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AXION MASS LIMITS FROM PULSAR X RAYS

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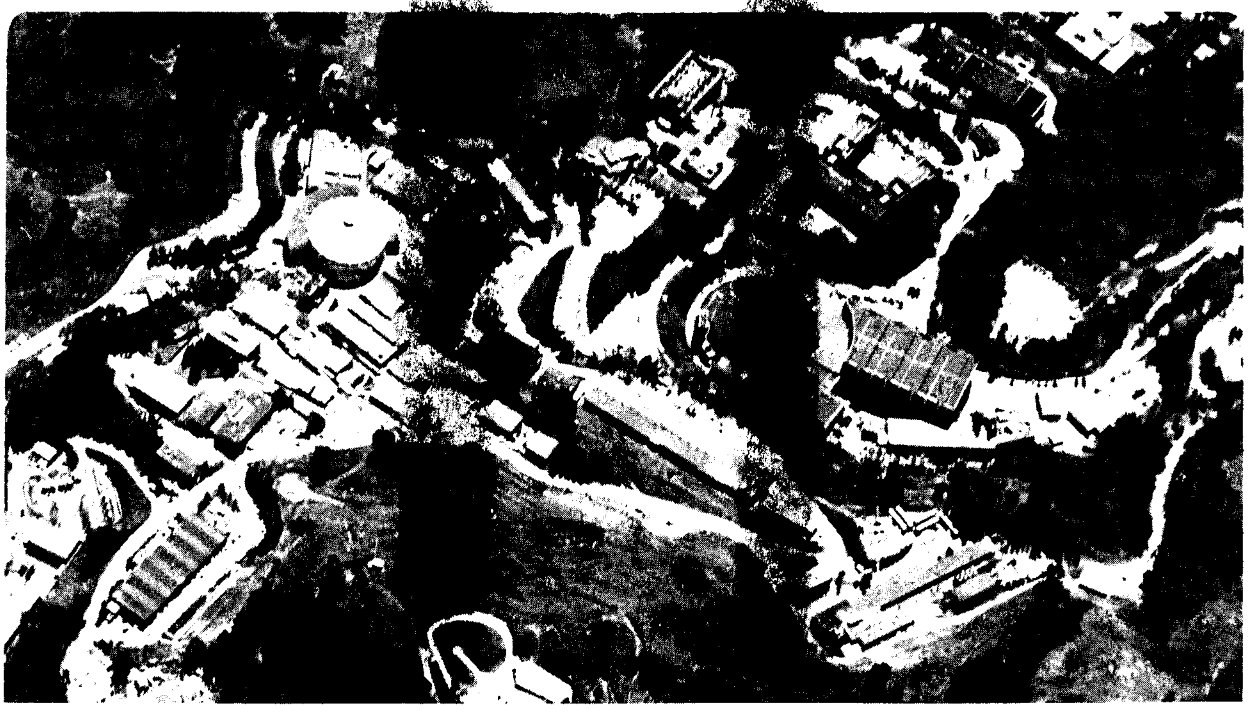

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Contents

Introduction

A natural explanation of the observed CP conservation in strong interactions was given by Peccei and Quinn[1], which resulted in the introduction of the axion[2], a light pseudo-scalar boson. The scheme was extended to grand unification scale[3] and led to the 'invisible' axion with $M_a \sim 10^{16}(\mathrm{eV})^2/F < 1$ eV, where F is the energy scale at which the postulated P-Q symmetry is spontaneously broken. Detection of the axion and determination of its mass is important for cosmology as well as elementary particle physics. The axion mass M_a has been limited by laboratory experiments[4] and by astrophysical arguments based on the consequences of axion emission on evolution of the sun[5,6] to $M_a < 6\times10^{-1}$eV and of red giant stars[5] to $M_a < 10^{-1}$eV. 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.[7] 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[8], which could provide the closure density, explain the formation of galaxies and provide the material of galactic halos[9], and explain[10] the observed large scale structure in the distribution of visible matter.

Sikivie[11] has 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. The author has proposed an improved detector[45] for the range $10^{-5}\mathrm{eV} < M_a < 4\times10^{-4}$eV. Moody and Wilczek[12] have proposed measurement of the extremely weak long range axionic force.[5] Recently Iwamoto[13] has 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 dominate and shorten the time for cooling to $T \sim T_1 = 2\times10^8$K if $M_a > 1.1$-1.7×10^{-2}eV. This limit is independent of the existence or absence of nuclear superfluidity as explained later.

Axion to X ray conversion by neutron stars:

In this paper we point out that axions emitted by a neutron star will be converted into X ray photons in the magnetosphere of of the star (see inset of Figure 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[13] at T_c the temperature of the core of the star, and convert into X rays with the same energy. (The axions will be red shifted as they travel out to the surface and the X ray photons will be redshifted as they leave the star.[14,15])

From the astrophysical limits given earlier, $M_a < 1\text{eV} \ll kT_c$, 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. Conversion may be quite efficient in the star's extremely strong magnetic field ($B > 10^{12}$ gauss) if the field has significant Fourier components with spatial frequencies in the range required for momentum conservation. An axion traveling radially outward through the magnetosphere converts 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, (the coupling is proportional[11] to $E_x \cdot B_*$ where E_x is the E field of the X ray photon, and 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 of opposite phase.

Axion emission from neutron stars:

First we will 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[13] 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 energy loss rate $\epsilon_{ANN} \propto M_a^2 T^6$ (1), from his equation 5 (correcting his expression for M_a). In case of nucleon superfluidity[16,17] this 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.[16] The second important process was found to be axion bremsstrahlung by electrons in the crust: $e^- + (Z,A) \rightarrow e^- + (Z,A) + a$, with energy loss rate $\epsilon_{Aee} \propto M_a^2 T^4$ (2), from equation 8 of Ref. 13. This process will dominate for $T < 2\text{-}3 \times 10^7$K because of the weaker temperature dependence, and will also dominate at higher temperatures if the first process is suppressed by neutron superfluidity.

Iwamoto compared the axion luminosity L_a with the neutrino luminosity L_ν and with the luminosity from surface thermal photon emission L_e 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 (BJ)[18], and a stiff equation of state by Pandharipande and Smith (PS)[19]. The neutrino luminosity had previously been calculated by Soyeur and Brown[20] using these two equations of state. Calculations for L_ν from the modified URCA process in the core[20,21] give $L_\nu \sim 10^{34}$ 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 $T_c \sim T_1 = 2 \times 10^8$K, if $M_a > 3 \times 10^{-3}$eV, so from (1), we have

$$L_a \sim 1.1 \times 10^{33} \text{ erg/sec } (M_a/10^{-3}\text{eV})^2 \, (T/T_1)^6 \qquad (3)$$

Axion emission from a neutron star with superfluid core.

Iwamoto found that if the neutrons and protons are superfluid throughout the core, the second process (axion luminosity due to bremsstrahlung by electrons in the crust) will dominate, so that at $T \sim 3\times10^8$K (BJ) or 2×10^8K (PS) the axion luminosity L_a will be equal to L_e the photon luminosity for thermal emission from the surface, if $F = 6\times10^8$GeV(BJ) or 9×10^8GeV(PS), that is if $M_a \sim 1.7\times10^{-2}$eV (BJ) or 1.1×10^{-2}eV(PS). Iwamoto used the photon luminosity calculated by Soyeur and Brown[20], who used the black body formula $L_e' = 4\pi\sigma R_*^2 T_s^4$, 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 figure 2 of Tsuruta[22]. The numerical values are $L_e \sim 3\times10^{34}$erg/sec at $T = 3\times10^8$K (BJ) or 1×10^{34}erg/sec at $T = 2\times10^8$K (PS). Then from relation (2),

$L_a \sim 2\times10^{31}$erg/sec $(M_a/10^{-3}\text{eV})^2\ (T/T_1)^4$ (4) for (BJ), or

$\sim 10\times10^{32}$erg/sec $(M_a/10^{-3}\text{eV})^2\ (T/T_1)^4$ (5) for (PS), which has a thicker crust.

Axion Mass Limits from Neutron Star Cooling

Although axion emission will dominate[13] the energy loss near T_1 if $M_a > 3\times10^{-3}$ in the absence of nucleon superfluidity in the core, inspection of the cooling curves calculated by several authors[23-26] for a range of nonsuperfluid models (see Table I) indicates that a moderate increase in cooling rate would lead to a temperature at a given age which is still within the range of uncertainty of the cooling calculations. So observations of the surface temperature would not confirm or contradict axion emission. For example, let $M_a = 10^{-2}$eV, then from (3), at $T = 7\times10^8$K, $L_a \sim L_\nu = 2\times10^{38}$erg/sec, and at $T = T_1 = 2\times10^8$K, $L_a \sim 10^{35}$erg/sec ~ 11 L . Consider model Vγ II (nonsuperfluid) of Ref 23, temperatures for this model are given in Table 1. The calculated increase of the cooling rate caused by axion emission below $T = 7\times10^8$K would lead to $T \sim T_1$ at $t \sim 10^4$years, instead of at $t \sim 10^5$years, giving a corresponding Te

$\sim 1.6\times10^{o}$K, which is quite consistant with observation. Similarly, in the superfluid case, although axion emission would dominate[13] for 10^9K $>$ T $>$ 3×10^8K (BJ) or 4×10^9 $>$ T$>$ 2×10^8K (PS) the total luminosity would increase by a factor less than ten for Ma$<$ 10^{-2}eV. This would still permit surface temperatures compatible with observation at ages of 10^3 and 10^4 years. We conclude that the limit on axion mass placed by cooling of neutron stars is $M_a < 1\text{-}2\times10^{-2}$eV for both superfluid and non superfluid models.

Temperature of neutron stars

The emission of axions is strongly dependent on temperature, but cooling calculations for different neutron star models with various equations of state, with superfluid and nonsuperfluid cores, and with various magnetic fields all give core temperatures between 1.5 and 4×10^8K at age $t\sim10^4$years (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.[27] It is interesting to note that the predicted surface temperature as seen by a distant observer $T_e^{\infty} \sim 1.2\text{-}3\times10^6$K at age 10^4 years, quite consistant with the value $T_e^{\infty} \sim 1.5\times10^6$K from observation of non pulsed soft x ray luminosity from the Vela pulsar,[28] although the emission has not yet been shown to have a thermal distribution. Similarly, for age $t\sim10^3$yrs, the predicted $T_e^{\infty} \sim 1.8\text{-}6\times10^6$K, is comparable to $T_e^{\infty} \sim 2\times10^6$K from observation of the Crab pulsar.[29] Alternatively, we may estimate the core temperature T_c from observations of T_e^{∞}. Following the most recent analysis[14] relating T_c and T_e^{∞} we expect $T_c \sim 2.8\text{-}3.6\times10^8$K for an observed $T_e^{\infty} \sim 1.5\times10^6$K (Vela pulsar) and $T_c \sim 4.5\text{-}6\times10^8$K for an observed $T_e^{\infty} \sim 2\times10^6$K (Crab pulsar). (A much lower estimate of $T_c \sim 0.5\text{-}2.5\times10^7$K for the Vela pulsar has been made[30] from analysis of post glitch relaxation in terms of vortex creep in the superfluid core.)

Efficiency of conversion into X Rays:

A general expression for the axion to x ray conversion cross section is given in equation 6 of ref 11

$$\sigma = \left(\frac{1}{4\pi}\right) \frac{1}{16\pi^2|\vec{\beta}_a|} \left(\frac{e^2 N}{3\pi^2 v}\right)^2 \sum_\lambda \int d^3k_\gamma \delta(E_\gamma - E_a) \left| \int_V d^3x\, e^{i\vec{q}\cdot\vec{x}} \vec{B}(\vec{x}) \cdot \vec{\epsilon}(\vec{k}_\gamma, \lambda) \right|^2, \qquad (6)$$

where $q = k_x - k_a = (M_a c^2)^2 / 2\hbar c E_a$ (7), as required for momentum conservation since the axions are highly relativistic.[31] $E_a \sim 1.8\ kT_c$ at the peak of the Plankian distribution. The factor $(1/4\pi)$ is a correction given by Sikivie. A simple method to calculate the cross section σ is to use the results of Ref 11 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: $(1/4\pi)\ 6\times10^{-3}\ S\ L^2\ (10^8 \mathrm{GeV}/v)^4\ (B/10T)^2\ N^2\ (8\pi R/E_a L)$/sec (equation 13 of Ref 11), by the solar axion flux: $0.8\times10^{17}\ (10^8\mathrm{GeV}/v)^2/\ m^2$ sec (equation 3 of Ref 11). We find

$$\sigma = 1.4\times10^{-23}\ S\ L^2\ (M_a/10^{-3}\mathrm{eV})^2\ (B/10T)^2\ R' \qquad (8)$$

where L is the length of the detector in meters, S is the area in sq. meters, and the result is expressed in terms of M_a by equation 2 of Ref 11: $M_a = 1.24\times10^{-3}\mathrm{eV}\ (10^{10}\mathrm{GeV}/v)\ (N/6)$. The response function R' of the detector is equal to the square of the Fourier transform of the normalized magnetic field inside the detection region. (In terms of R of equation 12 of Ref. 11, $R' = 8\ R/E_a L$.) 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. 11. We find the required Fourier transform below.

The field distribution may be approximated by a dipole field:

$$B(r) = (B_o/2)\,(R_*/r)^3\,(\hat{\Theta}\sin\Theta + 2\,\hat{r}\cos\Theta) \quad \text{for } r > R_*, \tag{9}$$

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_o is the (radial) field at the pole of the star. We note that the magnetic field at the equator $B_R = B_o/2$. For an oblique rotator with magnetic axis at angle α to the rotation axis, B_o may be determined[32] from the pulsar braking: $B_o=(3Ic^3P\dot{P}/8\pi^2)^{1/2}R_*^{\,3}\sin^{-1}\alpha$. We will take $I \sim 10^{45}(R_*/10\text{Km})^2$ gm 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 $B(r) = B_R\, b(r)\,\hat{\Theta} = (B_o/2)\, b(r)\,\hat{\Theta}$, 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 $\underline{b}(Q)$, where $Q= R_*\, q$, with power distribution $\underline{b}^2(Q)$ shown in figure 1. (We note that to a good approximation $b^2(Q) \sim (2.3+Q^{1.2})^{-5/3}$.) The integral of B(r) over $R_* < r < \infty$ is equal to $R_*\ B_R\,/2$, while in the limit $Q \to 0$, $\underline{b}^2(Q) \to 0.5$ so that $\underline{b}^2(Q) \to 0.25$ (see figure 2), therefore we set $L=R_*$ in equation 13 of Ref 11 to be consistant with the normalization of $\underline{b}^2(Q)$. The magnetic field of the neutron star may contain higher multipole components[33], which do not contribute to the braking since they fall off rapidly with distance from the star. This would increase $\underline{b}^2(Q)$ for $Q > 2\pi$, so we can consider the curves in figure 1 as giving lower limits at large Q. The possible existence of very large magnetic fields inside the star[34] 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 (8) 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:

$$\sigma/S \sim 0.035\, b^2(Q)\, (M_a/10^{-3}\mathrm{eV})^2\, (B_o/10^{12}\mathrm{Gauss})^2\, (R_*/10\mathrm{Km})^2 \qquad (10)$$

The dependence of σ/S on Q is indicated by curve Q $\underline{b}^2(Q)$ in Figure 1, since $\sigma/S \propto b^2(Q) M_a{}^2$ from (10) and $M_a{}^2 \propto q \propto Q$ from (7). However, the conversion efficiency cannot exceed 0.5 due to reconversion of X rays into axions, which was not considered in (6). The correct expression for the conversion efficiency $\eta = (1/2)(1-e^{-2\sigma/S})$ (11). We also note that when $\sigma/S > 0.5$ in (10), the modulation of the x ray signal with rotation of the pulsar will be suppressed. From (10) and Figure 1, for $R_* \sim 10$ Km, this can only happen if $B_o > 7\times10^{12}$gauss, and will occur near $M_a \sim 1\text{-}2\times10^{-3}$eV.

For sufficiently small B_o (giving $\sigma/S < 0.5$), the axion luminosity $L_a \propto M_a{}^2 \propto Q$ from (3), (4), (5), and (7), so the X ray luminosity from axion conversion $L_x = \eta L_a \propto Q^2 \underline{b}^2(Q)$, which is plotted in figure 1. This function indicates the dependence of the expected X ray luminosity on axion mass. It is nearly constant above Q=10 (where $M_a \sim 3\times10^{-3}$eV if $T \sim T_1 = 2\times10^8$K), but decreases rapidly for smaller Q (and M_a).

For $M_a < 7\times10^{-4}$eV, $Q < 0.4$ and from figure 1, $b^2(Q) \rightarrow 0.25$. Then, so long as $\sigma/S <$ 0.5 in (10), i.e. for $B_o < 7\times10^{12}\, (10^{-3}\mathrm{eV}/M_a)$ gauss, and the core is not superfluid, we may combine (10) and (3) to give

$$L_x \sim 1\times10^{31}\mathrm{erg/sec}\, (M_a/10^{-3}\mathrm{eV})^4\, (B_o/10^{12}\mathrm{gauss})^2\, (R_*/10\mathrm{Km})^2\, (T/T_1)^6 \qquad (12)$$

Comparison with observations.

We shall attempt to use observational limits on the modulated X ray flux from pulsars in conjunction with the preceeding analysis to place upper limits 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 (PSR0833-45): The best limit to modulated X ray emission of a reasonably young neutron star is for the Vela pulsar(PSR 0833-45) by Knight et al,[35] who found that the pulsed flux is less than 5×10^{-6}/Kev cm^2sec (3σ) over the range 15-175 keV, i.e. $<5\times10^{-4}$photons/cm^2 sec (95% confidence level). For $T=T_1$ and a redshift $\sim$1.16, the energy of observable redshifted X ray photons from axion conversion would be $\sim 1.8kT_1 x 0.86 \sim 27$keV. With this average photon energy, and since the distance of the Vela pulsar is $\sim$500 parsec, the corresponding (95% CL) upper limit on modulated X ray luminosity is $L_x < 7\times10^{32}$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 $M_*=1.3\ M_\odot$ (solar mass), and with $T=T_1=2\times10^8$K. For the nonsuperfluid models we see that to constrain the axion mass to $M_a < 2\times10^{-3}$eV, improvement in the present observational limit by a factor of 5 (BJ) or 12 (PS) is needed. To constrain $M_a < 6\times10^{-4}$eV will require an improvement by a factor of 100-200 (examples 5 &6). This sensitivity may be approached by the next generation of X ray telescopes.[36]

If the neutrons and protons are superfluid throughout the core axion emission is considerably reduced, so that to set a limit of $M_a < 2\times10^{-3}$eV (examples 3 and 4 of Table II), we require improvement of the present observational limit by a factor of 140-230. Examples 7 and 8 give L_x^∞ calculated for $M_a=1\times10^{-3}$eV in superfluid models, the required factor of improvement would be 500-1100.

The core neutrons may be nonsuperfluid in part of the star[16] 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). 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.[36] Axion emission would take place by process (1) from the nonsuperfluid region, leading to a limit on the axion mass similar to the nonsuperfluid case without requiring such a large improvement in the X ray observations.

<u>The Crab Pulsar(PSR0531+21)</u>: The pulsed X ray emission over the range 45-110 KeV is $2.1\pm0.7\times10^{-4}$photons/KeV cm^2 sec.[37] If $T_c \sim 4\times10^8$K, $E_a \sim 64$ KeV, then the energy flux $\sim 1.4\times10^{-9}$ erg/cm^2 sec. The distance d $\sim 2\times10^3$ parsecs, so the luminosity is 7×10^{35}erg/sec. From figure 2b of Ref 37 the sinusoidal part of the pulsed flux <40%, so $L_x^\infty < 3\times10^{35}$erg/sec.

The predicted core temperature from Table I is $T_c \sim 3.5$-8×10^8K. We take $T_c=4\times10^8$K and neglect superfluidity. Then we find $L_a \sim 2.8\times10^{35}$ erg/sec for $M_a = 2\times10^{-3}$eV from (3) and the calculated L_x^∞ from axion conversion[38] is $3(1.2)\times10^{34}$erg/s for BJ (PS). Even for a larger axion mass the calculated X ray flux from axion conversion is smaller than the measured pulsed X ray flux, so observation of the Crab pulsar cannot set any axion mass limit.

<u>PSR 1509-58</u>: This pulsar has a spin down age similar to the Crab, and a distance of about 4.2×10^3parsecs. It was recently discovered as a soft X ray[39] and radio[40] pulsar. The soft X ray data has been summarized and evaluated.[41] The increase of calculated axion emission at the (presumed) higher temperature of this younger neutron star can offset the reduction in X ray flux at the solar system due to the larger distance. This pulsar has a large $\dot{P}$ which gives $B_o \sim 12\times10^{12}$gauss for model BJ or $B_o \sim 6\times10^{12}$gauss for model PS. The axion to X ray conversion is limited since η saturates at 0.5, and as pointed out earlier, the modulation of the X ray flux will be suppressed. We roughly

estimate the degree of suppression by comparing the conversion effeciency η in the equatorial field $B_R = B_o/2$ when the magnetic equator is in line with the observer, with the effficiency for a transverse field of half this value $\eta_{1/2}$, to model the reduction of the transverse field component as the pulsar rotates. We take $T_c \sim 4\times10^8$ K as for the Crab pulsar, so for $M_a = 2\times10^{-3}$ eV, $L_a \sim 2.8\times10^{35}$ erg/sec and $Q = 1.75$ (2.6) for BJ (PS) as for the Crab. From (10), $\sigma/S \sim 2.07$ (0.77) for BJ (PS). The conversion effeciency $\eta = 0.49$ (0.39) while $\eta_{1/2} = 0.32$ (0.16). We estimate the X ray modulation to be $\eta - \eta_{1/2} = 0.17$ for BJ (or 0.23 for PS). The resulting X ray flux at the solar system is $1.8(2.8)\times10^{-4}$ /cm^2 sec for BJ (or PS). We see that if the modulated hard X ray flux from this pulsar is $< 1.8\times10^{-4}$/cm^2 sec then $M_a < 2\times10^{-3}$ eV if the pulsar core is not superfluid. This requires a threefold improvement in measurement sensitivity compared with the existing Vela observations. In superfluid models $L_a \sim 1.25$ (6.4) $\times10^{33}$ erg/sec for BJ (PS) from (4) and (5), giving a flux of $8(64)\times10^{33}$/cm^{2}sec. This requires a 600-fold (80-fold) increase in measurement sensitivity to limit $M_a < 2\times10^{-3}$ eV. No search for pulsed hard X rays from this pulsar have yet been made to the authors knowledge. A good upper limit on modulated X ray luminosity from this pulsar could set an axion mass limit.[49]

RCW 103: This X ray source may be a hot neutron star at $d \sim 3.3\times10^3$ parsecs, since soft X ray observations[42] are consistant with $T_e^{\infty} \sim 2\times10^6$K.

Young pulsars: The rate of pulsar formation in the galaxy[43] may be 1/20 to 1/80 per year. Young pulsars would have hot cores, and the hard ($\sim$100 keV) X rays from axion conversion would penetrate the galaxy. At age $t \sim 10^2$y the expected core temperature $T_c \sim 6\text{-}10\times10^8$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 $T_c \sim 7\times10^8$K and $M_a \sim 2\times10^{-3}$eV, $L_a \sim 8\times10^{36}$erg/sec and $E_a \sim 110$ KeV. We assume that the pulsar magnetic field (which can be determined from $P\dot{P}$) has reached at least 3×10^{12}gauss within that time. Then for model BJ (PS), $Q \sim 1.0$ (0.5), $\eta - \eta_{1/2} = 0.12(0.19)$

and L_x^{∞} $\sim 7(12)\times 10^{35}$erg/sec. For a typical distance d $\sim 1.3\times 10^4$ parsecs we find the modulated flux at the solar system measured over a 10^2 keV range would be $\sim 2.2(4)\times 10^{-6}$ photons/keV cm^{2}sec, (the same order as the present detection limit for pulsed X rays from the Vela pulsar).

A young pulsar, if found, could be very useful in setting an axion mass limit. There exist strong galactic X ray sources[44] of uncertain nature with flux of about 5×10^{-5}/Kev cm^{2}sec. A search for periodicity in these sources would be necessary to convirm that they are pulsars, evaluate their magnetic field strength, and set a limit on modulated X ray flux. Very recently, D. A. Green and S. F. Gull[48] have reported a 'filled center' supernova remnant G227.1+1.0 with possible pulsar only a few hundred years old, and likely distance d$\sim 10^4$ parsecs, which may be suitable.

Conclusions.

Axion emission by neutron stars can be detected by observation, unlike neutrino emission, since axions are efficiently 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 can be placed on the axion mass M_a from observational limits to modulated X ray flux from pulsars.

Improvement in observational limits on modulated X ray emission from the Vela Pulsar appear to offer the best prospects for limiting the axion mass to below 2×10^{-3}eV. In the absence of nucleon superfluidity in the core, and assuming standard cooling, which gives a core temperature $T_c \sim 2\times 10^8$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 12 can limit the axion mass to less than 2×10^{-3}eV if pulsed X ray emission of non-axion origin from the pulsar magnetosphere does not interfere. Future X ray telescopes with 230 fold increase in sensitivity may establish limits for $M_a < 2\times 10^{-3}$eV (for models with superfluid neutrons throughout the core), or for non superfluid models, $M_a < 6x10^{-4}eV$. Measurements of modulated X ray emission from PSR 1509-58 or a still younger pulsar may 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. The required sensitivity is on the same order as that already achieved in the measurements of the Vela pulsar. The remaining allowed range of axion mass $6x10^{-4}eV > M_a > 10^{-5}eV$ (the cosmological lower bound) may be covered by an improved wide range Sikivie type laboratory cavity detector[45] which can detect relic axions if they make up the galactic halo.

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49 Reduction of the theoretical axion coupling would not reduce the modulated X ray flux proportionately, since η is saturated in the high magnetic field. For example, if we reduce the cross section σ by a factor of 4, we find $\sigma/S = 0.52$ (0.19), $\eta = 0.32$ (0.16), $\eta_{1/2} = 0.11$ (0.046), and $\eta - \eta_{1/2} = 0.21$ (0.11) for BJ (PS) for non-superfluid models. The resulting modulated X ray flux is $2.2(1.3)\times10^{-4}/cm^2$ sec for BJ (PS), or 0.45 (0.25) of the present limit on modulated X rays from the Vela pulsar.

TABLE I

Neutron Star Cooling: Calculated Core and Surface Temperatures

Ref *	Model	E.O.S	M_* ($M_\odot$)	R_* (Km)	ρ_c 10^{14} g/cm^3	Super-fluid core	Core Temperature Tc (10^8K) neutron star age (years)						Surface Temp Te (10^6K) neutron star age (yrs)			
							10^0	10^1	10^2	10^3	10^4	10^5	10^2	10^3	10^4	10^5
23	V II	medium	1.07	12.3	7.4	yes	20	14	9	5.6	1.6	0.1	5	3	1.25	0.17
23	V II	medium	1.07	12.3	7.3	no	16	14	8	5.6	4	2.5	4.4	3	2.3	1.6
24	A **	soft	1.32	8	35	yes	28	16	10	8	3	0.22	8	6	3	0.25
24	A **	soft	1.32	8	35	no	10	8	5.2	3.5	2.7	-	4.7	3.5	2.7	0.7
25	PS	stiff	1.3	16.1	4	yes	16	13	9	5.2	3	-	-	-	-	-
25	PS	stiff	1.3	16.1	4	no	10	7.4	5.1	3.5	2.2	-	-	-	-	-
26	I	***	0.253	13	4.1	yes	19	13.5	7.2	3.8	2.1	-	2.7	1.8	1.2	-
26	IIA	***	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
26	IIB	***	0.822	10.7	9.1	no	11	7.2	5	3.4	2.2	-	3	2.3	1.7	-
26	III	***	1.54	9.5	18.9	yes	10	8	5.6	3.7	1.9	-	3.5	2.6	1.7	-

* other authors[46] have used low values of opacity[14] or have given only surface temperatures.[47]

** Equation of state: "ST" model from Ref 23, based on Reid potential, with $B \sim 5 \times 10^{12}$ gauss; all others for B=0.

*** BPS crust, modified interior.

Table II

Calculated Hard X Ray Luminosity of the Vela Pulsar from Axion Conversion in Various Models*

Example	1	2	3	4	5	6	7	8
M_a $(10^{-3}eV)$	2	2	2	2	0.6	0.6	1	1
Core	nonsuperfl.		superfluid		nonsuperfl.		superfluid	
Model	BJ	PS	BJ	PS	BJ	PS	BJ	PS
R_* (Km)	11	16	11	16	11	16	11	16
ϕ/c^2**	0.2	0.12	0.2	0.12	0.2	0.12	0.2	0.12
B_o $(10^{12}g)$	2.8	1.33	2.8	1.33	2.8	1.33	2.8	1.33
Q (see text)	3.5	5.1	3.5	5.1	0.32	0.46	0.88	1.28
$\underline{b}^2(Q)$ (10^{-2})	4	2.5	4	2.5	21	19	0.14	0.11
σ/S (10^{-2})	5.3	1.6	5.3	1.6	2.54	1.1	4.6	1.75
L_a $(10^{32}erg/s)$	44	44	0.8	4	4	4	0.2	1
L_x $(10^{30}erg/s)$	230	70	4.3	6.4	10	4.4	0.92	1.75
L_x^∞ $(10^{30}erg/s)$	160	56	3	5	7	3.5	0.63	1.4
Fraction of present limit	$\frac{1}{4.4}$	$\frac{1}{12.5}$	$\frac{1}{230}$	$\frac{1}{140}$	$\frac{1}{100}$	$\frac{1}{200}$	$\frac{1}{1100}$	$\frac{1}{500}$

* for Core $T_c=2x10^8K$

** $L = e^{-2\phi/c^2} L_x$ from Ref 14.

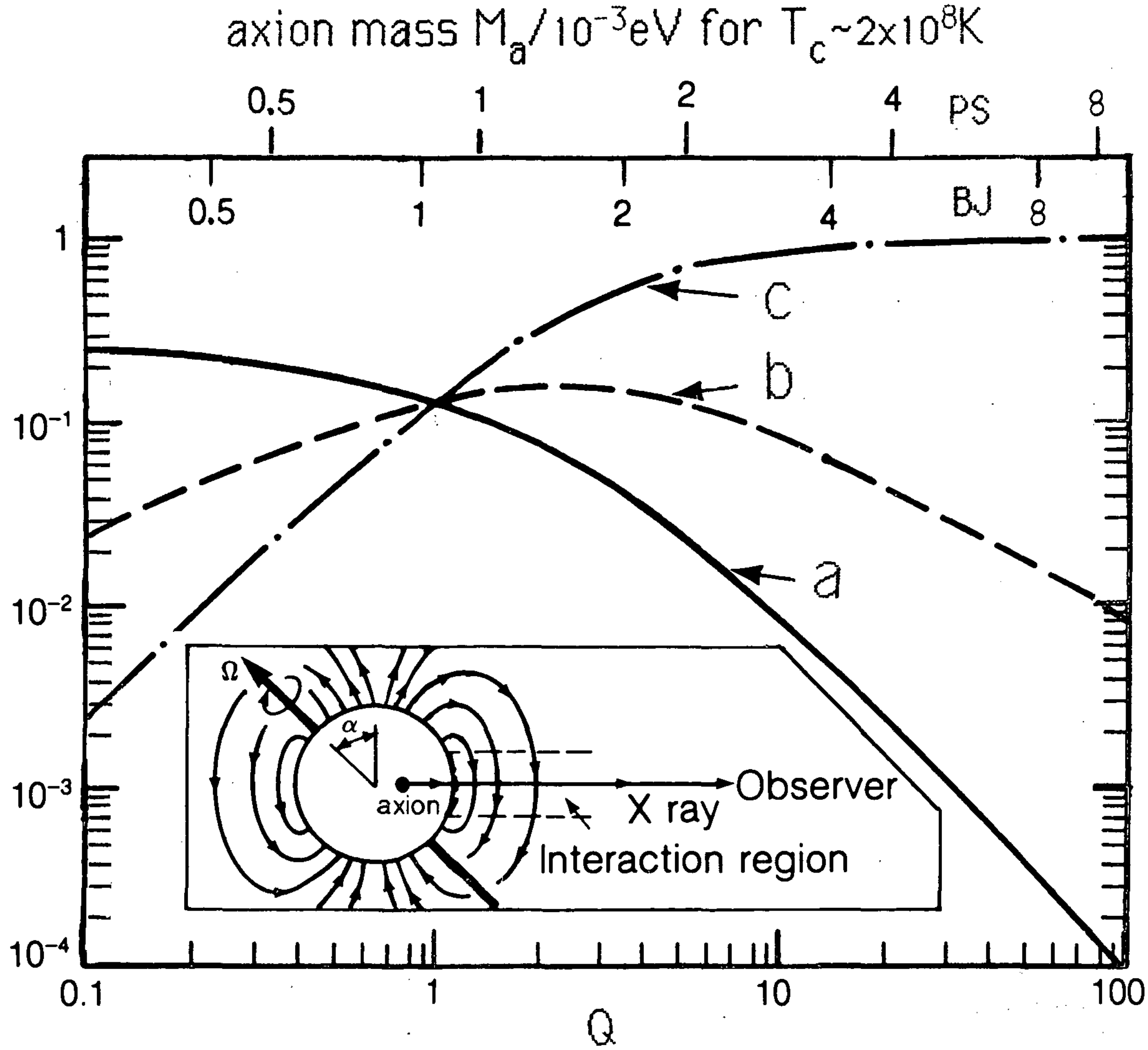

Figure 1. Axion to X ray Conversion at a neutron star: Dependence on normalized wave number $Q = R_* \cdot q = R_* \cdot M_a^2 c^3 / 2\hbar E_a$. Corresponding axion mass M_a for models BJ and PS at $T_c \sim 2 \times 10^8$K is indicated (see text).

a. The square of the Fourier transform of the normalized magnetic field $\underline{b}^2(Q)$

b. The axion axion to X ray conversion cross section $\sigma \propto M_a^2 \cdot \underline{b}^2(Q)$ $\propto Q\, \underline{b}^2(Q)$, which is plotted.

c. The x ray luminosity from axion conversion $L_x \approx \eta L_a \propto \sigma M_a^2 \propto Q^2 \cdot \underline{b}^2(Q)$, which is plotted. (when $\sigma/S < 0.5$ so that $\eta \sim \sigma/S$)

Inset: Axion to X ray conversion at a neutron star (see text).

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