PHYSICAL REVIEW D VOLUME 41, NUMBER 2 15 JANUARY 1990

Cosmology with 100-TeV γ-ray telescopes

F. Halzen
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

R. J. Protheroe
Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5001, Australia

T. Stanev and H. P. Vankov*
Bartol Research Institute, University of Delaware, Newark, Delaware 19716

(Received 23 February 1989; revised manuscript received 6 September 1989)

We show that the secondary photons which are by-products of the energy loss of extragalactic cosmic rays interacting with the cosmic background have a characteristic energy of 10–100 TeV. For a model where the extragalactic cosmic rays are uniformly distributed in space and in time over the past 10^9 yr the flux of 100-TeV photons is 10^{-5} of the cosmic-ray flux. Such fluxes are attractively close to the resolution of the new generation of γ-ray telescopes and their detection can provide important cosmological information.

I. INTRODUCTION

Ultra-high-energy cosmic rays may have been produced since galaxy formation. They may therefore carry cosmological information which can be extracted by detecting their interaction with the cosmic photon background. The dominant interaction mechanisms are Bethe-Heitler pair production[1] ($\gamma p \rightarrow e^+e^-$) and photoproduction of hadrons[2] ($\gamma p \rightarrow \Delta \rightarrow N\pi$). If the ultra-high-energy cosmic rays we detect today are of extragalactic origin, their interactions on the 3-K cosmic background would have two important consequences: (i) a sharp cutoff of the cosmic-ray spectrum above 10^{20} eV and (ii) the production of a flux of ultra-high-energy secondary γ rays, electrons, and neutrinos which are the final electromagnetic debris of the π^0's and e^+e^- pairs in the interactions of the cosmic rays with 3-K photons. While the produced neutrino fluxes are not changed during propagation to Earth (except for redshift for very long path length), the γ rays and electrons will themselves interact on the background and the shape of the first-generation electromagnetic radiation will be drastically changed.

It has been suggested to study the shape of the spectrum near the cutoff to derive information on the cosmological evolution of the cosmic-ray sources. These measurements will be challenging as fluxes are low and the understanding of the acceptance of the detectors essential. We investigate as an alternative method of observation the detection of γ rays which are the final electromagnetic debris of the energy loss of the ultra-high-energy cosmic rays in the 3-K background.[3] We will show that they have characteristic energies of 10–100 TeV and a flux which may be within reach of the new generation of high-energy γ-ray telescopes.[4]

This problem has been extensively discussed in the past, including the γ-ray fluxes associated with the cosmic-ray spectrum cutoff.[3] Here we want to make two important statements, which have not been previously emphasized. First, ultra-high-energy γ rays and electrons cannot survive the propagation on distances of order 100 Mpc. Second, the electromagnetic cascading on the 3-K background radiation creates a pile-up of γ rays in the 10–100-TeV region. The magnitude of the pile-up is attractively close to the sensitivity of the new generation of shower arrays and thus requires a more precise and updated estimate which is made in this paper. Qualitatively both statements can be understood by a simple inspection of the electromagnetic interaction cross section of photons cascading in the 3-K background. Figure 1 shows the relevant cross sections as functions of the γ ray or electron energy. There are four major processes: (i) pair production $\gamma\gamma \rightarrow e^+e^-$, (ii) inverse Compton scattering of the electrons on 3-K photons $e\gamma \rightarrow \gamma e$, (iii) electron pair production via virtual photons[5] $e\gamma \rightarrow e^+e^-e$, and (iv) double pair production[6] $\gamma\gamma \rightarrow e^+e^-e^+e^-$. The leading-order processes (i) and (ii) dominate in the intermediate-energy region between 10^{15} and 3×10^{17} eV. Above this energy-induced pair production (iii) dominates the energy loss until double pair production takes over at 7×10^{20} eV. In addition to these processes one has to take into account the interactions on radiowaves which become an important target above 10^{18} eV (Ref. 7). As a result, distances of 100 Mpc or more are not transparent to either ultra-high-energy γ rays or electrons. All the energy in such particles will be degraded in electromagnetic cascading to reappear in fluxes of particles below the interaction thresholds. The lowest of these thresholds is about 10^{15} eV for $\gamma\gamma$(3-K)$\rightarrow e^+e^-$; see Fig. 1.

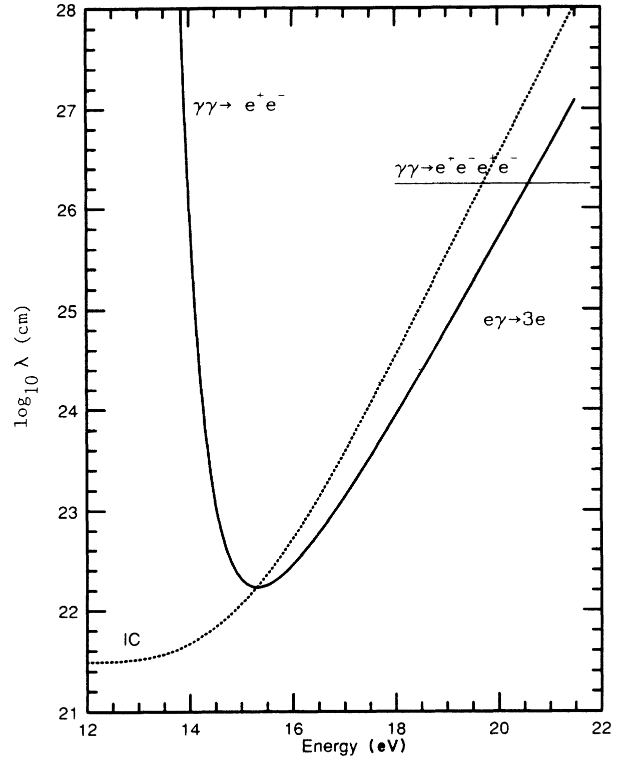

FIG. 1. Electromagnetic cross sections on the 3-K background radiation.

II. PARTICLE PRODUCTION ASSOCIATED WITH THE GREISEN CUTOFF

To verify our proposal we perform a conservative "benchmark" calculation. We assume that the highest-energy cosmic rays are extragalactic and that their density is uniform over cosmological distance and time. We compute the γ ray and electron emissivity from the measured density of cosmic-ray protons $\rho_p(E_p)$. We will assume that this density has remained unchanged over the recent history of the Universe, and postpone a discussion of this until later in this paper. The current proton density in the Universe is obtained from a fit to the data[8] with

$$\begin{aligned}\rho_p(E_p)&=\frac{4\pi}{c}I_p(E_p)\\&=1.5\times10^{-43}\left[\frac{E_p}{10^{18}\text{ eV}}\right]^{-2.94}(\text{cm}^3\text{eV})^{-1}\ .\end{aligned} \tag{1}$$

The protons with density ρ_p produce e^+e^- pairs on the 3-K background by the Bethe-Heitler process with radiation length λ_{BH}. For very energetic protons we can use the asymptotic form $\sigma_{\text{BH}}=\lambda_R/m_p$, where λ_R is the radiation length. For a 3-K photon target density $n_{\text{BB}}=400$ cm^{-3} we then obtain $\lambda_{\text{BH}}\simeq9\times10^{22}$ cm. The $e^\pm$ emissivity $Q(E)$, i.e., the number of particles produced per unit volume, time, and energy E, is

$$Q_e(E)\simeq2c\frac{m_p}{m_e}\frac{\rho_p(Em_p/m_e)}{\lambda_{\text{BH}}(Em_p/m_e)}\ . \tag{2}$$

Equation (2) follows from the consideration that the Bethe-Heitler electrons have characteristic energy $(m_e/m_p)E_p$ in the c.m. frame. For e,γ energies above 5×10^{18} eV the dominant process is hadron photoproduction $p\gamma\to\Delta\to\pi^0\to\gamma$ with interaction length $\lambda_{p\gamma}$. Photoproduction of π^0's via Δ resonance is the leading source of proton energy loss. The cross section reaches a maximum at $E_p=5\times10^{20}$ eV where $\lambda_{p\gamma}\simeq9\times10^{24}$ cm. On the average the photoproduced π^0's carry $\frac{1}{5}$ of the proton energy; therefore,

$$Q_{\pi^0}(E)\simeq\frac{5c}{\lambda_{p\gamma}(5E)}\rho_p(5E) \tag{3}$$

and

$$Q_\gamma(E)\simeq\int_E\frac{2Q_\pi(E)}{E}dE\ . \tag{4}$$

The electromagnetic component of energy loss is obtained from Eqs. (2) and (4). The contribution of Eq. (4) is enhanced by about 50% from decay of charged pions into electrons. The energy loss is shown in the region 10^{18} to 10^{20} eV in Fig. 2. The observed γ rays at Earth are only obtained after further cascading of this flux in the 3-K photon background. A most interesting result will be, however, that the final observable flux, concentrated in the 10–100 TeV region, only depends on the total injected energy, not on the particle type or detailed shape of their flux.

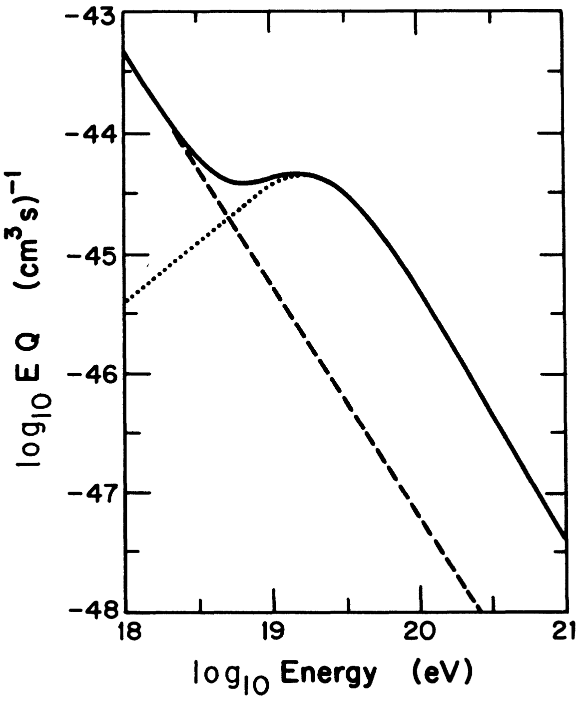

FIG. 2. Emissivity of electromagnetic particles. Photon and electron emissivity from photoproduction is shown with a dotted line, electrons and positrons from Eq. (2)—with a dashed line.

III. CASCADING OF PARTICLES IN THE 3-K PHOTON BACKGROUND

We first consider the electromagnetic cascade resulting from injection of a photon or electron with energy E_0. The relevant energy-loss processes have been tabulated in Fig. 1. (Synchrotron energy losses by electrons may inhibit cascading at high energies. Comparing the synchrotron energy-loss rate with that of the high-energy particle in a pair-production-inverse Compton cascade this would occur at 10^{20} eV for $B \gtrsim 10^{-11} G$. Inclusion of induced pair production[5] allows fields a factor ~ 5 higher. While little is known about intergalactic fields, fields as low as this are not ruled out. We will here assume that synchrotron losses can be neglected.) After propagating a distance R through the universal radiation fields the energy spectrum of photons and electrons of energy E in the cascade is $N(E_0,E,R)$.

The relevant quantity for the particle fluxes at Earth after cascading is the path-length integral

$$F(E_0,E)=\int_0^{R_{\max}} N(E_0,E,R)dR \ , \tag{5}$$

where the integration is carried out up to some appropriate maximum distance $R_{\max}$. This quantity corresponds to the path-length integral in classical cascade theory. Numerically, Eq. (5) is identical to weighing all particles generated in the cascade with their free path λ. One can qualitatively predict the result of the cascading from an inspection of the energy dependence of the relevant cross sections. The γ-ray absorption has a maximum at $\sim 2\times 10^{15}$ eV and vanishes at $E_\gamma \lesssim 10^{14}$ eV. In the same time the inverse Compton mean free path approaches its Thomson limit of ~ 1 kpc. All electrons in this energy range thus "inverse Compton scatter" to boost blackbody photons. The photons with $E_\gamma \lesssim 10^{14}$ eV have infinite path length and are weighted very heavily by Eq. (5). The yield of such photons will be only limited by the value of $R_{\max}$. At energies above 3×10^{15} eV all cross sections decrease with energy and ultra-high-energy photons and electrons will also be heavily weighted. Thus the spectra defined by Eq. (5) will be depleted of particles in the energy range around 3×10^{15} eV, while the γ rays below 10^{14} eV will be abundant.

We have used a slightly modified version of Monte Carlo code written by Protheroe[9] to calculate the yields of TeV γ rays from ultra-high-energy γ rays and electrons. This code follows individual photons and electrons interacting through pair production and inverse Compton scattering on blackbody radiation of temperature 2.96 K. $R_{\max}$ was set to 300 Mpc because at larger distances TeV γ rays may interact on optical light.[10] In such a case cascading on larger distances would not significantly contribute to the TeV γ-ray flux.

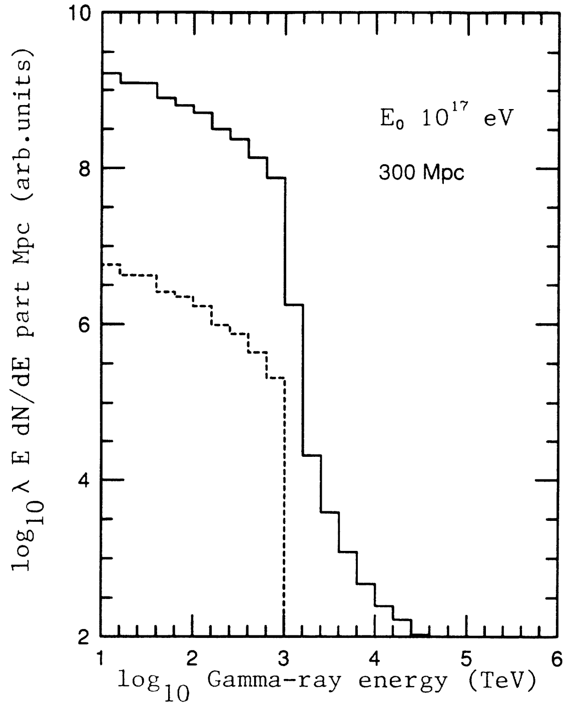

FIG. 3. Energy spectrum of photons after propagation on 300 Mpc. Solid line: all generated γ rays weighted with λ_γ (Mpc). Dashed line: γ rays surviving at 300 Mpc.

The results of the simulation for primary γ-ray energy of 10^{18} eV are shown in Fig. 3. The mean free paths of photons and electrons at this energy are significantly shorter than $R_{\max}$ and therefore neglecting second-order processes is a good approximation. The dashed histogram shows the energy distribution of photons after cascading on 300 Mpc in the background radiation. No photons with energy above 10^{15} eV survive. The solid histogram shows the energy distribution of all photons created in the cascade weighted by their free path λ_γ. The shape of this distribution should not depend on the primary energy for $R_{\max} \gg \lambda_\gamma$. Provided we can neglect the cascading on optical light the output in 10–100 TeV γ rays does not depend on the type of the primary particle, or on the input energy spectrum. The free path for both electrons and γ rays at intermediate energies is so much smaller than the distances in question, that *all input energy* is converted in *electromagnetic soup,* that in further cascade development appears in <100 TeV γ rays. These γ rays have a differential spectrum $\sim E_\gamma^{-1.75}$ with a normalization proportional to the input energy and $R_{\max}$.

The γ-ray intensity at Earth is obtained from

$$I_\gamma(E)=\frac{1}{4\pi}\int Q(E_0)F(E_0,E)dE_0 \ , \tag{6}$$

where $Q(E_0)=Q_e(E_0)+Q_\gamma(E_0)$ is the sum of emissivities given by Eqs. (2) and (4). This electromagnetic component of the proton energy loss in the $E > 10^{18}$ eV region is shown in Fig. 2 along with the resulting flux at Earth tabulated in Fig. 4. The "benchmark" calculation yields a γ-ray flux of order 10^{-5} of the cosmic-ray flux in the 10 to 100 TeV energy range where it is within reach of γ-ray experiments. It is qualitatively similar to the results of Wdowczyk *et al.* in Ref. 7. The photons are isotropic and can therefore be separated from photons from point sources or from interaction of cosmic rays on the interstellar medium. Both these components are concen-

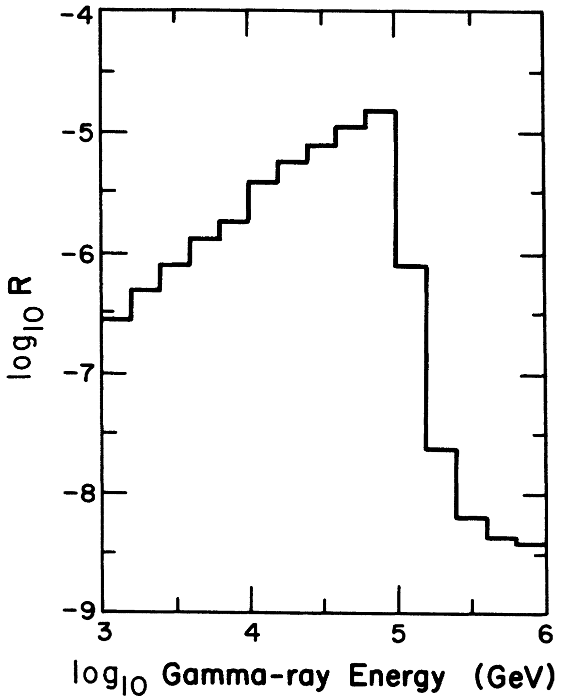

FIG. 4. Ratio R of the resulting diffuse γ-ray flux produced by extragalactic cosmic rays on the 3-K background photons, to the cosmic-ray flux in the TeV region.

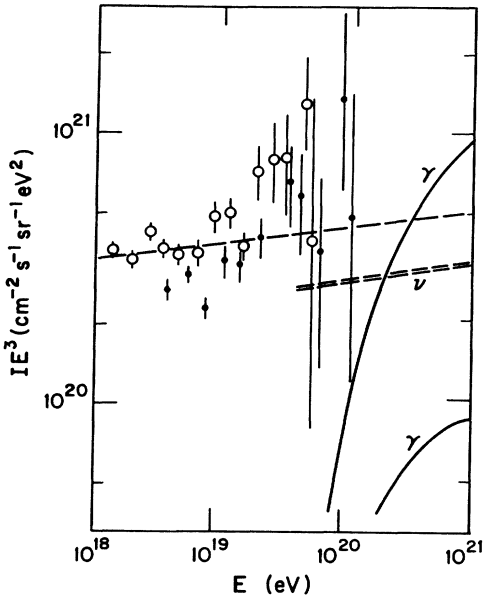

FIG. 5. Experimental data on the ultra-high-energy cosmic-ray flux and the parametrization of Eq. (1). Dots and circles are from Refs. 8 and 12, respectively. A range of predicted γ-ray fluxes is obtained from Eq. (7) with λ_{PP} (upper curve) and the total interaction mean free path (lower curve) used as input. The double-dashed line is the neutrino flux from charged π's from Δ production and decay, which is shown as a way to compare our fluxes to other calculations.

trated in the galactic plane and Wdowczyk and Wolfendale[11] estimate at 10^{15} eV the γ-ray intensity due to galactic sources could be as high as 5% of the cosmic-ray intensity within 10° of the plane. At 10 to 100 TeV their estimate would have been 0.3 to 1 %. At high galactic latitudes this ratio drops essentially to zero as individual sources are resolved.

A calculation of the ultra-high-energy flux is difficult, because all relevant processes as well as the interactions on the radio background have to be taken into account. A simple estimate can be obtained from

$$I(E)=\frac{1}{4\pi}Q_\gamma\lambda_\gamma \,. \tag{7}$$

We evaluate Eq. (7) using the emissivity Q_γ shown from Eq. (4) and two values of λ_γ: the pair production mean free path λ_{PP} and the total mean free path for all relevant processes. In Fig. 5 we compare the γ-ray fluxes obtained with the cosmic-ray spectrum of Eq. (1).

Throughout the calculation we have used present-day values for the cosmic-ray spectrum and radiation fields. Because of cosmological expansion and possible evolution of cosmic-ray sources, etc., this is not strictly correct. However, because our calculated intensities depend only on particle production and propagation within $R_{\max}\simeq 300$ Mpc (i.e., during the past 10^9 yr) this will not introduce serious errors. Over this time the temperature of the microwave background has not changed by more than 5%. We estimate that in models where continuous cosmic-ray production occurred our assumption of a constant cosmic-ray density may lead to an ambiguity of up to 10%. These uncertainties are, however, insignificant compared to that in our adopted $R_{\max}$ value and the approximation in Eq. (7).

The account for a "bright phase" when most of the ultra-high-energy cosmic rays were produced at some early epoch can only increase the flux of isotropic γ rays. The amount of increase and the resulting shape of the isotropic γ-ray energy spectrum will strongly depend on the "bright phase" model properties.

We are in the process of modifying our code to include the second-order processes and to be able to follow the cascade development in background radiation of changing temperature. Some models will undoubtedly yield much higher γ-ray fluxes, as the proton energy losses expected are orders of magnitude higher. The detection of the signals, however, depends not only on the size and the sophistication of the experiments but also on the properties of the atmospheric γ-ray showers. If γ-ray showers have the same muon content as hadronic showers the detection of any diffuse γ-ray fluxes will be impossible.

ACKNOWLEDGMENTS

We thank Professor J. Wdowczyk and Professor A. W. Wolfendale for helpful correspondence. This work was supported in part by the NSF (T.S.), the Australian Research Council (R.J.P.), the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881. R.J.P. and H.P.V. thank the Bartol Research Institute for hospitality.

*On leave of absence from the Institute for Nuclear Research and Nuclear Energy, Sofia 1784, Bulgaria.

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