METAGALACTIC PROTONS OF ULTRA-HIGH ENERGIES*

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(Received 29 April, 1974)

Abstract. The flux density of ultra-high-energy metagalactic protons generated by normal galaxies is calculated. Energetic losses of protons at interaction with the 2.7~ relict and infrared radiations are revised. The time change of the energy of protons with different energies is estimated. The influence of fluctuations of energetic losses of protons on their spectrum is evaluated. The measured spectrum of cosmic rays can have a steepening \((\Delta \gamma \approx 1.6)\) at \(E \sim 3 \times 10^{19}\) eV instead of a sharp break expected previously.

1. Introduction

Interest aroused by metagalactic cosmic rays (c.r.) in the energy range \(E \gtrsim 10^{19}\) eV is caused by the fact that at these energies even heavy nuclei (as heavy as iron) are retained weakly in the Galaxy and, therefore, the metagalactic c.r. have to play a considerable role. Up to 1971, experimental data (Andrews et al., 1970; Brownlee et al., 1969; Linsley, 1963; Vernov et al., 1968) have shown a marked flattening of the c.r. spectrum at the energies from \(4 \times 10^{17}\) to \(1 \times 10^{19}\) eV in various experiments, which has been interpreted as a transition from the galactic c.r. to the metagalactic ones. At the present time the situation has become less unambiguous. On the one hand, a new treatment of the experimental data of the Haverah Park team, of the Australian team (Bell et al., 1971) and of Linsley gives evidence in favour of a single power spectrum in the energy range \(3 \times 10^{15} - 1 \times 10^{19}\) eV and within the limits of statistical errors up to \(10^{20}\) eV. On the other hand, the data of the Moscow University (Khristiansen et al., 1974) and the new data of the Yakutsk (Yegorov, 1973) show the spectrum flattening (at \(E \sim 10^{18}\) eV for the Yakutsk equipment).

In the present paper possible transition from the galactic c.r. to the metagalactic ones is analysed. It is shown that in a general case this transition (if it takes place at \(E \lesssim 1 \times 10^{19}\) eV) is to be characterized by a strong flattening of the spectrum (up to the value of the spectrum integral index \(\gamma \approx 1.2\)), and by a subsequent sharp steepening of the spectrum at \(E \approx 3 \times 10^{19}\) eV. However, fluctuations in the space distribution of the c.-r. sources with small \(\gamma\) can lead to the transition from the galactic c.r. to the metagalactic ones occurring at \(E \sim (1-3) \times 10^{19}\) eV. In this case the integral spectrum of the c.r. will extend from \(3 \times 10^{15}\) to \(3 \times 10^{20}\) eV without the sharp steepening at \(E \sim 3 \times 10^{19}\) eV (see Figure 4). This conclusion is based on the analysis of the interaction of cosmic protons with 2.7~ relict radiation from which it follows that the main contribution to the metagalactic c.r. at \(E \gtrsim 1 \times 10^{19}\) eV comes from normal galaxies. In this paper the absolute magnitude of the flux density of metagalactic protons from these galaxies

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is evaluated with exponent $\gamma$ spectra distribution of the normal galaxies deduced from the radio indices distribution of these galaxies. A single power law spectrum of the proton generation extending up to the energy $E \sim 1 \times 10^{21}$ eV is assumed in the normal galaxies.

The arrangement of the paper is as follows:

In Section 2 energetic losses of protons at interaction both with the $2.7\,^\circ$ relict radiation and infrared radiation are considered. New data on cross-section were applied to photo-pion processes, which changed the value of energetic losses and their dependence on the energy a little. For photo-pion losses and losses due to pair-production simple analytical formulae were obtained at the asymptotic values of high and low energies.

In Section 3 the energy change of proton with time is calculated. For the energies $E<3 \times 10^{18}$ eV the energy change follows the law $E(z)=(1+z)E$ (where $z$ is the red shift characterizing the epoch, $E$ is the energy at the present time) up to $z=z_0(E)$, at $z>z_0(E)$ the energy begins to increase rapidly with $z$. At $E>3 \times 10^{18}$ eV the energy begins at once to increase sharply with $z$, which determines the modern ($z<1$) origin of the c.r. of these energies, and hence the predominance of the normal galaxies in the formation of c.-r. flux at $E \geq 1 \times 10^{19}$ eV.

In Section 4 the flux of c.r. with ultra-high energies from the normal galaxies is evaluated with distribution of the c.-r. spectra exponents $\gamma$ deduced from the radio indices distribution of normal galaxies.

The Appendix discusses the influence of the inhomogeneous distribution of galaxies in the Universe and the fluctuations in $\gamma p$-interaction on the spectrum of c.r. of ultra-high energies. The simplified kinetic equation describing the propagation of ultra-high-energy protons in photon gas is solved and it is shown that the solution accounting for the fluctuations differs only by 10% from the solution in the approximation of continuous losses.

2. Proton Energetic Losses by Electromagnetic Radiation in the Metagalaxy

Relative energetic losses of an arbitrary particle moving in photon gas with an arbitrary spectral density of photons $n(\omega)\, d\omega$ can be expressed (Berezinsky, 1970) in the form of an equation

$$\frac{-1}{E} \frac{dE}{dt} = \frac{c}{2\gamma^2} \int_{\omega_0}^{\infty} d\omega_0 \sigma(\omega_0)f(\omega_0)\omega_r \int_{\omega_r/2\gamma}^{\infty} d\omega \frac{n(\omega)}{\omega^2}, \tag{1}$$

where $(1/E)(dE/dt)$ is the fraction of energy lost by the particle in photon gas during a time unit, $\gamma$ is the Lorentz factor of the particle, $\omega_r$ is the photon energy in a system where the particle is at rest, $\sigma(\omega_r)$ is the total cross-section of the interaction of the particle with a photon, $\omega_0$ is the threshold of the considered reaction, $f(\omega_r)$ is the energy fraction in laboratory system lost by the particle at the collision with the photon of energy $\omega_r$, averaged over all directions of outgoing particles after collision, $\omega$ is the