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Abstract

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Astronomy

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THE NECESSITY OF A PERIOD OF NEUTRAL HYDROGEN IN THE EVOLUTION OF THE UNIVERSE

(Presented by Academician Ya. B. Zel'dovich on May 5, 1967)

In the hot model of the Universe, confirmed by recent radio observations (see the review (1)), it is assumed that at an early stage of expansion the completely ionized plasma is in equilibrium with the radiation. Cooling during expansion leads to recombination of hydrogen at $T \sim 4000^\circ \text{K}$ and $z \sim 1300^*$. With further expansion hydrogen should have remained neutral. Observations in the 21-cm line and measurements of absorption in the $Ly-\alpha$ lines in the spectra of distant quasars indicate the absence of neutral intergalactic hydrogen. It is difficult to imagine complete condensation of the gas into galaxies; therefore it is believed that the absence of neutral hydrogen indicates a high degree of ionization and, as a consequence, a high electron temperature of the intergalactic gas. In addition, modern theories of galaxy formation indirectly indicate the necessity of preliminary heating of the gas. In work (2) it is assumed that the gas was heated at $z \sim 10 \div 20$; the author of work (3) believes that heating of the gas occurred at $z \sim 100$, and in work (4)—at $z \gg 10^3$. Taking into account the complete uncertainty of the choice, it makes sense to give even a rough, but maximal, estimate of z at which the reheating occurred. Analysis of the energy balance of the intergalactic gas and of the available experimental data on its radio emission show that heating could not have occurred earlier than $z \sim 300$, i.e. at $300 < z < 1300$ the gas was neutral. Significant energy losses of the plasma lead to the fact that, in order to maintain a high temperature at $z > 300$, it is necessary to process into helium more than 30% of all matter, and this contradicts the observed data. A decrease in the temperature, however, leads to a contradiction with the observed background radiation in the radio range.

1. Energy losses of a hot plasma. The principal role in the cooling of intergalactic gas at $z > 6$ is played by energy losses by electrons through the inverse Compton effect on the relic radiation (5,6)

$$L_- = 4\sigma_0 \frac{kT}{m_e m_p c} \varepsilon_\gamma = 4.95 \cdot 10^{-12} (1+z)^4 T(z) \frac{\text{erg}}{\text{g} \cdot \text{sec}}, \quad (1)$$

where σ_0 is the Thomson scattering cross section; ε_γ is the energy density of the relic radiation. It is obvious that if W is the total possible energy release per gram of matter, then

$$\int L_- dt = H_0^{-1} \int_0^{z_{\max}} L_-(z) \frac{dz}{(1+z)^2 \sqrt{1+\Omega z}} < W, \quad (2)$$

where z_{\max} characterizes the beginning of reheating.

* We introduce the parameters Ω and z : $\Omega = 2q_0 = \rho/\rho_{\text{crit}}$, where $\rho_{\text{crit}} = 2 \cdot 10^{-29} \text{ g/cm}^3$, $n_{\text{crit}} = 10^{-5} \text{ cm}^{-3}$; during the expansion of the Universe the density changes according to the law $n = n_0(1+z)^3$; wavelength $\lambda_0 = \lambda(1+z)$; temperature of the equilibrium radiation $T = T_0(1+z)$; time from the beginning of expansion $t \approx t_0(1+z)^{-3/2}$, where $n_0 = \Omega n_{\text{crit}}$ is the present mean matter density in the Universe; $T_0 = 3^\circ\text{K}$ is the temperature of the relic radiation; $t_0 \sim H_0^{-1} = 3 \cdot 10^{17} \text{ sec}$. ($H_0 = 100 \text{ km/sec} \cdot \text{Mpc}$ is the Hubble constant) and λ_0 is the wavelength of the received radiation.

2. Radio emission of the intergalactic medium

The volume emission coefficient of a helium-hydrogen plasma (30% helium, 70% hydrogen—such is the chemical composition predicted by the hot model) in free-free transitions is

$$\varepsilon_{ff}(\nu, z) = 6 \cdot 10^{-39} g T^{-1/2}(z) e^{-h\nu(1+z)/kT(z)} n_0^2 (1+z)^6 \text{ erg/cm}^3 \cdot \text{s} \cdot \text{sr} \cdot \text{Hz} \quad (3)$$

We shall take the Gaunt factor to be equal to 10: for $h\nu \ll kT$,

$$g = \frac{\sqrt{3}}{\pi} \left(\ln \frac{4kT}{h\nu} - 0.577 \right).$$

Since $h\nu \ll kT$, the spectrum of the radio emission of the intergalactic plasma must be flat, which should facilitate its identification:

$$\varepsilon_{ff}(z) = 6 \cdot 10^{-48} \Omega^2 T^{-1/2}(z) (1+z)^6 \text{ erg/cm}^3 \cdot \text{s} \cdot \text{sr} \cdot \text{Hz}. \quad (4)$$

The flux of radio emission of the intergalactic gas ⁽⁷⁾

$$\int \frac{\varepsilon_{ff}(z) dl}{(1+z)^3} = c H_0^{-1} \int_0^{z_{\max}} \varepsilon_{ff}(z) \frac{dz}{(1+z)^5 \sqrt{1+\Omega z}} < \frac{2kT_b(\nu)}{\lambda_0^2}, \quad (5)$$

where T_b is the brightness temperature of the background radiation.

3. Determination of z_{\max}

We have a system of two functionals:

$$\int_0^{z_{\max}} \frac{(1+z)^2}{\sqrt{1+\Omega z}} T(z) dz < A, \quad A = 6.7 \cdot 10^{-7} W; \quad (6)$$

$$\Omega^2 \int_0^{z_{\max}} \frac{1+z}{\sqrt{1+\Omega z}} T^{-1/2}(z) dz < B, \quad B = 4 \cdot 10^3 T_b(\nu) / \lambda_0^2, \quad (7)$$

which makes it possible to determine z_{\max} for an extremal $T(z)$ (i.e., such that for any other function $T(z)$, z_{\max} will be smaller than the value found). The extremum of the functional

$$\int_0^{z_{\max}} \left(K \frac{(1+z)^2}{\sqrt{1+\Omega z}} T(z) + \Omega^2 \frac{(1+z)}{\sqrt{1+\Omega z}} T^{-1/2}(z) \right) dz < AK + B, \quad (8)$$

where K is an undetermined Lagrange multiplier, is the function

$$T(z) = (\Omega^2 / 2K(1+z))^{2/3}.$$

It is evident that the main contribution to the integrals (6) and (7) (for this form of the function $T(z)$) is made by large z ; therefore $\sqrt{1+\Omega z} \approx \Omega^{1/2} z^{1/2}$. Solving the system (6) and (7), we find that the maximum z_{\max} is attained for $K = B/2A$, and

$$T(z) = (A/B)^{2/3} \Omega^{4/3} z^{-2/3},$$

while

$$z_{\max} = 1.39(A^2 B^4 / \Omega^5)^{1/11}.$$

4. Heating of the gas

The actual helium content ($\sim 30\%$ by mass) in various objects (the interstellar medium, most stars, other galaxies, cosmic rays, etc.) shows that, in the heating of the intergalactic gas, the release of energy did not exceed

$$W_1 = 2 \times 10^{18} \text{ erg/g.}$$

The energy release in the formation of heavy elements ($W < 3 \cdot 10^{16}$ erg/g) may be neglected: their abundance is small ($\sim 2\%$ by mass). The gravitational

energy released during the condensation of galaxies and clusters of galaxies contributes no more than

$$W = GM/R = 3 \cdot 10^{14} \text{ erg/g}^*,$$

and the energy release of the powerful objects known to us today (quasars, quasi- and radio galaxies), possibly of non-nuclear origin, is negligible in comparison with the above figures; moreover, a count of weak radio sources indicates the existence of a limiting $z(\sim 2 \div 4)$, beyond which these sources are absent ⁽⁸⁾. Subcosmic rays could have appeared only as a result of explosions of various objects, i.e., their energy has already been taken into account.

* For a galaxy radius $R \sim 1 \text{ kpc}$, mass $M = 10^{10} M_{\odot}$.

The hot model of the Universe predicts the presence in matter that has not passed through the stellar stage of 28-30% helium ⁽¹⁾, i.e., no more than $W_2 = 3 \cdot 10^{17} \text{ erg/g}$ could have gone into heating the gas, which corresponds to the processing into helium of $\sim 5\%$ of the matter. If, however, one takes into account the contribution to the chemical composition of the Galaxy from first-generation stars and recalls the efficiency factor, then the estimates of the energy expended on heating the intergalactic plasma can be reduced at least to $W_3 = 3 \cdot 10^{16} \text{ erg/g}$.

5. Background radio range. Measurements by Howell and Shakeshaft ⁽⁹⁾ ($\alpha = 13^h 00^m$, $\delta = 52^\circ$) showed that at the frequency 610 MHz $T_b(610) = 7.6 \pm 0.8^\circ \text{ K}$. The results of work ⁽¹⁰⁾ give, for the same coordinates, $T_b(404) = 19.4 \pm 2.0^\circ \text{ K}$ at 404 MHz. Taking into account the relic radiation T_R and the large slope of the spectrum of the Galactic and isotropic metagalactic component of the radio background T_1 ⁽¹¹⁾, we find the upper limit of the thermal radio emission of the gas T_2 :

Table 1

Ω	$W, \text{ erg/g}$	$W, \text{ erg/g}$	$W, \text{ erg/g}$
	$2 \cdot 10^{18}$	$3 \cdot 10^{17}$	$3 \cdot 10^{16}$
3	160	115	75
1	270	190	125
0.3	465	310	205
0.1	765	540	300*
0.035	1200	630*	250*

* For $\Omega < 0.1$, the emission of the plasma is small and z_{max} can be found from the condition $z_{\text{max}} < 1.2 \times 10^{-1} \Omega^{1/5} W^{2/5}$, which is easily obtained from (6), setting $T = 10^4 \text{ K}$ (at lower temperatures hydrogen is neutral).

$$T_1(610) + T_2(610) = T_b(610) - T_R, \quad (9)$$

$$T_1(404) + T_2(404) = T_b(404) - T_R. \quad (10)$$

The spectral slope of the Galactic and isotropic background of radio sources ($T_1 \sim \nu^{-\alpha}$ in the frequency range under consideration is $\alpha = 2.7 \pm 0.2$ ⁽¹¹⁾); for the thermal component $\alpha = 2$. Therefore

$$aT_1(610) + bT_2(610) = T_b(404) - T_R, \quad (10')$$

where $a = (610/404)^{2.7 \pm 0.2}$ and $b = (610/404)^2$.

From (9) and (10') we obtain that $T_2(610) < 1^\circ \text{ K}$, i.e., the flux of radio emission of the intergalactic plasma cannot exceed $I_\nu = 2kT_2(\nu)/\lambda_0^2 \approx 10^{-19} \text{ erg/cm}^2 \cdot \text{sec} \cdot \text{Hz} \cdot \text{ster}$. A somewhat cruder estimate can be obtained by comparing the data on measurements of the relic radiation at 0.254 and 20.7 cm, and also by analyzing the contribution of various sources to the minimum brightness temperature of the radio sky at 178 and 404 MHz.

6. Results. Table 1 gives z_{\max} for different Ω and W ($\Omega = 0.035$ corresponds to the observed matter in galaxies).

Since the redshift of hydrogen recombination is practically independent of Ω , it follows from the data of the table that a period of neutral hydrogen is necessary even for the maximum possible energy release, for any matter density in the Universe that does not contradict observations. The energy release W could not have exceeded $3 \cdot 10^{16} \text{ erg/g}$ (see Sec. 4); therefore hydrogen at $300 < z < 1300$ was neutral, and the formation of various objects began at $z < 300$.

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CITED LITERATURE

1. Ya. B. Zel' dovich, *UFN*, **89**, 4, 647 (1966).
2. A. G. Doroshkevich, Ya. B. Zel' dovich, I. D. Novikov, *Astr. Zhurn.*, **44**, 2, 295 (1967).
3. R. Weymann, *Astrophys. J.*, **145**, 2, 560 (1966).
4. M. Kaufman, *Nature*, **207**, 4998, 736 (1965).

5. A. S. Kompaneets, *ZhETF*, **31**, 877 (1956).
6. R. Weymann, *Phys. Fluids*, **8**, 11, 2112 (1965).
7. V. G. Kurt, R. A. Syunyaev, *Cosmic Research*, **5**, 573 (1967).
8. M. S. Longair, *Monthly Notices*, **133**, 3, 421 (1966).
9. T. E. Howell, J. R. Shakeshaft, Report to the XIII IAU Assembly, Prague, 1967; *Nature* (in press).
10. I. I. Pauliny-Toth, J. R. Shakeshaft, *Monthly Notices*, **124**, 61 (1962).
11. A. H. Bridle, *Monthly Notices*, **136**, 2, 219 (1967).

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