Axion Mass Limits from Cooling Neutron Stars

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Abstract

The thermal evolution of a neutron star is studied by including the energy loss due to axion emission. Two axion models and three types of neutron-star matter equation of state are used with the effects of nucleon superfluidity properly taken into account. In comparison with the observational data of PSR0656+14 from ROSAT, the upper limits on the axion mass are found to be $m_a < 0.06 - 0.3$ eV and $0.08 - 0.8$ eV for the KSVZ and DFSZ axion models, respectively, with the soft equation of state giving the most stringent limits.

The axion arises as a solution to the strong CP problem (Turner 1990, Raffelt 1990). While the standard axion model was excluded by experiments, the invisible axion model has survived mainly because the axion’s coupling to matter is weak, which is an unknown parameter in the theory. Over the years, various laboratory experiments as well as astrophysical arguments have been used to constrain its parameters. Since laboratory experiments can explore only a limited parameter regime, including those planned in the foreseeable future, astrophysical considerations have played an important role in placing the limits on the axion parameters. Within these limits, the axion remains as one of the candidates for dark matter.

There are two types of axion models—the KSVZ (hadronic) model (Kim 1979, Shifman et al. 1980) and the DFSZ model (Dine et al. 1981, Zhitnitskii 1980). In the KSVZ model, the axion couples only to the photons and hadrons, while in the DFSZ model the axion couples to the charged leptons as well. The axion-fermion and axion-photino coupling constants as well as the axion mass are unknown parameters in these theories. Currently, cosmological arguments give $m_a > 10^{-5}$ eV (Abbott and Sikivie 1983, Dine and Fischler 1983). The limit from Supernova 1987A, which used to give $m_a < 10^{-3}$ eV, is now somewhat relaxed $m_a < 0.01$ eV (Raffelt and Seckel 1991, Janka et al. 1996). The red giant limit $m_a < 0.009 / \cos^2 \beta$ (Raffelt and Weiss 1995) applies only to the DFSZ model. The laboratory experiments give weaker limits.

In the present paper we study how axion emission affects the thermal evolution of neutron stars. We use the neutron star evolutionary code with three types of equation of state to calculate the surface temperature of neutron stars. We compare theoretical cooling curves with observation and obtain the upper limits on the axion mass, which are weaker than, but comparable with, the limit from SN 1987A.

Axion Emissivity: In neutron stars, the dominant axion emission mechanisms are the following bremsstrahlung processes in the stellar core: $n + n \rightarrow n + n + a, p + p \rightarrow p + p + a$, and $n + p \rightarrow n + p + a$, where $n, p, a$ are the neutron, proton and axion. The energy loss rate of each process, in the units $\bar{\epsilon}$, is given by (Iwamoto 1998):

$$\epsilon_{\text{ann}} = \frac{31 g_{\text{ann}}^2}{3780 \pi} m_n^2 p_F(n) \left( \frac{f}{m_\pi} \right)^4 F(x)(k_B T)^6,$$

$$\epsilon_{\text{app}} = \frac{31 g_{\text{app}}^2}{3780 \pi} m_p^2 p_F(p) \left( \frac{f}{m_\pi} \right)^4 F(y)(k_B T)^6,$$

$$\epsilon_{\text{app}} = \frac{31 g_{\text{app}}^2}{5670 \pi} m_p^2 p_F(p) \left( \frac{f}{m_\pi} \right)^4 G(x, y)(k_B T)^6,$$
where

\[ F(z) = 1 - \frac{3}{2} \sqrt{2} \arctan \left( \frac{1}{z} \right) + \frac{z^2}{2(1+z^2)}, \quad (4) \]

\[ G(x, y) = \frac{1}{2}(g^2 + h^2)F(y) \]
\[ + (g^2 + \frac{1}{2}h^2) \left( F\left( \frac{2xy}{x+y} \right) + F\left( \frac{2xy}{y-x} \right) \right) \]
\[ + \left( \frac{y}{x} \right) \left( F\left( \frac{2xy}{x+y} \right) - F\left( \frac{2xy}{y-x} \right) \right) \]
\[ + (g^2 + h^2)(1 - y \arctan(1/y)), \quad (5) \]

\[ g \equiv g_{app} + g_{ann}, \quad h \equiv g_{app} - g_{ann}; \quad x \equiv m_{\pi}/2p_F(n), \quad y \equiv m_{\pi}/2p_F(p); \quad f \approx 1 \text{ is the pion-nucleon coupling constant;} \]
\[ p_F(n) \approx 340(\rho/\rho_0)^{1/3} \text{ MeV/c}, \quad p_F(p) \approx 85(\rho/\rho_0)^{2/3} \text{ MeV/c are the nucleon Fermi momenta;} \]
\[ m_p, m_n, \text{ and } m_{\pi} \text{ are the proton and neutron effective masses and pion mass, respectively.} \]

\[ g_{au} = \frac{c_i m_N}{f_a/12} \quad (6) \]

is the axion-nucleon coupling constant, where \( i = p \) (proton) or \( n \) (neutron), \( m_N \) is the nucleon mass, and \( f_a \) is the axion decay constant. \( c_i \) depends on the models: the DFSZ model gives

\[ c_p = -0.10 - 0.45 \cos^2 \beta, \quad c_n = -0.18 + 0.39 \cos^2 \beta, \quad (7) \]

and the KSVZ (hadronic) model gives

\[ c_p = -0.385, \quad c_n = -0.044. \quad (8) \]

The axion mass is related to \( f_a \) via

\[ m_a = \frac{0.0074}{f_a/(10^{10} \text{GeV})} \text{ eV.} \quad (9) \]

We note that axion emission is suppressed if nucleons become superfluid, as in the case of neutrino emission involving nucleons.

**Results and Discussion:** We employ the numerical calculation code essentially the same as the one described in Umeda et al. (1994), except for the inclusion of the energy loss due to axion emission. We neglect internal and other possible heating mechanisms as well as the existence of non-standard cooling mechanisms. The baryon mass of the neutron star is set to 1.4 \( M_\odot \).

Theoretical cooling curves are compared with the observational data for three pulsars: PSR 1055-52, Geminga, and PSR 0656+14 (see Tsuruta 1998 and Becker 1994 for references). The energy loss rate due to axion emission is proportional to the axion mass squared, \( m_a^2 \); therefore, we can obtain the upper limit on the axion mass from the condition that the cooling curve does not pass below the lower bounds on the observational points.

In Figure 1, we show the standard cooling curve and those with the KSVZ axion model for four different axion masses (or \( f_a \)). The FP equation of state and the TT neutron \( ^3P_2 \) superfluid energy gap (Takatsuka and Tamagaki 1993) are adopted. Since the data point for PSR 1055-52 is located above the standard cooling curve, we do not use this data: this is likely to be due to some other (unknown) effects. Conservative limits can be obtained by using the other two data. Figure 1 shows that the PSR 0656+14 gives a more stringent limit than Geminga, and hence we obtain the axion mass limit from the lower bound on the PSR 0656+14 data.

The results for both the KSVZ and DFSZ axion models with stiff (PS), medium (FP) and soft (BPS) equations of state are summarized in Figures 2-4. The BPS model gives the more stringent limit. This is because the TT gap vanishes in the high density region (i.e., inside the stellar core) with this equation of state; thus, axion emission is not suppressed. Extending superfluidity to higher density regions will have an effect similar to increasing the stiffness of the equation of state. For example, in the FP model, if the AO neutron \( ^3P_2 \) gap (Amundsen and Østgaard 1985) is adopted, \( m_a^{\text{max}} \) is 0.3 eV, while if there is no neutron \( ^3P_2 \) superfluid, \( m_a^{\text{max}} \) is 0.06 eV. Note, however, that the AO model probably overestimates the energy gap at high densities, because the density dependence of the neutron effective mass is neglected. Future refinements of the observation will provide more stringent limits.

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References
Abbott, L. F., and Sikivie, P., 1983, Phys. Lett., B120, 133
Amundsen, L., and Østgaard, E., 1985, Nucl. Phys., A437, 487
Becker, W., 1994, Ph.D. Thesis, München University
Dine, M., Fischler, W., and Srednicki, M., 1981, Phys. Lett., 104B, 199
Dine, M., and Fischler, W., 1983, Phys. Lett., B120, 137
Iwamoto, N., Umeda, H., Tsuruta, S., Nomoto, K., and Qin, L., 1998, in preparation
Janka, H.-T., Keil, W., Raffelt, G., and Seckel, D., 1996, Phys. Rev. Lett., 76, 2621
Kim, J. E., 1979, Phys. Rev. Lett., 43, 103
Raffelt, G., 1990, Phys. Rep., 198, 1
Raffelt, G., and Seckel, D., 1991, Phys. Rev. Lett., 67, 2605
Raffelt, G., and Weiss, A., 1995, Phys. Rev., D51, 1495
Shifman, M., Vainshtein, A., and Zakharov, V., 1980, Nucl. Phys., B166, 493
Takatsuka, T., and Tamagaki, R., 1993, Prog. Theor. Phys. Suppl., 112, 27
Tsuruta, S., 1998, Phys. Rep., 292, 1
Turner, M. S., 1990, Phys. Rep., 197, 67
Umeda, H., Tsuruta, S., and Nomoto, K., 1994, ApJ, 433, 256
Zhitnitskii, A. P., 1980, Sov. J. Nucl. Phys., 31, 260

Fig. 2. Axion mass limits ($m_a^{max}$) in the FP model

Fig. 3. Same as Fig. 2 in the PS model
Fig. 4. Same as Fig. 2 in the BPS model