Some astrophysical limitations on the axion mass

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A comparison of the axion luminosity of the sun with the observed photon luminosity leads to the lower bound $\mu_a > 25$ keV. This bound can be raised to $\mu_a > 200$ keV by resorting to modern ideas concerning the structure of supergiants.

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The possible existence of a light pseudoscalar Higgs meson, the so-called "axion" a,[1,2] is now a subject of lively discusison. The purpose of this article is to obtain the lower bound of the mass of such a particle on the basis of modern ideas concerning the structure and luminosity of stars.

Axion emission in hot cores of stars can greatly change their luminosity or alter radically their structure. A lower bound of the axion mass can therefore be obtained on the basis of the models developed in detail for the sun and red supergiants.

In the calculations that follow we use a system of units with $\hbar=c=k=1$. The interaction of the axion with quarks (q) and leptons (l) is of the form $H_{\text{int}}=\sqrt{G}\, m_{q(l)}\bar{\psi}_{q(l)}\gamma_5\psi_{q(l)}\phi_a$. Greatest interest attaches to axion production processes $\gamma\gamma\to a$, $\gamma e\to ae$, $\gamma N\to aN$ and to the reactions of absorption $ae\to\gamma e$, $aN\to\gamma N$ and decay $a\to 2\gamma$. The axion photoproduction cross section near threshold is given by

$$\sigma(\gamma_e \to ae) \approx G_a\left(\frac{m_a}{m_e}\right)^2\sqrt{\frac{\omega_\gamma}{m_a} - 1}\,, \tag{1}$$

and the specific losses due to this reaction amount to ($T < m_a$)

$$q(\gamma l \to ae) = n_e e^{-\frac{m_a}{T}}\left(\frac{m_a T}{2\pi}\right)^{3/2}\sqrt{\frac{T}{m_a}}\,\frac{2}{3}\,a\,G\frac{m_a^2}{m_e^2} = 2\cdot 10^7 \mu_a^4 T^2 e^{-\frac{\mu_a}{T}}\ \text{erg/g-sec} \tag{2}$$

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where $\mu_a = m_a$ keV^{-1}, $T = T$ keV^{-1}, and n_e is the electron density. The cross section for the production of an axion in the reaction $\gamma\gamma \to a$ is obtained from the matrix element $M = F_a \epsilon_{\mu\nu\lambda\rho} k_{1\rho} k_{2\lambda}$, $F_a = (a/\pi)\sqrt{G}\,\Sigma Q^2$ (the summation is over all the charged quarks and leptons):

$$\sigma(\gamma\gamma \to a) = G m_a^2 \frac{a^2}{8\pi} \delta(s - m_a^2)(\sum_i Q_i^2)^2, \tag{3}$$

and the corresponding rate of energy loss is given by $(T < m_a)$

$$q = m_a \frac{a^2 G (\sum_i Q_i^2)^2 m_a^3}{64\pi^3} e^{-\frac{m_a}{T}} \left(\frac{m_a T}{2\pi}\right)^{3/2} = 4\cdot 10^8 \mu_a^{11/2} T^{3/2} e^{-\frac{\mu_a}{T}} \text{ erg/cm}^3\text{ sec}, \tag{4}$$

where μ_a and T are in keV.

Comparing expressions (2) and (4) we see that in the temperature and density regions of interest to us we can disregard the photoproduction reaction and the inverse radiative-capture reaction. The mean free path is therefore determined by the decay length l_a

$$l_a \sim \tau v_a \sim \frac{10^{15}}{\mu_a^3} \sqrt{\frac{T}{\mu_a}} \text{ cm}. \tag{5}$$

From the condition that the rate of energy loss by the sun as a result of radiation of axions does not exceed its photon luminosity $L_\odot \approx 4 \times 10^{33}$ erg/sec, assuming a core mass $M \approx 10^{-2} M_\odot$, a density $\rho \approx 10^2$ g/cm^3, and a temperature $T \approx 1$ keV, we obtain the lower bound of the axion mass:

$$L_a = q \frac{M}{\rho} > L_\odot .$$

Hence

$$m_a > 25 \text{ keV}. \tag{6}$$

The axions emitted by the sun will decay into photons with energy $m_a/2$. Therefore the axion luminosity should be compared with the x-ray luminosity of the sun. For the axion luminosity (6), with allowance for the dependence of the decay length of the mass (5), we have at $T = 1$ keV the following luminosity on the sun's surface ($R_\odot = 7 \times 10^{10}$ cm):

$$L_a = 10^{38} \mu_a^{11/2} e^{-\mu_a - 7\cdot 10^{-5} \mu_a^{7/2}} \text{ erg/sec}. \tag{7}$$

Using the data of the observations of the x-ray luminosity of the quiescent sun[3] and expressing the radiation wavelength λ in terms of the axion mass we obtain an expression for the observed x-ray luminosity at $\lambda = 2\pi\hbar c/(m_a/2)$

$$L_{\odot x} = 4\cdot 10^{22}\left(\frac{\mu_a}{2}\right)^3 e^{-3\mu_a} \text{ erg/sec.} \quad (8)$$

However, this formula has been verified in experiment only up to $E_\gamma \approx 1.5$ keV, corresponding to $m_a \approx 3$ keV, and therefore does not raise the lower bound (6) of m_a.

A larger value of the lower bound of the axion mass can be obtained on the basis of the model of red supergiants. In the model of[4] an isothermal helium core has a temperature $T_c \approx 15$ keV and a radius $R_c \approx 10^{10}$ cm. The radius of the core greatly exceeds the decay length of axions with $m_a \gtrsim 100$ keV. Therefore the axion luminosity L_a is determined by the emission of the axions from an outer layer of the core with thickness $\sim l_a$. The energy imparted by the axions to the extended rarefied shell can exceed its binding energy $E_b \sim 10^{49}$ erg.[2)] If this energy is imparted to the shell in a time shorter than the local hydrodynamic time, then the shell will be dumped. From the very fact that red supergiants exist we therefore deduce that:

$$\Delta E \approx L_a t_H \approx 2\pi R_c^2 l_a q t_H < E_b,$$

where $t_H \sim 10^3/\sqrt{\rho} \sim 10^4$ sec is the hydrodynamic time of the shell, while q and l_a are given by (4) and (5), respectively.

This yields for the axion mass the lower bound $m_a > 200$ keV. On the other hand, the axion energy flux into the shell must not exceed the energy flux transferred by radiant thermal conductivity, for otherwise the lifetime of the red supergiants would be much shorter and they would not be observed. From the condition that

$$L_a < L = \frac{\sigma T_c^4 4\pi (R_c + l_a)^2}{3\kappa \bar{\rho} l_a} \quad (9)$$

at a shell opacity $\kappa = 0.2$ cm^2/g and the density $\rho \sim 10^{-2}$ g/cm^3 we obtain $m_a > 200$ keV. Thus, from the condition that the energy transfer due to axions in red supergiants does not alter their structure and lifetime, we get

$$m_a > 200 \text{ keV.} \quad (10)$$

However, (10) is connected with detailed assumptions concerning the supergiants and is less reliable than (6).

The theoretical predictions made for the axion mass in[1,2] are quite indefinite $m_a = 100 \times 10^{\pm 1}$ keV and $m_a = 23$ N/sin2α keV (N is the number of the quarks), respectively. We note that the lower bound deduced by us for the axion mass from the structure of the supergiants excludes the symmetrical variant of the model of[2] with tan$\alpha = 1$ for $N = 6$: in this variant $m_a = 138$ keV.

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[1)]The lifetime of the axion with respect to 2γ decay is estimated in[1,2] at $t \approx (3\times 10^4)/\mu_a$, with μ_a in keV; knowing this time we easily obtain (4) directly from the equilibrium axion density and from the detailed balancing condition.

[2)]This value was obtained at $M_c \sim 4M_{\odot}$, $M_{sh} \sim 12M_{\odot 6Ps} \leq$ and $R_{sh} \sim 10^{12}$ cm, and is an upper bound of the binding energy of the shell.

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