Reheated Universe by Unstable Neutrinos

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(Received 2 May 1988)

The possibility is explored that moderately massive neutrinos (1–10 keV) with a lifetime shorter than the age of the Universe, decaying predominantly without emitting radiation but with a small branching ratio to the photon channel, have reheated the Universe after recombination. For a reasonable parameter range, it is possible to explain the recently observed spectral distortion of the cosmic microwave background radiation (CBR). Implications are also discussed for the interpretation of the anisotropy measurement of the CBR.

PACS numbers: 98.80.Cq, 14.60.Gh, 95.30.Cq, 98.70.Vc

Recent measurement of the submillimeter spectrum of the 2.7-K cosmic background radiation (CBR) shows a significant distortion of the blackbody radiation on the short-wavelength side of the peak.[1] The amount of energy corresponding to this radiation is so huge (5×10^{-14} erg/cm^3) that no known astrophysical heat sources can account for it. One of the primary mechanisms potentially giving rise to such a distortion is inverse Compton scattering of CBR photons off electrons,[2-5] as first suggested by Zeldovich and Sunyaev.[2] Another possibility is microwave emission from intergalactic dust which might have been produced from primordial stellar objects.[3,6] In either of the two scenarios, one needs extravagant heat sources that modify our understanding of the thermal history of the Universe for $z=1000$–10, and the problem of the heat source remains at a speculative stage.

In this Letter I point out that the decay of relic neutrinos with a mass of 1–10 keV (or some other weakly interacting particles with a mass of a similar order) may provide the heat source leading to the reionization of the Universe. The energy that would be stored in massive relic particles is in fact huge, and the required energy would easily be accounted for if only a tiny part is transferred to the intergalactic medium in an efficient way. The reason that this possibility has not attracted much attention[7] is that such a massive particle, if it decays emitting a photon, would produce an excessive x-ray background[8] and would also violate a constraint involving x rays from white dwarfs[9] and constraints from stellar evolution.[10] In the scenario proposed below these difficulties are not encountered.

A few years ago three groups, Turner, Steigman, and Krauss,[11] Fukugita and Yanagida,[12] and Gelmini, Schramm, and Valle[13] proposed independently a scenario for galaxy formation with moderately massive, unstable particles which would have decayed, without emitting photons, fast enough to satisfy the cosmological mass-density constraint, but slowly enough to trigger the formation of the structure of the Universe. What was not considered in this scenario is that such particles (e.g., neutrinos) are most likely to decay also by emitting photons with a long partial which means a small branching ratio to the photon decay mode. In what follows it will be shown that this photon decay is sufficient to reionize the Universe without conflicting with any astrophysical or cosmological constraints. The properties of such particles seem acceptable from the viewpoint of particle physics as well. I point out also that the conventional interpretation[14] of the 2.7-K CBR anisotropy measurement undergoes a substantial modification in this case. In the following considerations, it is assumed that the unstable particle is one of the heavier neutrinos (ν_μ, ν_τ, or a fourth-generation neutrino) which is most familiar to us, and that it decays at a red shift $1+z_d$.

Constraints on reheating were studied by Stebbins and Silk[15] in the case of a matter-dominated (MD) Universe. In our scenario the University is most likely radiation dominated (RD), at least for some period after the decay, which makes the constraints more severe than those in the MD Universe. The ionization of hydrogen after recombination ($z_r\sim1300$) is caused by bound-free transitions. The constraint that the bound-free transition occurs within one expansion time of the Universe is

$$d\tau_{\mathrm{BF}}/d\ln(1+z) \approx 5.7\times10^6(1+z)\Omega_b(1\ \mathrm{Ry}/h\nu)^{7/2}h \gtrsim 1, \qquad (1)$$

where τ_{BF} is the bound-free optical depth defined by $d\tau_{\mathrm{BF}}=n_e\sigma_{\mathrm{BF}}c\,dt$ with σ_{BF} given in Ref. 16, n_e the density of free electrons, Ω_b the baryon density in units of the closure density, $H_0=100h$ km/s Mpc the Hubble constant, and 1 Ry$=13.6$ eV the Rydberg constant. The factor $(1+z)$ is replaced by $(1+z)^{3/2}$ if the Universe is MD. If, however, the available photons are much more abundant than baryons, the condition that all of the hydrogen be ionized within one expansion time is relaxed by a factor $r=$(number of photons from neutrinos)/(number of baryons). The constraint then reads

$$h\nu \lesssim (1.2\ \mathrm{keV})[r\Omega_b h]^{2/7}(1+z_d)^{2/7}, \qquad (2)$$

where $h\nu$ is taken to be $m_\nu/2$.

The distortion of CBR due to the Compton process[2] is described by a single parameter y_C, the Compton optical depth, as defined by

$$dy_C = n_e \sigma_T (kT_e/m_e) c\, dt, \tag{3}$$

with σ_T the Thomson scattering cross section, and T_e the electron temperature. The observed CBR distortion is given by integration of this expression from $t = t_0$ back to the reionization epoch t_d. In the calculation I take the approximation that the Universe remained at a certain temperature for one expansion time.[15] $y_C = 0.02 \pm 0.005$ is taken as an acceptable value. ($y_C = 0.019$ is given in Ref. 1.) This requires that

$$(1+z_d)(T_e/1\ \text{keV}) \approx (100\text{–}180) h^{-1} \Omega_i^{-1}, \tag{4}$$

where the ionized fractional mass density Ω_i is set equal to Ω_b, and T_e is taken to be $h\nu = m_e/2$. The constraints (2) and (4) are shown in Fig. 1 together with that from the mass density of the Universe,[17]

$$m_{\nu'} < 98(1-\Omega_b)(1+z_d)h^2\ \text{eV}. \tag{5}$$

Here $h = 0.5$ is taken (to make the age of the Universe consistent with observations) and $\Omega_b = 0.2$. The ionization constraint is derived from the limit on uv flux, which gives an upper limit on r. Most interesting is the case when the parameters are located near the crossing point of (4) and (5),

$$m_{\nu'} \sim 7\ \text{keV}, \quad 1+z_d \sim 330. \tag{6}$$

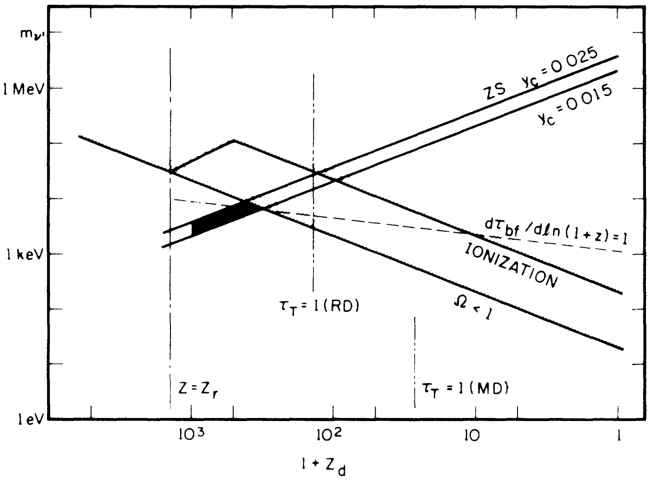

FIG. 1. Constraints on the mass and decay lifetime of neutrinos which reheat the Universe. $\Omega < 1$ is the mass-density constraint (5). The ionization constraint means that hydrogen is fully ionized in one expansion time below the line. ZS represents lines corresponding to the observed distortion of CBR. My favored region is shown by shade. The epochs corresponding to the unit Thomson optical depth ($\tau_T = 1$) and recombination (z_r) are also denoted.

The constraint on the radiative lifetime τ_γ comes from the ultraviolet (uv) astronomy.[8,18] The emitted photons undergo an energy loss due to Thomson scattering, but it is at most a few percent because of a large Thomson optical depth in the RD Universe (see below). The energy of the photons decreases by red shift as the Universe expands, yielding a diffuse background radiation with $50h^2(1-\Omega_b)\ \text{eV} \gtrsim h\nu \gtrsim 3\ \text{eV}$ at the present epoch for my allowed parameter range. The photon flux is given by

$$\lambda i_\lambda = \frac{1}{4\pi H_0} \frac{n_{\nu'}}{\tau_\gamma} \left[\frac{\lambda_0}{\lambda}\right]^2 \exp\left[\frac{-t(z)}{\tau_{\nu'}}\right], \tag{7}$$

with λ_0 the wavelength at the time of emission ($= m_{\nu'}/2$), λ that at the observation, $\tau_{\nu'}$ (τ_γ) the lifetime (radiative lifetime) of the neutrino. A flat (RD) Universe is assumed for simplicity. The bound on the radiative decay is weakened compared with the conventional case by the red-shift factor and by a weaker constraint on uv light compared with that on x rays. The observational data available at $\lambda = 1300\text{–}2000$ Å, which led to $\tau = \tau_\gamma \geq 10^{23}$ s for the conventional case,[18] give in this case $\tau_\gamma \gtrsim 4\times10^{19}\ \text{s}\ (m_{\nu'}/1\ \text{keV})^{-2}$. The constraint on the photon branching ratio is accordingly

$$B_r(\nu' \rightarrow \nu + \gamma) = \tau_\nu \tau_\gamma$$
$$\lesssim 3\times10^{-6} \left[\frac{m_{\nu'}}{2\ \text{keV}}\right]^2 \left[\frac{1+z_d}{100}\right]^{-2}, \tag{8}$$

or

$$r \leq 200 \left[\frac{m_{\nu'}}{5\ \text{keV}}\right]^2 (\Omega_b h^2)^{-1} \left[\frac{1+z_d}{100}\right]^{-2} \tag{9}$$

along the line (5). It is easy to see that hydrogen is fully ionized in one expansion time if (5) is satisfied. The constraints from stars[9,10] are generally weaker than that from the uv background and are also satisfied. The lower bound on B_r is given by $r = 1$, which reads $0.5\times10^{-8}(\Omega_b h^2/0.05)$. If B_r takes a value close to the upper limit set by (8), the residual uv or optical light should be visible. Especially interesting is the case close to (6), for which the red-shifted residual photons have energies $h\nu \approx 1$ Ry at the present epoch and cause a significant ionization of hydrogen in interstellar or intergalactic H I clouds. A value $B_r \sim 0.2\times10^{-6}$ just below the bound may explain the excess ionization observed in the H_α line.[19,20] Such photons might also have ionized He at red shift $z \gtrsim 4$.

It is expected that the hydrogen in intergalactic space is fully ionized as it has been in a radiation bath with energy $h\nu \gtrsim 1$ Ry up the the present or a small z epoch. This explains the extremely scarce abundance of neutral hydrogen[21] ($n_{\text{H I}} < 10^{-13}\ \text{cm}^{-3}$) as inferred from the Gunn-Peterson test.

This reionization of the Universe after recombination alters the interpretation of the CBR anisotropy measurement.[22] The Thomson optical depth is given by $d\tau = \sigma_T n_e c\,dt$ or

$$d\tau/d\ln(1+z) = 7.0\times 10^{-2}\Omega_i h(1+z), \qquad (10)$$

when compared to the expansion time in the RD Universe. Therefore, the last scattering surface is located at $1+z_{ls} \approx 140$ for $\Omega_i \approx 0.2$ rather than $z \approx z_r \approx 1300$. When the neutrino decays at $z \approx z_d$, the emitted photon streams almost freely until $l \approx \lambda_{\rm MFP} \approx ct_d$ while it occasionally ionizes hydrogen (ct_d is the size of the horizon at the epoch $1+z_d$). This effect smooths out the primordial fluctuations seen in CBR up to the angular scale $\theta \approx 2/z_d \approx 0.4°$. Fluctuations at a scale smaller than this size, if observed, should be ascribed to those caused by the galaxy formation itself rather than primordial fluctuations.[22,23]

Let us now discuss galaxy formation in the framework of gravitational instability theory. There are also various nongravitational scenarios which might be relevant to my model. However, they seem to be too flexible to give a definite prediction, and hence I confine my considerations to the gravitational clustering theory. My model is close to the cold-dark-matter scenario,[24] since the damping scale[25] of heavy neutrinos is

$$\lambda_{\nu d} \approx (0.25\ {\rm Mpc})(m_{\nu'}/5\ {\rm keV})^{-1}(1+z)^{-1},$$

or the mass $1.2\times 10^{11} M_{\odot}(m_{\nu'}/5\ {\rm keV})^{-2}$.

The structure forms on smaller scales first and develops hierarchically up to the larger scales. The fluctuations start to grow at $1+z_{eq} = (1.5\text{-}2)\times 10^6(m_{\nu'}/5\ {\rm keV})$. The overall growth up to the epoch of neutrino decays is $(1+z_{eq})/(1+z_d) \sim 5\times 10^3$, sufficient to make structure. On the other hand, the shift of the growing period to an earlier epoch brings a larger fluctuation amplitude at the time of recombination, which usually receives a strong constraint[26] from the null experiment of CBR anisotropy at a few arcminutes.[27] In the decaying-particle scenario, the increase of the fluctuation amplitude at the time of recombination comes from the two facts;[28,29] the lesser growth after the decay and the shorter distance scale in the RD Universe.

The growth since the recombination time is given by $\sim z_r/0.5(1+z_d)^{1.5}$.[29] This requires a factor of 20 larger fluctuations at z_r. Furthermore, if the amplitude is normalized at $7h^{-1}$ Mpc where $\delta\rho_0/\rho_0 \sim 1$ at the present epoch, the fact that the distance scale in the RD Universe is half as large as in the MD Universe causes another factor of 1.9 increase in the required magnitude of fluctuations at the time of recombination. This would lead to an anisotropy $\Delta T/T$ a factor ~ 10 larger than the observation and is ruled out in the conventional decaying-particle scenario[28,29] ($z_d \lesssim 10$ was derived in this way in Ref. 29). In the case of my model, however, this anisotropy is erased at a few-arcminutes scale by reheating and the observation[27] does not give a direct constraint. The larger magnitude of the anisotropy will probably appear at a large scale which exceeds $\theta \sim 1°$ through the Sachs-Wolfe effect.[30] The value given by a recent observation at 8°-10° ($\Delta T/T \simeq 5\times 10^5$ with a beam size 3.5°)[31] is typically an order of magnitude larger than that predicted in the cold-dark-matter scenario or decaying-matter scenario ($z_d \lesssim 4$). The increased fluctuations required in my scenario with $n=1$ might be compared with the reported value (n is a power index of the Fourier fluctuation spectrum as defined by $|\delta_k|^2 \propto k^n$). This leaves the possibility that the observed fluctuations are indeed real, although they are usually considered too large for reasonable models of gravitational clustering. A potential difficulty with the present scenario[32] is that the system might be disrupted when the neutrino decays, since its lifetime is shorter than the typical dynamical time scale of the galaxy.[11,12] Numerical N-body simulations should be invoked to clarify this point.

Finally, I should make a brief comment on the particle-physics model for the present scenario. Examples of candidates[33] leading to nonradiative decay include the models of familons and majorons. For the latter, particle-physics constraints are so weak that almost any parameters are allowed. More restrictive is the familon model which receives a strong constraint from the absence of $\mu \to e + \chi$ and $\tau \to e + \chi$. My parameter set (6) requires a symmetry-breaking scale $v \sim 6\times 10^9$ GeV, which is consistent with the experiment, but also with the value which I am thinking of for such a model.[33] The lifetime of radiative decays also appears reasonable. The upper bound on the radiative lifetime $\tau_\gamma \sim 6\times 10^{20}$ s is only 3.5 orders of magnitude shorter than the standard-model predictions with three generations, and may be explained if there is a fourth-generation heavy lepton with a mass ~ 100 GeV. The transition magnetic moment corresponding to my desired τ_γ is $\mu = [(3\times 10^{-17})\text{-}(8\times 10^{-16})]\mu_{\rm B}$ ($\mu_{\rm B}$ = Bohr magneton) for $m_{\nu'} \sim 7$ keV. These values are on the right order of magnitude in the left-right-symmetric model, the simplest extension of the standard theory.

I would like to thank Toshio Matsumoto, Jerry Ostriker, and Paul Richards for useful discussions, and John Bahcall for his encouragement. I am grateful to Jeremy Goodman and Jerry Ostriker for reading the manuscript. This work is supported in part by National Science Foundation Grant No. PHY-8620266.

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