ON THE DEGRADATION OF STELLAR AND COSMIC NEUTRINOS

1963

Abstract

Full Text

PHYSICS

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(Presented by Academician L. A. Artsimovich, 17 XII 1962)

In ([1]) we estimated the intensity of the generation of neutrinos and antineutrinos by various sources in the universe and considered possible processes of neutrino absorption. In particular, the process of double capture was considered (the unstable product formed after the capture of a neutrino or antineutrino captures an antineutrino or neutrino before decay occurs), as well as the annihilation of a neutrino and an antineutrino. It was found that, within the framework of the known processes and interactions, neutrinos and antineutrinos are practically not absorbed, so that a continuous accumulation of neutrinos takes place, which naturally raises the question of their further fate.

Recently B. Pontecorvo and Ya. Smorodinskii ([2]) suggested that the matter of the universe known to us could have arisen as a result of fluctuations against a once existing sufficiently dense neutrino-antineutrino background. During the fluctuations the energy density of the neutrino background was, as should also be the case for fluctuations, much greater than the energy density of the "ordinary" matter produced in the fluctuation. Subsequently, as the universe expanded, the energy density of the "ordinary," "heavy" (nonrelativistic) particles fell as R^{-3}, whereas the energy density of the relativistic particles—neutrinos, photons—because of the Doppler shift, fell as R^{-4}: a particle with zero rest mass "ages," whereas a "heavy" particle with nonzero rest mass remains "young."

One can estimate the energy density of the neutrino background that should have remained from the original background in which the fluctuation (or fluctuations) occurred. As long as the heavy particles remained relativistic, their energy density decreased in the same way as that of the light particles. Consequently, it is necessary to consider the expansion only from the moment when the heavy particles ceased to be relativistic.

Let $\varepsilon_{\nu 0}$ be the energy density of the neutrinos at this moment, ε_{m0} the rest-energy density of the heavy matter ($m \neq 0$), and ε_{k0} the density of the kinetic energy of matter with $m \neq 0$. Suppose that, since that time, the neutrino energy density has decreased because of red shift by a factor k and has become equal to ε_ν (we do not write the change in energy density due to the simple increase in the volume of the universe, since it does not affect the relative densities). Then the mean momentum of the heavy particles at the time under consideration is $p =$

p_0/k, where p_0 is the mean momentum of the heavy particles at the beginning of the stage of expansion being considered, i.e., when the heavy particles had already ceased to be relativistic. Consequently, the kinetic energy of the heavy particles after expansion is

$$E_k = \frac{p^2}{2M} = \frac{p_0^2}{2Mk^2} = \frac{E_{k0}}{k^2}.$$

A particle ceases to be relativistic when $E_{k0} \approx Mc^2 = 10^9$ eV $= 10^{13}$ °K. Therefore, $k = (E_{k0}/E_k)^{1/2} \simeq \delta^{-1/2}$, where δ is the ratio of the kinetic energy E_k of the particles to their rest energy in our epoch. Taking $E_{k\,\max} \sim 10^4$ °K, $E_{k\,\min} \sim 1$ °K (the first estimate is in any case too high), we obtain $\delta \sim 10^{-9} \div 10^{-13}$ and $k \sim 3 \cdot 10^4 \div 3 \cdot 10^6$.

Since we are not writing out the change in energy density due to the increase in the volume of the universe, the rest-energy density of the heavy particles has not changed: $\varepsilon_{m0} = \varepsilon_m$.

Consequently, if at the moment of fluctuation the rest-energy density of the neutrino was α times greater than the energy density of the particles that arose in the fluctuation, then at present the density is $\varepsilon_\nu \sim \alpha\varepsilon_m/k$, where ε_m is the rest-energy density of heavy particles in our epoch. Hence an upper bound is obtained for α, and therefore also for the size of the fluctuation: from cosmological considerations (see (2)), ε_ν is in any case no greater than ε_m, and, consequently, $\alpha < k$. Since at the moment of separation of the "heavy" and "light" matter the energy of individual neutrinos, under the assumption of temperature equilibrium, was $\sim E_{k0} = 10^9$ eV, the energy of these "relic" neutrinos is now $\sim 10^9/k = 3 \cdot 10^4 \div 300$ eV; their flux, equal to $\varepsilon_\nu c/(Mc^2/k)$, is not more than $\sim \alpha\varepsilon_m c/Mc^2$. Taking $\varepsilon_m \sim 10^{-5}$ proton/cm^3, we find

$$n_\nu \sim 10^{-5}\alpha c \cong 10^{10} \div 10^{12} \text{ cm}^{-2}\text{sec}^{-1}.$$

Analogous considerations can be used to estimate the maximum energy density of neutrino and antineutrino fields from stars and cosmic rays. According to (1), the intensity of neutrino generation in stars, per unit volume of the universe, is $2 \cdot 10^{-24} \div 2 \cdot 10^{-23}$ neutrinos/cm^3 sec. On the other hand, if for the Hubble constant one adopts the value $60 \div 120$ km/sec per Mpc, then the relative decrease in neutrino energy density due to redshift is $2 \div 5 \cdot 10^{-18}$ sec^{-1}. Equating these two quantities, we find that the equilibrium density ρ of neutrino energy is $(4 \div 10) \cdot (10^{-7} \div 10^{-6}) E_\nu$, where E_ν is the mean energy of the neutrino emitted by stars. For $E_\nu \cong 1 \div 3$ MeV, $\rho \cong 10^{-6} \div 10^{-5}$ MeV/cm^3. This value may be compared with the cosmological density (the density of heavy matter), equal to $\sim 10^{-2}$ MeV/cm^3.

For cosmic rays we obtain analogously: the generation intensity, according to (1), is $5 \cdot 10^{-22} \div 5 \cdot 10^{-24}$ neutrinos per 1 cm^3 per second ($k_{\nu,\tilde{\nu}}$ is taken to be

$\cong 5$ (1)). Taking the mean energy of neutrinos generated by cosmic rays to be $\cong 100$ MeV, we obtain $\delta\rho_{\text{cosm. ray}} \cong 5 \cdot 10^{-20} \div 5 \cdot 10^{-22}$ MeV/cm^3·sec, and the equilibrium value of the energy density of the corresponding neutrinos is $(2 \div 5) \cdot 10^{17}$ times larger, or equal to $2 \cdot 10^{-2} \div 10^{-4}$ MeV/cm^3, i.e., in any case not higher than the limiting value allowed by cosmological considerations (see (2)). The mean energies of the corresponding neutrinos will be, as an estimate, $\sim 10^4$–10^6 times smaller than at the moment of generation, i.e., they will be $\sim 1 \div 100$ eV for neutrinos generated by stars, and $10^2 \div 10^4$ eV for neutrinos generated by cosmic rays. The absolute fluxes will be very large–many orders of magnitude greater than the neutrino flux from the Sun in the vicinity of the Earth.

Limiting values of the fluxes can also be obtained from the Pauli principle. If one assumes that all levels are filled and that the neutrino energy density is equal to the density of heavy matter, then the maximum energy of such neutrinos will be $\sim 10^{-2}$ eV, and their flux $\sim 1.5 \cdot 10^{19}$ particles/cm^2·sec.

Received
17 X 1962

References

1. V. M. Kharitonov, *DAN*, **141**, No. 1, 66 (1961).

2. B. Pontecorvo, Ya. Smorodinsky, Preprint of the Joint Institute for Nuclear Research, April 1961.

Note: Figure translations are in progress. See original paper for figures.