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The 17 keV Neutrino in the Light of Astrophysics and Cosmology

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Abstract

The possible discovery of a 17 keV neutrino in β -decay experiments is a challenge to both astrophysics and cosmology. Should such a species exist, its contribution to the present mass density would play havoc among the heavens unless that neutrino decays with a lifetime shorter than $\simeq 30,000$ years. If so, its radiative decays should neither overcool red giant stars, nor exceed the upper bound set upon the γ -ray flux from supernova 1987A by the Solar Maximum Mission satellite. In addition, radiative decays should not distort the microwave background radiation, whose spectrum is quasi-Planckian as observed by COBE. Combining those various arguments, we conclude that the branching ratio B_γ to photons cannot exceed 4×10^{-5} . Such a limit severely constrains the most naive models of the 17 keV neutrino, and points towards unconventional physics.

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1 - Introduction.

There is new evidence, in β -decay experiments [1], that the electron neutrino oscillates in one percent of the cases to another neutrino of mass 17 keV. According to our present knowledge, the mass of the muon neutrino cannot exceed 10 keV whilst the number of light neutrino generations, N_ν , is three as measured by the LEP experiments [2]. Therefore, the 17 keV neutrino may be either the tau neutrino, or an additional species with vanishing hypercharge.

In this letter, we focus on the insuperable astrophysical and cosmological constraints that face the 17 keV neutrino. As a matter of fact, this analysis could easily be extended to any neutrino mass in the range between 1 and 100 keV. In section 2, we evaluate the neutrino contribution to the mass density of the Universe and point out that this species must be unstable, with lifetime smaller than 30,000 years. In section 3, we compute for the first time the cooling rate of red giant stars through plasmon decay into massive $\nu\bar{\nu}$ pairs. The plasma frequency inside the helium core of red giants turns out to be ~ 20 keV, just above the kinematic limit for the production of the 17 keV neutrino. In section 4, we reinvestigate in detail the limit set upon the radiative lifetime, by the γ -ray fluence measured by the Solar Maximum Mission satellite in coincidence with the neutrino burst from SN1987A. Section 5 is devoted to the potential spectral distortions of the Cosmic Microwave Background Radiation implied by the 17 keV neutrino radiative decays. Those various arguments are summarized in section 6. We finally conclude that astrophysics and cosmology severely constrain the properties of the 17 keV neutrino to be unconventional.

2 - The closure constraint.

The 17 keV neutrino interacts weakly with other particles. Above a temperature $T_F \sim 1$ MeV, the rate of its collisions with the other neutrino species and the electrons, $\Gamma_{\text{collision}} \sim G_F^2 T^5$, exceeds the expansion rate of the Universe $H \sim T^2/M_{Pl}$. The parameter G_F (or M_{Pl}) denotes the Fermi constant (or the Planck mass).

Below T_F , neutrinos decouple from thermal equilibrium. If they are stable, they contribute to the average mass density a factor

$$\rho_\nu = \frac{6}{11} \frac{\zeta(3)}{\pi^2} T_\nu^3 n_\nu, \quad (1)$$

as soon as they become non-relativistic, for a photon temperature $T_\nu < m_\nu$. As a matter of fact, the closure density ρ_c^0 inferred from the present value H^0 of the Hubble parameter [3] is $\rho_c^0 \sim 11.25 h^2 \text{ keV cm}^{-3}$ where h , the Hubble constant expressed in units of 100

km/s/Mpc, lies in the range between 1/2 and 1. As is the case for the other neutrino species, the present density of the 17 keV neutrino is $\sim 100 \text{ cm}^{-3}$ so that, should this particle be stable, its mass would overclose the Universe by a factor $\Omega_\nu = \rho_\nu/\rho_c^0 \sim 170 h^{-2}$. Current cosmological observations rule out such a large value [4]. In particular, the age of the Universe is known to be at least larger than the age of the earth, i.e., 5 billion years. From the luminosity function of white dwarves and its peculiar cut-off at low luminosities, the age of the galactic disk has been inferred [5] to be ~ 9 billion years. Finally, the magnitude shift between the main-sequence turn-off and the horizontal branch of the Hertzsprung-Russell diagram of globular clusters is compatible [6] with an age of population II stars greater than 15 billion years. A value of H^0 as low as 50 km/s/Mpc associated with a large closure density $\Omega_\nu \sim 700$ implies a Universe not older than ~ 1 billion years. Such a possibility is ruled out so that we readily conclude that the 17 keV neutrino must be unstable.

Should the decay products be non-relativistic, they would merely dominate the expansion of the Universe just as if the neutrino was stable. That species must therefore decay into relativistic products whose energy density may be red-shifted. If decays occur at temperature T_γ^D , the decay products contribute today a factor

$$\Omega_{dp} = 170 h^{-2} \left(\frac{2.735 \text{ K}}{T_\gamma^D} \right)^4, \quad (2)$$

to the closure density, so that the earlier the decay, the larger T_γ^D and the lower Ω_{dp} . Provided that the 17 keV neutrino decays before the temperature reaches down ~ 500 to 2000 K, its decay products do not overclose the Universe [7]. We infer an upper bound on the neutrino lifetime in the range $10^{13} - 10^{14}$ seconds.

Consistency requires an accurate evaluation of the present value of the Hubble parameter and of the age of the Universe as a function of the neutrino lifetime τ_ν . To commence, we assume a flat Universe and a baryon to photon ratio $\eta_B = 3 \times 10^{-10}$ as required by primordial nucleosynthesis [8]. The temperature T_γ evolves as

$$\frac{d \ln T_\gamma}{dt} = - \left(\frac{8\pi}{3M_{Pl}^2} \rho_{tot} \right)^{1/2}, \quad (3)$$

where the total energy density ρ_{tot} accounts for the presence of photons, light neutrino species, baryons and the 17 keV neutrino ρ_ν with its debris ρ_{dp} . Note that ρ_ν decays exponentially in time while the debris density evolves according to

$$\frac{d\rho_{dp}}{dt} = -4H\rho_{dp} + \frac{\rho_\nu}{\tau_\nu}. \quad (4)$$

In figure 2, the evolution of H^0 is presented as a function of τ_ν , assuming pure flatness. Note that for very low τ_ν , the decay products are red-shifted so much that baryons today

dominate the Universe. With $\eta_B = 3 \times 10^{-10}$, pure flatness implies $H^0 \simeq 10 \text{ km/s/Mpc}$. Such a low value leaves plenty of room for the decay products of the 17 keV neutrino. When τ_ν increases, the amount of red-shift undergone by the decay debris decreases so that their present density may eventually dominate the expansion of the Universe. According to figure 2, for $\tau_\nu \geq 1 - 2 \times 10^{13} \text{ sec}$, the Hubble constant H^0 exceeds the observational upper bound of 100 km/s/Mpc.

We have relaxed our assumption on the pure flatness of the Universe and varied its present curvature Ω_0 - at constant τ_ν , the larger Ω_0 , the larger the age of the Universe and the smaller H^0 . Note also that if τ_ν increases at fixed Ω_0 , the age of the Universe decreases while H^0 increases. By requiring a Universe older than 5 billion years and a value H^0 larger than 50 km/s/Mpc, we derive an upper bound $\tau_\nu \leq 3.5 \times 10^{13} \text{ sec}$. If we demand an age of 10 billion years, that closure constraint becomes $\tau_\nu \leq 1.0 \times 10^{12} \text{ sec}$. The corresponding limit is presented in figure 1 as the heavy vertical line (a).

3 - The red giant limit.

Unlike all other cases, observations of red giant stars supplemented by our understanding of stellar evolution leads to a constraint on the neutrino-photon coupling strength which is free from any assumption about the initial neutrino population. Indeed, neutrinos appear only as final states of the plasmon decay reaction $\gamma \rightarrow \bar{\nu}\nu$ [9]. The red giant core just before the helium flash is made of a degenerate and weakly coupled plasma at a temperature $T \simeq 10^8 \text{ K}$ and a density of $\rho \simeq 10^6 \text{ g cm}^{-3}$. Electrons are relativistic with a Fermi momentum of $p_F \simeq 400 \text{ keV}$ which leads to a plasma frequency $\omega_0 \simeq 20 \text{ keV}$, just above the kinematic limit for plasmon decay into a 17 keV species.

The 17 keV neutrino ν_2 may couple to the lighter species ν_1 and a photon. Such an interaction is described by the effective lagrangian

$$\mathcal{L} = \bar{\nu}_1 \mu_{12} \sigma_{\mu\nu} \nu_2 F^{\mu\nu} + h.c., \quad (5)$$

with the non-diagonal magnetic moment μ_{12} . The energy loss rate for transverse plasmon decay into a $\nu_2 \bar{\nu}_1$ pair may be expressed as

$$\epsilon_T(\text{plasmon} \rightarrow \nu_2 \bar{\nu}_1) = \frac{1}{6\pi^3} |\mu_{12}|^2 \int Q^2 dQ (q^2 - m_\nu^2)^2 \left(1 + \frac{2m_\nu^2}{q^2}\right) \frac{Z_T}{e\beta\omega - 1}, \quad (6)$$

where $q = (\omega, \vec{Q})$ is the four-momentum of the decaying photon. We have assumed that one of the neutrinos is massive while the other is massless. An expression similar to

relation (6) holds for the longitudinal mode, except for an overall factor of $1/2$. Photon propagation inside matter is taken into account and

$$Z_T = \frac{2\omega^2 q^2}{3\omega_0^2 \omega^2 - q^2} \quad (7)$$

is the wave function renormalization constant of the electromagnetic field (in this case, it is always very close to unity). Furthermore, Q and ω are related to each other through the dispersion relation [10]

$$\omega^2 - Q^2 = \frac{3}{2} \omega_0^2 \left\{ \frac{\omega^2}{Q^2} + \frac{\omega}{2Q} \left(1 - \frac{\omega^2}{Q^2}\right) \ln \left(\frac{\omega + Q}{\omega - Q}\right) \right\}, \quad (8)$$

for the transverse mode and in the case of an *ultra-relativistic* plasma of electrons. As recently pointed out [11], most of the past literature [12] assumed a *non-relativistic* behaviour of the stellar gas, relying therefore upon fairly incorrect dispersion relations, especially for the longitudinal mode. The conditions which prevail inside red giant cores do imply a ultra-relativistic behaviour of the electron gas.

Given the vacuum decay width,

$$\Gamma_0(\nu_2 \rightarrow \nu_1 \gamma) = |\mu_{12}|^2 \frac{m_\nu^2}{2\pi}, \quad (9)$$

we can easily plot (figure 3) the allowed region for the neutrino lifetime as a function of its mass, by requiring that the energy loss rate via plasmon decay should not exceed the other standard mechanisms, i.e., $\epsilon_T + \epsilon_L \leq 30 \text{ erg g}^{-1} \text{ s}^{-1}$. For a 17 keV neutrino ν_2 , we infer the following bound

$$\tau_\nu \geq (7.5 \times 10^9 \text{ sec}) B_\gamma. \quad (10)$$

The domain of figure 1 above the short dashed curve (b) is excluded by the requirement that red giant stars should not be overcooled.

4 - The Solar Maximum Mission bound.

Data from the Gamma-Ray Spectrometer [13] on the Solar Maximum Mission (SMM) satellite [14] show no excess γ -ray emission coincident with the $\sim 10 \text{ second}$ neutrino burst from supernova 1987A. From the absence of a detectable signal, an upper bound on the fluence $\mathcal{F}_\gamma$ of MeV photons from the supernova may be derived. That γ -ray fluence is less than $\sim 1 \text{ photon cm}^{-2}$, during a period of observation $\Delta t_{\text{obs}} \sim 10 \text{ seconds}$ encompassing the neutrino burst.

5 - The COBE limit.

The recent COBE measurements [18] show that the spectrum of the cosmological microwave background (CMB) is pure black-body... as predicted by the theory of the hot Big-Bang - with a temperature of 2.735 K and a chemical potential $\mu \leq 9 \times 10^{-3}$.

Any heat release into the primordial plasma of electrons and photons may distort the radiation spectrum [19]. Through Thomson collisions with free electrons, photons achieve thermal equilibrium until recombination occurs at $T_\gamma \sim 4000$ K, at a time $t_{\text{rec}} \simeq 3 \times 10^{11}$ seconds. If energy is released into the photon gas at early times, before $10^4 - 10^5$ seconds, both double Compton ($\gamma e \rightarrow \gamma\gamma e$) and bremsstrahlung ($e p \rightarrow e p \gamma$) reactions restore the Planckian shape of the spectrum. Therefore, between, say, 10^5 seconds and recombination, a μ -distortion may occur if energy is dumped into the radiation

$$d\mu = 1.4 \frac{d\rho_\gamma}{\rho_\gamma} \quad (15)$$

Spectral distortions of the CMB may be generated by the radiative decays of a massive neutrino [20] through the associated energy release $d\rho_\gamma$. As a result of the process $\nu_2 \rightarrow \gamma\nu_1$, the electromagnetic energy density increases with time

$$d\rho_\gamma = n_\nu(t) \frac{m_\nu}{2} B_\gamma \frac{dt}{\tau_\nu} \quad (16)$$

In what follows, we focus only on massless final states. Since the temperature of interest is much less than 17 keV, massive neutrinos may be considered at rest so that the photon energy is $m_\nu/2$ on average. The density of the massive species exponentially decays in time while the resulting μ -distortion evolves as

$$d\mu = 7.07 \times 10^{-2} \left(\frac{m_\nu}{T_\gamma} \right) B_\gamma e^{-t/\tau_\nu} \frac{dt}{\tau_\nu} \quad (17)$$

We have numerically integrated equation (17) and set the constraint $\mu \leq 9 \times 10^{-3}$ from the COBE observations. The resulting upper bound on B_γ is presented in figure 1 as a function of τ_ν (solid line(d)). Note that curve (d) exhibits a dip for $\tau_\nu \simeq 1.4 \times 10^{11}$ seconds $\sim t_{\text{rec}}$. Two regimes may be distinguished.

If neutrinos decay before recombination, the evolution equation (17) may be naively integrated with a photon temperature set equal to $T_\gamma(\tau_\nu)$, leading to

$$B_\gamma \leq 0.127 \left(\frac{T_\gamma(\tau_\nu)}{m_\nu} \right), \quad (18)$$

so that the larger τ_ν , the lower B_γ .

During the explosion of the type-II supernova 1987A, the binding energy of the $1.4 M_\odot$ neutron star remnant is released as an intense neutrino flux. Each neutrino species carries out approximately 10^{53} ergs. At a distance of 55 kpc, the neutrino fluence $\mathcal{F}_\nu$ is $\sim 1.4 \times 10^{10} \text{ cm}^{-2}$ for a neutrino sphere temperature $T_\nu \simeq 4$ MeV, in fairly good agreement with the observations by the IMB [15] and Kamiokande [16] collaborations.

If neutrinos decay radiatively in flight between the supernova and the solar system, a lower bound onto their radiative lifetime $\tau_{\nu \text{ rad}}$ may be placed from the SMM observations. Since the neutrino mass of 17 keV is significantly smaller than the average kinetic energy (E_ν) $\simeq 3.15 T_\nu \sim 12$ MeV, the decay photons point towards the same direction as their progenitor. Assuming the same energy for all the neutrinos and a decay photon energy $E_\gamma = E_\nu/2$ - which is only strictly correct on average - we may relate the γ -ray fluence $\mathcal{F}_\gamma$ to the total neutrino fluence $\mathcal{F}_\nu$ of the 17 keV neutrino by

$$\frac{\mathcal{F}_\gamma}{\mathcal{F}_\nu} = \frac{2E_\nu}{m_\nu} \frac{\Delta M_{\text{obs}}}{\tau_{\nu \text{ rad}}} \quad (11)$$

The previous expression leads to the gross bound $\tau_{\nu \text{ rad}} \geq 10^{11}$ seconds.

We have refined the previous analysis [17] by integrating $\mathcal{F}_\gamma$ over the energy spectrum of the emitted neutrinos, i.e., a Fermi-Dirac distribution at temperature T_ν . In addition, the decay photon energy is related to the neutrino energy by

$$E_\gamma = \frac{E_\nu}{2} (1 + \cos \theta), \quad (12)$$

where θ denotes the angle between the photon and neutrino momenta in the rest frame of the neutrino. We also have integrated over the isotropic distribution of angle θ in order to deal with the spread in energy of the decay photons for fixed value E_ν . The resulting photon fluence in the energy band $[E_{\text{min}}, E_{\text{max}}]$ is a mere superposition of truncated Fermi-Dirac distributions with temperature varying from 0 to T_ν .

$$\frac{\mathcal{F}_\gamma}{\mathcal{F}_\nu} = \frac{\Delta M_{\text{obs}}}{\tau_{\nu \text{ rad}}} \left(\frac{4T_\nu}{3\zeta(3)m_\nu} \right) \int_0^1 dx \int_{y_{\text{min}}}^{y_{\text{max}}} dy \frac{y^3}{e^y + 1}, \quad (13)$$

where the lower (or upper) bound $y_{\text{min}} = E_{\text{min}}/x T_\nu$ (or $y_{\text{max}} = E_{\text{max}}/x T_\nu$). The strongest limit is set by a photon fluence $\mathcal{F}_\gamma \leq 0.4 \text{ cm}^{-2}$ in the energy band between 10 and 25 MeV. We infer the lower limit on the neutrino lifetime

$$\tau_\nu \geq (1.49 \times 10^{11} \text{ sec}) B_\gamma, \quad (14)$$

as a function of the radiative branching ratio B_γ . The region of figure 1 above the long dashed curve (c) is therefore excluded.

On the other hand, if neutrinos decay after recombination, most of the decay photons will not interact with the radiation and should show up today as a diffuse background. Nevertheless, the small fraction t_{rec}/τ_ν of the photons produced prior recombination may still distort the CMB so that the bound becomes

$$B_\gamma \leq 0.212 \left(\frac{T_\gamma(t_{\text{rec}})}{m_\nu} \right) \left(\frac{\tau_\nu}{t_{\text{rec}}} \right) \sim \frac{\tau_\nu}{7 \times 10^6 \text{ sec}}. \quad (19)$$

6 - Discussion.

The above-mentioned astrophysical and cosmological arguments are quite insuperable and definitively face the 17 keV neutrino. Additional bounds may further constrain the properties of that particle. However, they rely on more model-dependent assumptions which may not be valid. We present these softer limits as well as the arguments to evade them.

The most severe constraint upon τ_ν comes presumably from the formation of large scale structures, i.e., galaxies and associated clusters. Density fluctuations in the matter distribution are fairly small at the time of recombination. Unsuccessful searches for angular anisotropies in the CMB place indeed the limit $\delta\rho/\rho \sim \Delta T/T < 10^{-4}$. On the other hand, matter inhomogeneities should have increased since recombination and become non-linear, because galaxies do exist today. If the 17 keV neutrino decays after $\sim 10^6$ seconds, the Universe has been radiation dominated since recombination by the neutrino debris, so that density fluctuations have remained constant at the very low value inferred from the CMB observations, preventing structures from forming. In order to avoid that catastrophe, the 17 keV neutrino should decay much earlier than the limit which we set in section 1, and a much more severe bound obtains, i.e., $\tau_\nu < 10^6 \text{ sec}$ [21]. However, that constraint may be evaded if neutrinos radiatively decay with branching ratio $B_\gamma \leq 10^{-7} - 10^{-6}$, provided that the decay photons reionize the primordial plasma [22] and erase the CMB anisotropies. The growth of density fluctuations should also be evaluated consistently, in the presence of the heavy neutrino and its decay products.

A bound on the mass of the muon and tau neutrinos may be inferred from the overcooling by helicity flip in SN1987A, i.e., $m_{\nu_\mu, \tau} \leq 14 \text{ keV}$ [23]. Owing to uncertainties in the precise calculation of that neutrino flip in the dense matter of the supernova (finite temperature and density effects may be large and should be properly incorporated [24]), and to uncertainties in the data (only nineteen neutrinos have been detected [15, 16]), that limit does not eradicate a 17 keV neutrino. Furthermore, it does only apply to Dirac species and is evaded by Majorana particles.

The constraints of figure 1 rely on conventional physics and should stand firm. The most important outcome of the potential discovery of a 17 keV neutrino is the need for new physics beyond the Standard Model, the pertinence of which has nevertheless been brilliantly confirmed by the LEP experiments [2]. We can summarize the contents of figure 1 by

$$B_\gamma \leq 4 \times 10^{-5} \quad \text{and} \quad \tau_\nu \leq 10^{12} \text{ sec}. \quad (20)$$

Since any model has to satisfy those two limits, the 17 keV neutrino must predominantly decay into some other species than the photon. It may decay into other neutrinos. This is actually the case in mirror models where the mass eigenstates ν_1 and ν_2 are rotated by an angle $\theta \sim 0.1$ with respect to the weak interaction eigenstates [25]. If the latter are not in the same gauge representation, the GIM cancellation does not apply so that the dominant decay mode is the three body reaction $\nu_2 \rightarrow 3\nu_1$ mediated by Z^0 exchange, with width $\sim \theta^2 m_\nu^5/M_W^4$. In addition, the radiative decay $\nu_2 \rightarrow \gamma\nu_1$ through a W and charged lepton loop has width $\sim \alpha \theta^2 m_\nu^3 (m_\nu/M_W^2)^2$, i.e., only a factor α smaller than the main channel. The radiative branching ratio for those models is naively $B_\gamma \sim \alpha \sim 10^{-2}$, well above the constraint (20). Furthermore, the main decay mode has total lifetime $\tau_\nu \sim M_W^4/m_\nu^5 \sim 10^{16-17} \text{ sec.}$, which exceeds the closure limit (20). Such models are therefore ruled out.

Other decay mechanisms require new particles in the final state, which, because the neutrino mass is so small, have to be massless with respect to the electroweak and grand unification scales. The majoron and the axion are two well-known examples of such hypothetical particles. They couple to matter with characteristic strength $1/f$, where f is the energy scale of the theory and is already constrained to be in the range $10^8 - 10^{12} \text{ GeV}$ [26]. By varying f , the neutrino lifetime may be adjusted [27] to satisfy the closure limit (20). Furthermore, the photon branching ratio is extremely small, $B_\gamma \simeq (m_\nu/f)^2 \simeq 10^{-31} - 10^{-28}$, so that both constraints (20) are satisfied.

The discovery of a 17 keV neutrino, if confirmed, would be an exciting clue for the existence of a new scalar species, and would revive the interest in axion, majoron or familion theories. It would definitely point towards unconventional physics.

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Figure captions

Figure 1 : Astrophysical and cosmological arguments constrain the 17 keV neutrino to lie in specific domains of this (τ_ν, B_ν) diagram. The region on the right-hand side of the closure bound (a) (heavy line) is excluded. The domain above curves (b), (c) and (d) is also forbidden. The short dashed curve (b) is the red giant limit. The long dashed curve (c) is derived from the solar maximum mission data. Finally, the quasi-Planckian spectrum of the CMB implies the constraint (d).

Figure 2 : The present value H^0 of the Hubble parameter is plotted as a function of τ_ν , assuming a flat Universe. The heavy horizontal line is the upper value inferred from observation.

Figure 3 : The region of the $(n_\nu, \tau_{\text{rad}})$ space which does not conflict with the overcooling of red giant stars by plasmon decay lies above the curves. The solid (or short dashed) line corresponds to ultra-relativistic (or non-relativistic) electrons inside the stellar material of the helium core.

Figure 1

Figure 2

Figure 3