Condensation of photons in the hot universe and longitudinal relict radiation

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Assuming that the photon mass differs from zero, a hypothesis is advanced that a photon condensate existed in the universe at earlier expansion stages. The evaporation of the condensate as a result of interaction with charged particles has led to the formation of longitudinal relict radiation that constitutes possibly the bulk of the mass of the universe.

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We consider in this paper some cosmological and astrophysical consequences of the assumption that the photon mass is not zero, $m_\gamma \neq 0$. It is immaterial in this case how the photon mass came into being, i.e., whether we are dealing with massive electrodynamics or whether the photon has acquired a mass as a result of spontaneous breaking of symmetry in gauge theory. The weak current nonconservation which arises in the latter case does not affect our conclusions. We shall show that despite the strong experimental bound on the photon mass, $m_\gamma < 10^{-49}$ g[1,2] the assumption that m_γ is finite can lead to far reaching cosmological consequences.

We start with the remark that a massive photon gas can undergo a phase transition in which some of the photons land in a Bose-Einstein condensate with a degeneracy temperature (in the ultrarelativistic approximation)

$$T_0 = \hbar c\left(\frac{\pi^2}{g\,\zeta(3)}\,\rho\right)^{1/3}, \tag{1}$$

where ρ is the total number of photons per cm^3, $g=3$ is a statistical factor, and $\zeta(x)$ is the Riemann function. Subject to the limitation $m_\gamma < 10^{-49}$ g, this approximation is valid at $T_0 \gg 10^{-15}$ K. Comparing (1) with the expression for the photon-gas temperature

$$T = \hbar c\left(\frac{\pi^2}{g\,\zeta(3)}\,\rho_{p>0}\right)^{1/3}, \tag{2}$$

where $\rho_{p>0}$ is the number of photons with nonzero momentum, we see that the ratio $\rho_{p>0}/\rho)^{1/3} \approx T/T_0$ is a free parameter of the theory and is not fixed by the specified value of the photon-gas temperature T. The number of photons in the condensate is given by

$$\rho_{\text{condens}} = \rho\left(1 - (T/T_0)^3\right).$$

Applying these considerations to the theory of the hot universe during the earlier stage of expansion, we see that in the case $m_\gamma \neq 0$ there could exist an entire class of cosmological models characterized, besides everything else, by the value of the parameter T/T_0, which specifies the degree of degeneracy.

An essential factor in the solution of the problem of the possibility of the precipitation of the photons into a condensate is a consideration of the conditions of thermodynamic equilibrium between the massive photon gas and the matter in the universe. For transversely-polarized photons[1] the equilibrium conditions are satisfied at 10^{-45} sec $< t < 10^{12}$ sec; the question of whether equilibrium exists between the charged particles and the photons near the singularity remains open (see[3]). The cross section of the interaction of a longitudinally polarized photon with a charged particle is

$$\sigma_{\parallel} \sim (m_\gamma/\omega)^2 \sigma_{\perp} , \tag{3}$$

where $\sigma_\perp$ is the interaction cross section of a transversely polarized photon, and ω is the photon energy in the c.m.s. The cross section for the production of a longitudinal photon also differs from the cross section of the production of a transverse photon by a factor $(m_\gamma/\omega)^2$. It can be shown that for longitudinal photons in an expanding universe thermodyamic equilibrium could take place at

$$t > 10^{54}(m_0/m_\gamma)^2 \text{ sec} , \quad m_0 = 10^{-49} \text{ g}$$

(see the analogous analysis in[5]). Thus, at no time, with the possible exception of the very earliest stages of the expansion of the universe, are the longitudinal photons in equilibrium with charged particles. It is not excluded, however, that near the singularity, at $t < (G\hbar/c^5)^{1/2} \approx 10^{-43}$ sec, the longitudinal photons are in equilibrium with the matter because of gravitational interactions (for a discussion of the question of thermodynamic equilibrium for gravitons see[3]). We assume that the quenching time for gravitons is $t \sim 10^{-43}$ sec. Then the photon condensate could be produced not later than at that time.

Let us assume that the condensate has been produced and let us trace its subsequent fate. We consider the evaporation of the condensate starting with the instant of the quenching of the longitudinal component (we assume $t \approx 10^{-43}$ sec). Charged particles, interacting with a condensate, remove photons from the latter, and the transverse part of the photons then returns to the condensate, since the thermodynamic-equilibrium conditions are not violated for them up to $t \sim 10^{12}$ sec. On the other hand, the longitudinal photons do not interact subsequently with anything, and consequently, the plasma energy is effectively transferred to the longitudinal photons. The change of the condensate density and the cooling of the plasma on account of expansion and heating of the condensate are described by the approximate system of equations

$$\frac{d\epsilon}{dt} = -\frac{1}{2}\frac{\epsilon}{t} - \sigma_\perp c m_\gamma \rho_{\text{condens}}$$

$$\frac{d\rho_{\text{condens}}}{dt} = -\frac{3}{2}\frac{\rho_{\text{condens}}}{t} - \rho_{\text{condens}}\, c\sigma_\perp n(t)\left(\frac{m_e}{\epsilon}\right)^2 \tag{4}$$

where ϵ is the average particle energy, m_e is the electron mass, and n is the concentration of the charged particles. A rough estimate of the characteristic condensate-evaporation time yields

$$t^* \sim 10^{-33} \text{ sec}$$

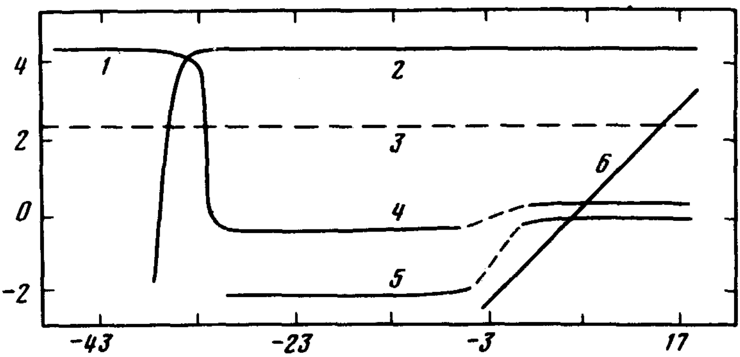

FIG. 1. Time dependences: 1) of the total energy density (Σ), 2) of the longitudinal radiation produced as a result of the evaporation of the condensate ($\epsilon_{\parallel}$). 3) of the thermal longitudinal radiation ($\Sigma-\epsilon_{\parallel}-\epsilon_{\parallel}^{\text{therm}}$), and after $t\sim 10^6$ sec also of the matter, 5) of the transverse relict radiation, 6) of the matter (ρ_m). The abscissa is calibrated in $\log(t/\text{sec})$, and the ordinate in $\log(\epsilon/\rho_m^{4/3})$.

so that in the epoch $t>t^*$ no condensate is left, for it has been entirely converted into a gas of longitudinal photons. It can be shown that the reverse process–interaction of longitudinal photons with matter–proceeds extremely slowly (the change of the density of the gas of longitudinal photons because of interaction with matter amounts to $\Delta\rho_{\parallel}/\rho_{\parallel}\sim 10^{-16}$). The overall picture of the time variation of the density of the gas of longitudinal photons of the (transverse) relict radiation and matter is shown in Fig. 1. We have normalized Fig. 1 in such a way that the total density is $\rho_{\text{cr}}\sim 1\times 10^{-29}$ g/cm^3. We see that the longitudinal-photon gas makes up the bulk of the mass of the universe at all times. Curve 3 on Fig. 1 pertains to the thermal longitudinal relict radiation with temperature $T\sim 10$ K, quenched at the instant $t\sim 10^{-43}$ sec. A rough estimate of the average energy of the longitudinal photons yields $\bar{\epsilon}_{\parallel}\sim 10^{-6}$ eV (m_{γ}/m_0 and $m_0=10^{-49}$ g, which makes their density $n_{\parallel}\sim\rho_{\text{cr}}/\epsilon_{\parallel}\sim 10^{11}$ cm$^{-3}(m_0/m_{\gamma})$. Does so large a density (and energy density) of the gas of longitudinal photons contradict anything? It can be shown that such a density does not influence, at any rate, the propagation of cosmic rays in the universe.

Thus, we consider it perfectly possible that in the case when m_{γ} is not equal to zero the universe is filled with a gas of longitudinal photons produced by evaporation of a photon condensate, and this gas can play a decisive role in the expansion of the universe.

We note in conclusion that a finite photon mass should lead to emission of streams of longitudinal photons by the sun and by the earth, to an additional heat transport process in the interior of the sun, and to other effects which we shall consider in a separate paper.

Experimental searches for streams of longitudinal photons (longitudinal radiowaves), in view of the weakness of their absorption by matter, require apparently low-background conditions and could be carried out, for example, deep underground.

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[1] In view of the exceptional smallness of the mass, the photon effectively "memorizes" its polarization. Thus, the Lorentz transformation of the longitudinal-photon production operator is of the form $Ua_{\parallel}^{+}U^{+} \sim -m_{\gamma/\omega}(\sin\alpha+\sin^2\alpha)a_{\perp}^{+}+(1-\cos\alpha)\,a_{\parallel}^{+}$, where α is the angle between the photon momentum and the direction of motion of the new coordinate system.

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[1] L. Davis, Jr. A.S. Goldhaber, and M.M. Nieto, Phys. Rev. Lett. **35**, 1402 (1975).
[2] A.S. Goldhaber and M.M. Nieto, Rev. Mod. Phys. **43**, 277 (1971).
[3] Ya.B. Zel'dovich and I.D. Novikov, Stroenie i evolyutsiya Vselennoĭ (Structure and Evolution of the Universe), Nauka, 1975.
[4] L. Bass and E. Schrödinger, Proc. R. Soc. London Ser. A **232**, 1 (1955).