G. B. Khristiansen. *Energy spectrum of superhigh-energy cosmic rays.* The development of techniques for individualized study of extensive air showers at sea level has made it possible to obtain new data on the primary energy spectrum of cosmic rays at superhigh energies ($10^{14}-10^{20}$ eV).

The Moscow State University extensive air shower installation has used a technique in which the electronic and muonic components of EAS are registered simultaneously. At the installation of the USSR Academy of Sciences, Siberian Division, Institute of Space Physics Research and Aeronomy near Yakutsk, the procedure is to register the Cherenkov radiation and the electronic component of the EAS simultaneously. The MSU EAS installation was designed to study cosmic rays with energies of $10^{15}-3\cdot10^{17}$ eV, and the Yakutsk installation for the energy range $3\cdot10^{17}-10^{20}$ eV. The MSU installation was used to measure the EAS spectra in terms of the numbers of electrons N_e and muons N_μ. If the N_e (N_μ) spectrum is represented in power-law form, $N_e^{-(\varkappa_e+1)}dN_e$ (or $N_\mu^{-(\varkappa_\mu+1)}dN_\mu$) then the exponents are specified by $\varkappa_e=\gamma/s$ and $\varkappa_\mu=\gamma/\alpha$, where γ is the exponent of the primary cosmic ray energy spectrum and s and α are larger than and smaller than 1, respectively. The electron- and muon-number EAS spectra measured on the MSU installation[1] indicate that these spectra cannot be represented by pure power laws. The exponents of the spectra differ sharply: $\varkappa_e$ and $\varkappa_\mu$ increase significantly as N_e or N_μ varies by several fold. The simultaneous increase of $\varkappa_e$ and $\varkappa_\mu$ may be interpreted within the framework of general conceptions of the nuclear-cascade process in the atmosphere only as a result of a corresponding sharp increase of the exponent γ of the primary energy spectrum. However, in light of modern conceptions of the hadron interactions at superhigh energies (above 100 TeV), we may not exclude the possiblity of production of new particles with high values of the Feynman parameter x. These particles eventually decay into ordinary hadrons and leptons, and it is possible that a significant part of the primary-particle energy E_0 is transferred to leptons in this manner. This part of the energy may increase with E_0, which would reduce the part of E_0 that is released in the atmosphere and create the extensive air shower proper. In this case, the "kink" on the N_e and N_μ spectra would merely reflect a kink in the spectrum of the "energy-releasing" primary cosmic radiation in the Earth's atmosphere. To verify this extreme assumption, EAS muon energy spectra were measured[2] on the MSU EAS installation using a high-precision underground magnetic spectrometer, and it was shown that the fraction of the primary energy E_0 carried away by all EAS muons does not exceed 15% and does not increase, instead decreasing with the transition from $N_e=10^5$ to $N_e=10^6$, i.e., in the range where $\varkappa_e$ changes. Thus, the "kinks" in the EAS N_e and N_μ spectra should be attributed to a "kink" in the energy spectrum of the primary cosmic radiation.

At the Yakutsk installation, EAS were investigated after energy calibration of recorded EAS with the aid of the Cherenkov radiation flux that accompanies the shower.[3] The EAS Cherenkov radiation flux can be related with the aid of the Tamm-Frank equation to the energy released by the EAS in the atmosphere down to the observing level. For sea-level, this energy is closer to the primary particle energy E_0 the smaller E_0 becomes, but even for the E_0 registered on the Yakutsk installation the corrections to consider the energy released by the EAS below observing level are quite small (~30%). The coefficient of conversion from the number of EAS electrons (or, more precisely, from the electron density at a distance from the EAS axis that is characteristic for the particular installation) to the primary-particle energy E_0 was determined in the range

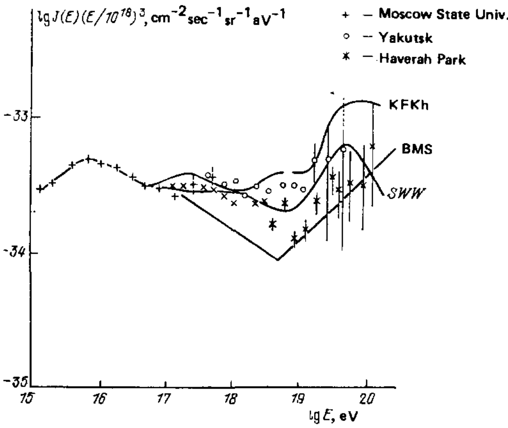

FIG. 1.

$E_0=10^{17}-10^{19}$ eV. Figure 1 shows experimental data on the primary cosmic ray energy spectrum in the range $E_0\approx10^{15}-10^{20}$ eV as obtained by extrapolation of the coefficients found at the Yakutsk installation for conversion from the number of EAS electrons to E_0. It should be noted that the correctness of extrapolation is confirmed for $E_0\sim10^{15}-10^{16}$ eV by direct experimental data on the EAS Cherenkov radiation that were obtained by other authors at sea level (see Ref. 1b). As we see from Fig. 1, we may expect, together with the sharp change in the exponent γ from 1.6 to 2.3 in the range $E_0=(2-4)\cdot10^{15}$ eV, another irregularity in the range $E_0=10^{17}-10^{18}$ eV: a decrease in the exponent γ to 1.8–2.0 (according to data from the MSU and Yakutsk installations). However, the "kink" in the spectrum in the range $E_0=(2-4)\cdot10^{15}$ eV must be regarded as an established fact: the results from the MSU installation have been confirmed by more than ten laboratories worldwide. But the irregularity at $E_0=10^{17}-10^{18}$ eV evidently requires further study. Figure 1 also includes primary cosmic radiation intensity data obtained at the Haverah Park installation (Great Britian). Here the coefficient for conversion from the charged-particle density ρ_{600} at a distance of 600 meters from the EAS axis to the primary energy E_0 was found by comparing ρ_{600} with E_0 observed with the same intensity at the Haverah Park installation and at Yakutsk. Figure 2 presents the integral energy spectrum of superhigh-energy cosmic rays (including the Haverah Park data) and compares it with calculations that were made using a universal metagalactic model of the origin of cosmic rays[4] and took account of Zatsepin and Greizen's effect

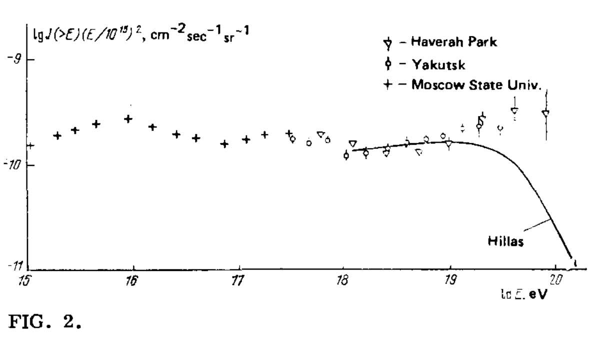

FIG. 2.

of interaction with the relic radiation. We see from Fig. 2 that the Yakutsk energy calibration of the EAS, used for the Haverah Park data, makes possible rejection with a high degree of certainty of the universal metagalactic model (in any event for $E_0 > 10^{19}$ eV).

There is hardly any doubt as to the galactic origin of cosmic rays with energies below 10^{17} eV or as to their quasisteady generation due (basically) to supernovas. The solid BKW curve in Fig. 1 represents the calculation of Ref. 5 in a diffusion model that takes account of the irregular and regular magnetic fields of the Orion spiral arm and the dependence of the diffusion coefficient on E_0. The size- and field-magnitude distribution of the magnetic inhomogeneities needed to explain the experimental data agrees well with astrophysical observations at distances up to 500 parsecs from the sun. The models begin to diverge at $E_0 > 10^{17}$ eV The BMS[6] and KFKh[7] curves correspond to galactic-origin models for cosmic rays with $E_0 > 10^{17}$ eV. In the BMS model,[8] quasistationary generation is considered over the entire range $E_0 = 10^{15}-10^{19}$ eV, with diffusion being in fact absent already at $E_0 > 10^{18}$ eV. The KFKh model[7] considers nonstationary generation of cosmic rays with $E_0 > 10^{17}$ eV due to explosion of the nucleus of the Galaxy; here diffusion waves corresponding to particles with different charges Z contribute to the intensity at different E_0.

The touchstone for Galactic models at $E_0 > 10^{17}$ eV would, of course, be study of the chemical composition of the primary cosmic rays, for example by the method described in Ref. 8, using large muon-detector areas in an installation of the DUMAND type.

Nor, strictly speaking, it is possible at this time to exclude metagalactic origin for cosmic rays with energies of $10^{17}-10^{19}$ eV in the spirit of the universal metagalactic model, though with a weak dependence of cosmic-ray source intensity on epoch in an expanding-metagalaxy model (see SWW curve[9]). Here the galaxies of the local group are a source of cosmic rays with energies of $10^{18}-10^{20}$ eV in the SWW model.

The choice between the galactic and metagalactic models of the origin of cosmic rays with $E_0 = 10^{17}-10^{20}$ eV must be preceded by careful measurements of the cosmic ray flux anisotropy in this energy range.

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