would be independent of possible superfluidity of the core at lower temperatures.

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