Light Pseudoscalar Particle and Stellar Energy Loss

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A bound on the coupling strengths of a very light pseudoscalar particle is derived from stellar energy loss at various stages of evolution: the sun, red giants, and cooling white dwarfs. The dimensionless Yukawa and 2γ couplings must be less than 10^{-11}.

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Light or massless particles that couple weakly to matter are notoriously difficult to observe. Relic neutrinos and gravitons that are perhaps cosmologically abundant belong to this class of particles. In some cases the existence of weakly interacting particles is inferred if their effect adds up coherently to give a long-range force, as in the case of gravitons. Unlike the familiar examples of the neutrino and the graviton, a spinless boson which has a weak pseudoscalar coupling to matter may well have escaped detection in terrestrial experiments. But if its coupling to matter is appreciable, such a pseudoscalar, once emitted in stars, may deplete stellar energy generated by nuclear fuel or gravitational contraction, and endanger our present understanding of stellar evolution. In this paper we shall establish allowed coupling strengths of such pseudoscalar particles from various astrophysical arguments. The upper bound on coupling constants (Yukawa coupling and 2γ coupling normalized to the electron mass) thus obtained is roughly of order 10^{-11}, which lies between the weak coupling ($G_F^{1/2}m_e \sim 2\times10^{-6}$) and the gravitational coupling ($G^{1/2}m_e \sim 4\times10^{-23}$).

Various kinds of light pseudoscalar particles have been postulated in modern gauge theories. We only mention two examples: the Dine-Fischler-Srednicki (DFS) axion[1] and the Majoron.[2,3] Axions emerge as pseudo Nambu-Goldstone bosons of the Peccei-Quinn symmetry[4] which was introduced as a solution to the strong CP problem.[5] The standard axion[6] of Weinberg and Wilczek seems to be excluded by experiments, but its extended version by Dine, Fischler, and Srednicki does not contradict any observation. The Majoron is a hypothetical massless particle that results from a spontaneous breakdown of global lepton number conservation. For the rest of this discussion what matters is the coupling constant g_{Uf} of the pseudoscalar particle U to a matter field f defined in the form $ig_{Uf}\bar{f}\gamma_5 fU$. These couplings are related to more fundamental mass scales of new physics, v_0 and v_T, in the two examples; $g_{Ai} \simeq m_i/v_0$ ($x=v_u/v_d=1$ assumed) for the DFS axion, and $g_{Mi}=2\sqrt{2}\,G_F v_T m_i$ for the Majoron of Ref. 3. We assume that the mass of U is $m_U \lesssim 100$ eV.

The strength of the induced vertex, $U_{\gamma\gamma}$, is also well bounded from astrophysical arguments below. This vertex is defined by an effective Lagrangian density, $(\alpha c_{U\gamma\gamma}/m_e)UF_{\mu\nu}\tilde{F}^{\mu\nu}$, and is estimated either from current algebra ($c_{A\gamma\gamma} \simeq 0.36Nm_e/4\pi v_0$ for the DFS axion with N generations) or from a direct computation of the triangular loop which gives

$$c_{U\gamma\gamma}=(m_e/8\pi)\textstyle\sum_i e_i^2 g_{Ui}/m_i, \qquad (1)$$

with e_i an electric charge of i in units of the elementary charge. When U is massive, its dominant decay mode is $U\to 2\gamma$, and its lifetime is much larger than the age of our universe, typically of order $(10^{25}\ \text{sec})[(1\ \text{eV})/m_A]^5$. Its lifetime may be shortened if U couples to a neutrino of mass $m_\nu < m_U/2$. The decay $U\to\nu\bar{\nu}$ may then dominate,[7] but none of our conclusions in what follows are altered by this complication.

The essential point in the derivation of astrophysical constraints[8] is that stable stars tend to emit particles with total energies less than thermal energy in the stellar bath. Since the postulated pseudoscalars couple weakly to matter, their mean free path is much larger than a typical size of stars and they may remove stellar energy too rapidly. This catastrophe can only be evaded by limiting their coupling strength to matter.

The basic mechanisms of stellar energy loss due to pseudoscalar emission are the Compton-like process [Fig. 1(a)], the Primakoff process [Fig. 1(b)], the annihilation process, $e^-+e^+\to U+\gamma$, and plasma decay, $\gamma_{\text{pl}}\to U+\gamma$. In stars at relatively low densities ($\rho=10^2-10^4\ \text{g cm}^{-3}$) the Primakoff process is relatively important as a mechanism of energy loss for main-sequence stars ($T\sim10^7$ K), while the Compton-like process is likely to be dominant for red giants ($T\sim10^8$ K). This is due to different temperature dependences

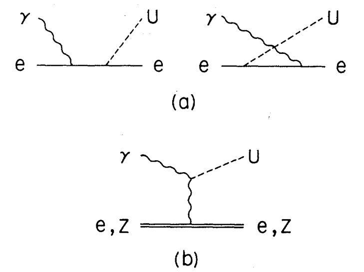

FIG. 1. (a) Compton-like process. (b) Primakoff process.

of the two energy loss rates: $\sim T^4 \ln T$ for the Primakoff and $\sim T^6$ for the Compton-like process. The annihilation process becomes important only at $T \gtrsim 10^9$ K since the energy loss is $\sim T^3 \exp(-2m_e/T)$, and the plasma decay is always negligible. In Fig. 2 we have plotted energy loss rates vs T at three values of ρ. The plasma effect in the Primakoff process is significant whenever the plasmon mass $\omega_0 \gtrsim m_U$, and cuts off the momentum transfer to matter, which was ignored by Dicus *et al.*[8]

The energy loss rate due to the pseudoscalar emission is now compared with the energy generation rate at various stages of stellar evolution to derive upper bounds on coupling strengths. We have considered the sun (a main-sequence star), red giants burning helium at the core, and stars in advanced phases of evolution. The result is summarized in Fig. 3, and a brief discussion is given below. The sun, a main-sequence star, is known to emit radiation at the rate of $L_\odot \simeq 3.90 \times 10^{33}$ erg $\sec^{-1}$. If the energy loss due to U emission exceeds this luminosity, evolution of the sun would grossly deviate from what we understand now.[9] By demanding that

$$\int_0^{M_\odot} dm\, \epsilon_U(T,\rho) < L_\odot, \tag{2}$$

we find that

$$0.028 g_{11}^2 + 13 c_{11}^2 < 2.0. \tag{3}$$

Here $\epsilon_U(T,\rho)$ is the total energy loss rate due to U, $g_{11} = g_{Ue} \times 10^{11}$, and $c_{11} = c_{U\gamma\gamma} \times 10^{11}$. In carrying out the integral (2) we used the numerical data of T, ρ, and chemical composition parameters given by evolutionary calculations[9] as functions of the solar mass variable $m(r)$. It is found that the plasma effect reduces the integral by a factor 2.5. One might contemplate whether a larger energy loss could be compensated by a larger energy generation with an increased temperature. But this is impossible because the temperature dependence of the energy loss $\propto T^4$ exceeds that

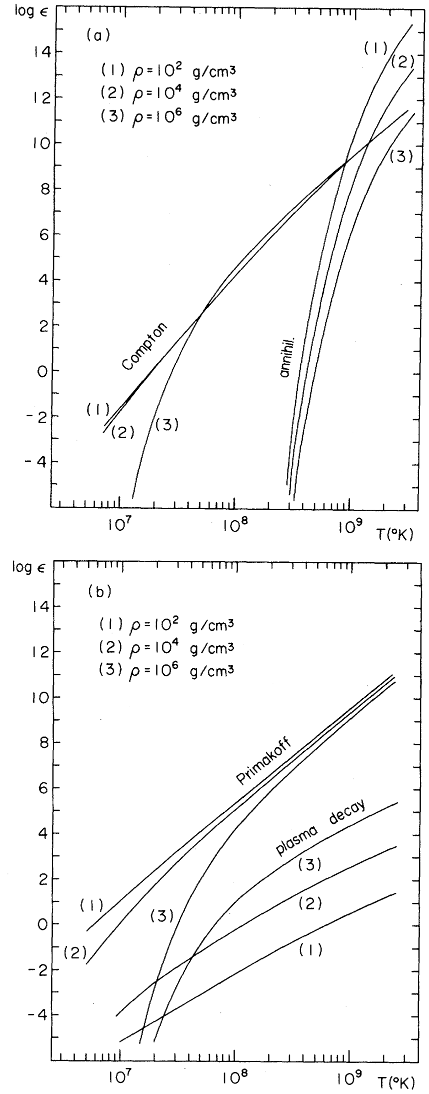

FIG. 2. Energy loss rate due to pseudoscalar particle emission through (a) Yukawa coupling and (b) 2γ coupling. The energy rate ϵ is calculated in a stellar bath of pure hydrogen and shown in units of erg/g sec. Curves are presented for $g = 1 \times 10^{-11}$ or $c = 1 \times 10^{-11}$. Plasma effects are taken into account in all curves and the relativistic correction is included in the Compton-like process.

of the energy generation rate of the main pp chain $\propto T^{3.9}$. The constraint (3) is therefore regarded as a firm limit. We also mention, as first noted by Dicus *et al.*,[8] that the energy loss, if coupling strengths are reduced by a factor 2 from the bound (3), can be compensated by an increased temperature, which, however, increases the neutrino flux from ^{8}B by a factor 3 compared with the standard estimate.

A better bound is derived from helium-burning

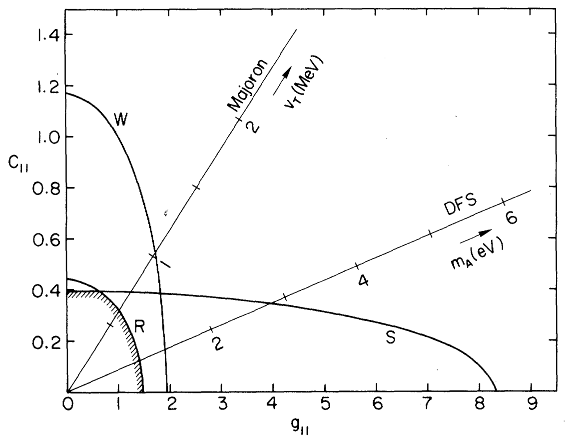

FIG. 3. Bounds on the dimensionless couplings g_{11} and c_{11} from the sun (S), globular clusters (R), and cooling white dwarfs (W). The straight lines show the cases for the DFS axion and the Majoron of Ref. 3.

red giants. By taking a typical set of parameters for a light red giant, $T = 1\times10^8$ K, $\rho = 10^4$ g cm^{-3}, and the nuclear energy generation $\epsilon_N = 10^2$ erg g^{-1} sec^{-1},[8,9] we have $0.96 g_{11}^2 + 11 c_{11}^2 < 10^{-2}$, by demanding that the energy loss rate $\epsilon_U < \epsilon_N$. This bound, however, depends critically on models[10] of stellar evolution which give the temperature and density of a helium-burning core. In fact, the energy generation rate of the 3α reaction depends very sharply on temperature, $\propto T^{40}$ in the vicinity of $T = 10^8$ K, which makes it possible to compensate the energy loss with a slight increase of temperature. This rather model-dependent bound was not included in Fig. 3. A less model-dependent argument[11] may be developed to give $0.82 g_{11}^2 + 3.3 c_{11}^2 < 1500$. If this bound is violated, helium burning in the nondegenerate region should be at an extremely high rate, $\epsilon_{3\alpha} \gtrsim 10^8$–$10^9$ erg g^{-1} sec^{-1} to compensate the energy loss, which makes the lifetime of red giants $\tau \lesssim 1$ yr in conflict with observation.

Another constraint is derived from an evolutionary argument of the globular clusters, e.g., $M2$, $M3$, $M5$, $M13$, $M15$, ω Cen. In the Hertzsprung-Russell diagram of the globular clusters[12] the blue horizontal branch is ascribed to stable helium-burning stars with a low mass $M = (0.5-1.0) M_\odot$ after the helium flash.[13] In such stars energy liberation is quite slow and stars are considered to be very old. If the bound,

$$0.96 g_{11}^2 + 11 c_{11}^2 < 2.1, \tag{4}$$

is violated, the nuclear energy generation should be more than a hundred times larger and the time scale of evolution would become shorter by that factor. This should significantly modify the distribution of stars in the horizontal branch.

At an advanced state of evolution the neutrino energy loss affects the time scale of gravitational contraction in cooling white dwarfs. In these stars the temperature is not very high, and nuclear energy generation is no longer available. Thus, evolution of these white dwarfs would be much affected by a new source of energy loss mechanism. Stothers[14] has made an analysis of the luminosity functions for blue subluminous white dwarfs of the Hyades, and concluded that the agreement with observation would be destroyed if the neutrino cooling is a hundred times stronger than that predicted by the charged current. We may quote this result to give a bound for the possible energy loss due to the pseudoscalar U. In the relevant ρ, T region the neutrino energy loss is predominantly due to the plasma decay into a $\nu\bar{\nu}$ pair and carries away the energy at a rate 5×10^{-3} erg g^{-1} sec^{-1} (or less) in a star with a luminosity $L \simeq 10^{-1.6} L_\odot$ (or less).[15] By comparing this value with the energy loss due to U (the composition of 80% oxygen and 20% carbon is taken) and by taking the above allowance factor of 100, we obtain a bound

$$1.5 g_{11}^2 + 4.0 c_{11}^2 < 5.5. \tag{5}$$

In deriving this limit it is important to include plasma effects on transverse photons in the formulas of the Compton-like and Primakoff processes for U production, since the plasma frequency ω_0 is considerably larger than average photon energy ($\omega_0/T \simeq 5-20$) in the relevant ρ, T region.

In conclusion, our astrophysical arguments of stellar energy loss, summarized by (3)–(5), give bounds on respective coupling strengths,

$$g_{Ue} < 1\times10^{-11}, \quad c_{U\gamma\gamma} < 0.4\times10^{-11}.$$

In the case of the DFS axion $c_{A\gamma\gamma} \simeq 0.087 g_{Ae}$ for three generations of fermions and a bound on the axion mass related to the singlet vacuum expectation value v_0 is given by[16]

$$m_A < 1 \text{ eV}, \quad \text{or} \quad v_0 > 4\times10^7 \text{ GeV}. \tag{6}$$

For the Majoron of Ref. 3, $c_{M\gamma\gamma} = N g_{Me}/3\pi$ from (1), and the triplet vacuum expectation value v_T of lepton number nonconservation is bounded by $v_T < 600$ keV for the model with three generations. For the Majoron of Ref. 2, the singlet vacuum expectation value v_0' of the lepton nonconservation is limited by $v_0' > (1 \text{ keV})[m/(0.5 \text{ MeV})]^2$, with m a magnitude of Dirac mass mixing.

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