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Photon/proton ratio as a diagnostic tool for topological defects as the sources of extremely high-energy cosmic rays

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The hypothesis of topological defects (from grand unified and/or Planck scales) as the sources of extremely high-energy ($>10^{18}$ eV) cosmic rays predicts an unusually high content of γ rays at energies $E \gtrsim 10^{20}$ eV ($\gamma/p \geq 1$) and $E \lesssim 10^{14}$ eV ($\gamma/p \gtrsim 10^{-3}$). This can be used as a signature for testing the hypothesis in forthcoming experiments.

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The acceleration of the cosmic rays (CR's), observed up to energies $E \gtrsim 10^{20}$ eV [1], poses a serious challenge for any particle acceleration mechanism [2]. This has recently motivated some authors [3,4] to consider the possibility that CR particles above some energy may have a more "fundamental" origin in the sense that they may not have been accelerated at all; instead, they may simply be the decay products of some sufficiently massive particles surviving from an early cosmological epoch. One possible realization of such a "nonacceleration" origin of CR's is the process of collapse or annihilation of topological defects (TD's) [3,4] such as magnetic monopoles, cosmic strings, domain walls, superconducting cosmic strings, etc. [5], formed in a phase transition at some high-energy scale such as the grand unified theory (GUT) scale or the Planck scale.

Because of their topological stability, the defects can survive indefinitely; however, they can occasionally be destroyed due to collapse or annihilation, releasing the energy trapped in them in the form of massive quanta (hereafter referred to as X particles) of the various fields (gauge bosons, Higgs bosons, superheavy fermions) that "constitute" the defects. The X particles can then decay into quarks, gluons, leptons, etc. The quarks and gluons would hadronize, that is, produce jets of hadrons. The latter would be mostly pions, together with a small fraction ($\sim 3\%$) of baryons (which finally end up as nucleons). The neutral pions decay producing γ rays while the charged ones produce neutrinos. We thus obtain a natural mechanism of production of nucleons, γ rays, and neutrinos with energies up to $\sim m_X$, the mass of the X particles. (For GUT energy scale defects, m_X can be as large as $\sim(10^{16}$ GeV). We shall refer to this topological-defect-induced CR particle generation process as the "TD model" in order to distinguish it from the conventional acceleration scenarios ("A model").

The expected proton and neutrino spectra in the TD model have been calculated in Ref. [4]. In this paper we present the expected γ-ray and proton spectra, and point out the unusually high content of γ rays in CR ($\gamma/p \geq 1$) at the highest energies, predicted in the TD models.

The diffuse extragalactic γ rays in the A model have a secondary origin. They are produced by the decay of π^0 mesons resulting from the interactions of CR protons with microwave background radiation (MBR). In contrast, the γ rays in the TD model are of "primary" origin in the sense that they are the direct by-products of the decay of the X particles ($X \to q \to \pi^0 \to \gamma$). Moreover, the π^0 mesons along with the charged pions are the dominant products of the X-particle decays, the production ratio of π^0/p being $\xi \approx \frac{1}{3}(\frac{0.97}{0.03}) \approx 10$ assuming $\sim 3\%$ nucleon content of the hadronic by-products of each X particle. In addition, of course, there are γ rays of secondary origin due to interactions of the protons (produced by the decays of X particles) with MBR, but the contribution of this channel is much less.

Throughout our discussions we will be interested in energies $E \geq 10^{19}$ eV, which allow us to ignore possible cosmological evolutionary effects associated with both the CR sources and the MBR, since at these energies the path lengths of protons as well as photons in the intergalactic medium (IGM) are much less than the horizon (Hubble scale) of the Universe. Here we assume that the process of particle production occurs uniformly throughout the Universe. The production spectrum of protons in the A model generally has a power-law behavior: $q_p(E)=q_0E^{-\alpha}$. In the TD model the production spectrum is determined by the physics of quark fragmentation into hadrons. The resulting production spectrum in the TD model can also be approximated [4] by power laws with $\alpha \simeq 1.32$ in the energy range $10^{-10}m_X/2 \leq E \leq 10^{-2}m_X/2$, and $\alpha \simeq 1.95$ for $10^{-2}m_X/2 < E \leq 0.32m_X/2$.

The value of the constant q_0 in the production spectrum is also, in principle, known in TD models. At the present time, however, for the specific TD-induced processes studied so far, there are uncertainties in the numerical values of the parameters that determine q_0. For example, in the process involving collapsing cosmic-string loops (Bhattacharjee and Rana [3]), q_0 depends on the product of μ, the mass per unit length of the string, and the fraction f of all primary-cosmic-string loops formed in collapsing configurations. While there are constraints (upper limits) on the "intrinsic" parameter μ for cosmic strings from cosmology (e.g., from MBR anisotropy measurements, from primordial nucleosynthesis arguments, etc.) there is no reliable estimate of the fraction f from the existing numerical simulations of cosmic string evolution. Similarly, in the case of a process involving collapsing monopole-antimonopole bound states (Hill [3]), q_0 depends on, among other factors, the monopole/photon ratio in the Universe which again is uncertain.

It is, however, clear that no process should predict CR flux that exceeds the observed flux at any energy. This sets constraints on the parameters that determine q_0 for any given TD-induced process. Such constraints can be obtained from the general results given by Bhattacharjee, Hill, and Schramm [4]. In the following we will not go into any specific TD-induced process, but consider TD models in general. We shall illustrate our results for the proton and γ-ray fluxes by arbitrarily "normalizing" q_0 at some convenient value (see below). The actual particle flux for any specific TD-induced process (for which the value of q_0 is known) can then be obtained simply by an appropriate scaling (i.e., by shifting the relevant curves in Figs. 1 and 4 in the upward or downward direction appropriately), since the *shape* of the spectrum at the relevant energies is *universal*, i.e., independent of the specific TD-induced processes, as shown in Bhattacharjee, Hill, and Schramm [4]. Note in this context that our results for the *γ/p ratio* presented in Fig. 3 are, of course, *independent* of the value of the "normalization" constant q_0.

The equilibrium spectrum of protons I_p may be obtained in the continuous energy loss (CEL) approximation [6]: $I_p(E)=[q_0E^{-\alpha}/4\pi(\alpha-1)]\lambda_p(E)$, where $\lambda_p(e)\equiv Ec/(dE/dt)_p$ is the mean attenuation length of protons due to interactions with MBR as well as due to expansion of the Universe. At 10^{19} eV $\leq E \leq 3\times10^{19}$ eV and $E \gtrsim 3\times10^{20}$ eV the energy-loss rate, determined mainly by the processes of e^+e^- pair production and photomeson production, respectively, is proportional to $E(\lambda_p \sim \text{const})$ [7]. Therefore the equilibrium spectrum in these energy ranges repeats the shape of the production spectrum: $I_p(E) \propto E^{-\alpha}$. The deviation from the shape of the production spectrum occurs between 3×10^{19} and 3×10^{20} eV. The energy $E_{1/2}$ of the "blackbody cutoff" [8] of the proton spectrum is $\sim5\times10^{19}$ eV. Note that the universal equilibrium spectrum, the maximum occurring at $E\sim4\times10^{19}$ eV (see Fig. 1) has nothing to do with the recoil proton "bump" which, however, is a feature of the spectrum of a single point source [9] (or a discontinuous distribution of such sources), but is simply the result of the positive index of the function $E^3I(E)\propto E^{3-\alpha}$ (for $\alpha<3$) at $E\leq E_{1/2}$.

The equilibrium proton spectra calculated for the TD model, p(TD), as well as for the A model, p(A2) and p(A3) (for $\alpha=2$ and 3, respectively), are shown in Fig. 1. The spectra p(A2) and p(TD) are normalized to the experimental fluxes at $E\sim4\times10^{19}$ eV, where there is relatively good agreement between Fly's Eye and Haverah Park

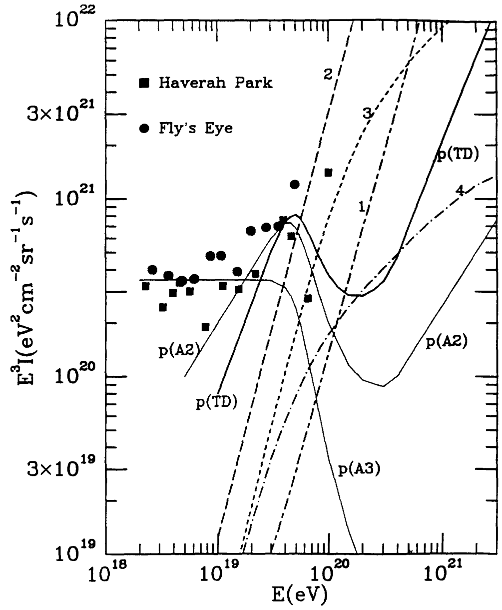

FIG. 1. Equilibrium spectra of protons and γ rays. The curves p(A2) and p(A3) are the proton spectra in the A model with $\alpha=2$ and 3, respectively. The curve marked p(TD) is the proton spectrum in the TD model. The curves 1,2,3,4, are equilibrium γ-ray spectra calculated for TD model: (1) direct γ rays; (2) cascade γ rays neglecting interactions with the intergalactic magnetic field ($B \ll 10^{-12}$ G) and universal radio background ($w_{\text{URB}} \ll w_r$); (3) cascade γ rays with $w_{\text{URB}}=w_R$, $B=3\times10^{-11}$ G; (4) same as (3) with $B=10^{-10}$ G.

data. While this normalization is at this state arbitrary, it does not contradict any known limits on any of the parameters that determine the value of q_0 for the specific processes that have been studied so far [3,4].

The hard production spectrum ($\alpha=1.32$ for the TD model and $\alpha=2$ for the A model) may, in principle, explain an absence of a noticeable cutoff in the measured flux above 5×10^{19} eV [10]. At the same time the hard production spectra are unable to explain the CR fluxes measured at $E\leq10^{19}$ eV, even under extreme assumptions concerning cosmological evolutionary effects. Therefore, for the lower energy part of the spectrum we need to assume an additional soft (galactic?) component of CR. The CR spectrum at $E\leq10^{19}$ eV may, in principle, be explained also by an extragalactic component of CR with $\alpha=3$; however, in this case the spectrum is in conflict with the reported CR fluxes above 5×10^{19} eV (see Fig. 1), although this might be remedied with a discontinuous distribution of sources [9].

A general feature of the TD model is the unusually flat behavior of the proton production spectrum. The power-law index of the hardest spectrum provided by any reasonable acceleration mechanism (e.g., by shock waves) is $\alpha\sim2$. Therefore the spectral measurements of CR above $E_{1/2}$ in forthcoming experiments would, in principle, provide a choice between the TD and A models. As seen in Fig. 1, at a given normalization the difference between p(TD) and p(A2) becomes noticeable at $E<10^{19}$ eV and again at $E > 10^{20}$ eV. At $E < 10^{19}$ eV discrimination between these models is problematic due to the presence of the stronger component of the observed CR, and so the analysis of the proton spectrum at $E \geq 10^{20}$ eV seems preferable. However, as we argue in the following, a more reliable and unambiguous parameter for recognition of the origin of the highest energy cosmic rays is the γ/p ratio near and above $E_{1/2}$.

The γ-ray production spectrum in the TD model can be obtained from the pion production spectrum as

$$q_\gamma(E)=2\int_E^\infty dE' E'^{-1} q_{\pi^0}(E') \ ,$$

where $q_{\pi^0}(E)=\zeta q_p(E)$, and $\zeta \simeq 10$ is the π^0/p ratio in the decay of X particles. The γ rays as well as electrons and positrons (from the charged pion decays) initiate electromagnetic cascades in the photon fields of the MBR and the universal radio background (URB). In general, it is necessary to consider the integro-differential kinetic equations for the cascade development because of the catastrophic nature of both e^+e^- pair production and Compton processes that give rise to the cascade. Nevertheless, in the extreme Klein-Nishina regime the cross sections of these processes become similar, which reduces the cascade problem to the much *single* high-energy "particle" transfer problem [11]. This particle, which spends its lifetime in two states ("electron" and "photon"), is hereafter called an e/γ particle. Because of the strongly catastrophic nature of the elementary processes, when one of the secondaries (e or γ) carries the main part of the primary energy, the energy loss of the e/γ particle is essentially gradual. Thus the equilibrium spectrum of cascade γ rays may be obtained in the continuous energy-loss approximation [12]:

$$I_\gamma(E)=\frac{\zeta(1+\kappa)}{2\pi\alpha(\alpha-1)} q_0 E^{-\alpha} \lambda_\gamma^{\rm cas}(E) \ , \quad (1)$$

where the parameter κ takes into account the contribution from $e^\pm$ (from the charged pion decays) to the cascade development; $k \simeq 0.85$ for $\alpha=1.32$. In Eq. (1) $\lambda_\gamma^{\rm cas}(E)$ is the path length (effective penetration length) of the cascade γ rays, which has been calculated in Ref. [12] for different assumptions concerning the URB and the intergalactic magnetic field (IMF). In calculating $\lambda_\gamma^{\rm cas}(E)$ the following processes were considered: (i) single and double pair production at γ-γ interactions and Compton scattering of the electrons in the fields of MBR and URB, (ii) synchrotron cooling of the cascade electrons, and (iii) the triplet pair production (TPP) (e + MBR $\to e^+e^-e'$). The TPP, which may be considered as a gradual energy-loss process for the cascade electrons, has recently been realized [13] to be an important process in astrophysical objects. For instance, this process reduces the path length of the cascade γ rays at $E=10^{20}$ eV in the field of MBR by more than a factor of 5 [12].

The path lengths of extremely high-energy γ rays and protons in the intergalactic medium are shown in Fig. 2. The path length of cascade γ rays strongly depends on the density $w_{\rm URB}$ of URB and on the strength B of the IMF. Unfortunately, both these parameters continue to be highly uncertain. The present estimate of B based on

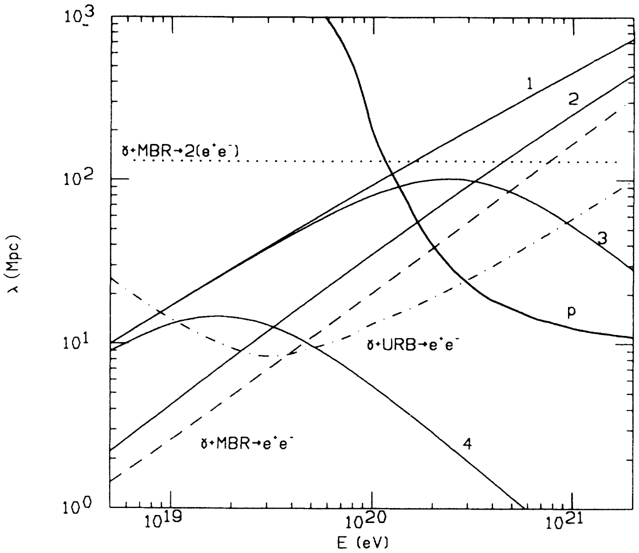

FIG. 2. The attenuation lengths of γ rays and protons in the intergalactic medium. The curve marked p is the attenuation length of protons in the MBR. The dashed and dot-dashed curves are the γ-ray absorption lengths due to single pair production in the MBR and URB fields, respectively. The dotted curve is the absorption length of γ rays in MBR due to double pair production. The curves marked 1, 2, 3 and 4 correspond to the effective penetration lengths of cascade γ rays obtained under different assumptions: (1) cascade in the MBR field only; (2) cascade in the MBR and URB ($w_{\rm URB}=w_R$) fields; (3) and (4) cascade in the MBR, URB, and IMF fields for $B=3\times10^{-11}$ and 10^{-10} G, respectively.

the Faraday rotation measurements is as low as 3×10^{-11} G [14], though much higher values of B, especially in the local supercluster, cannot be excluded. Additionally, it is known that attribution of the measured density of the isotropic radio flux ($w_R \sim 10^{-7}$ eV cm^{-3}) to the URB faces certain problems (see, e.g., [15]). For $B \leq 10^{-12}$ G and $w_{\rm URB} \ll w_R$, the mean attenuation length of cascade particles at $E \geq 10^{20}$ eV becomes more than the attenuation length of protons, and therefore, in this energy domain, the ratio of $\gamma/p \sim q_\gamma\lambda_\gamma/q_p\lambda_p \gtrsim 10$. A more realistic assumption on the value of $w_{\rm URB}$, e.g., $w_{\rm URB} \approx w_R$, leads to an essential reduction of the attenuation length of cascade particles. Moreover, even at relatively low values of the magnetic field, $B \sim 10^{-10}$ G, the cascade development at $E \geq 10^{20}$ eV due to synchrotron cooling of electrons becomes inefficient (see Fig. 2), and, therefore, the γ-ray flux is determined mainly by the "direct" (i.e., not interacting with the ambient photon gas) γ rays.

The equilibrium γ-ray spectra calculated for different values of B and $w_{\rm URB}$ are shown in Fig. 1. It is seen that even for extreme values of B and $w_{\rm URB}$, namely, $B \gg 10^{-10}$ G, and $w_{\rm URB}=w_R$, the ratio of γ/p at $E \geq 10^{20}$ eV due to direct γ rays should exceed unity in the TD model. The flux of direct γ rays has some uncertainty (by a factor of ~ 2) connected with the value of the cutoff frequency in the spectrum of the measured radio background; however, this uncertainty cannot influence the general conclusion concerning a high γ/p ratio at the highest energies. As seen from Fig. 3, even for the extreme (and rather unrealistic) assumptions, namely, $B \ll 10^{-12}$ G and $w_{\rm URB} \ll w_R$, which give the most optimistic estimates, the γ/p ratio in the A model (curves 5 and 6) remains below the level of γ/p ratio expected in the TD model for the opposite extreme assumptions, namely, $w_{\rm URB}=w_R$, and $B \gg 10^{-10}$ G, which give the most pessimistic estimates (curve 1). So the curve 1 in Fig. 3 can be considered as a boundary between TD and A "domains."

In the PeV energy range the most reliable criterion of separation of γ- and proton-induced showers is the muon content in the cascade, provided the character of interaction of γ rays is not changed dramatically. However, at primary energies $E \geq 10^{18}$ eV, due to high penetrability of the low-energy ($E \sim 1$ GeV) γ rays in the electromagnetic cascade, the "muon poorness" criterion becomes inefficient [16]. Fortunately, in this energy range the effective separation of primary protons and γ rays is still possible owing to Landau-Pomeranchuk-Migdal (LPM) effect. The latter leads to a strong suppression of electromagnetic cascades in the atmosphere up to depths ≥ 1000 g/cm^2, providing noticeably different profiles of the longitudinal development of showers initiated by primary γ rays and nucleons. At highest energies, $E \geq 10^{20}$ eV, when the primary γ rays start to interact with the geomagnetic field, the criterion based on the analysis of cascade curves of showers is limited by a certain region of zenith angle of incidence of primary particles. For example, for detectors installed at middle latitudes (e.g., for Fly's Eye), the primary γ rays coming at angles $\Theta \geq 30°$, effectively interact with geomagnetic field due to electron-positron pair production. But it does not mean that these γ rays cannot be detected. In fact, the secondary electrons and positrons produce in the Earth's magnetosphere a beam of synchrotron photons with energy dominantly between 10^{15} and 10^{19} eV for which the magnetosphere is transparent. These secondary photons initiate electromagnetic cascades in the atmosphere, and since practically the whole energy ($\geq 99\%$) of the primary photon is redistributed between the beam photons, the superposition of these showers will imitate a single shower with energy close to the energy of the primary particle [16]. Because of the relatively low energy of the beam photons, the LPM effect is "switched off," and generally this shower is similar to a proton-induced shower. Nevertheless, some differential parameters, e.g, the *muon/electron* ratio at large distances from the core of the shower, can be used for effective separation of "multiphoton"-induced showers from the background cosmic ray showers. These remarkable features of γ-induced showers, arising at extremely high energies [16], allow us to hope that the boundary between TD and A domains shown in Fig. 3 will be probed by the forthcoming powerful detectors, in particular by high-resolution Fly's Eye [17] or by proposed recently "5000 km^2" giant air-shower array [18].

These experiments can provide unambiguous arguments for or against the proposed TD model. Moreover, in the case of realization of the TD model, it may be possible to probe the intergalactic magnetic field in the $10^{-12}-10^{-10}$ G domain by measuring the γ/p ratio between $\sim 5\times10^{19}$ and 5×10^{20} eV (compare curves 1, 2, and 3 in Fig. 2).

Valuable information about the origin and propagation of extragalactic CR is expected to be contained also in the γ-ray fluxes at $E \lesssim 100$ TeV [19]. The spectrum of γ

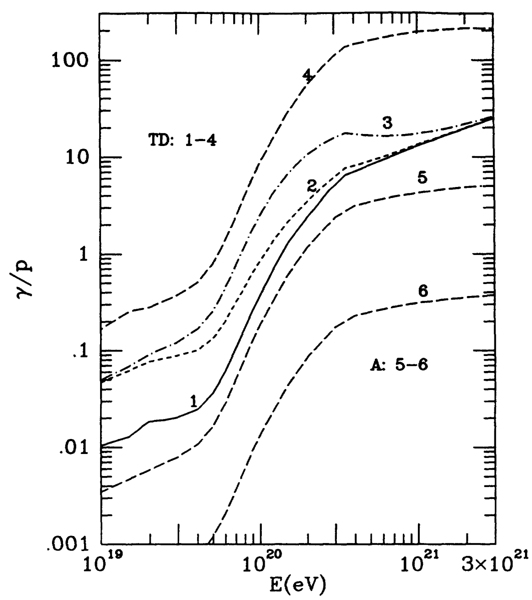

FIG. 3. The γ/p ratio expected in the TD and A models. The curves marked 1, 2, 3, and 4 are for the TD model. The curves 5 and 6 are for the A model with $\alpha=2$ and 3, respectively. (1) Direct γ rays; (2) cascade γ rays with $w_{\rm URB}=w_R$ and $B=10^{-10}$ G; (3) same as (2) except $B=3\times10^{-11}$ G. The curves 4, 5, and 6 are for $w_{\rm URB} \ll w_R$ and $B<10^{-12}$ G.

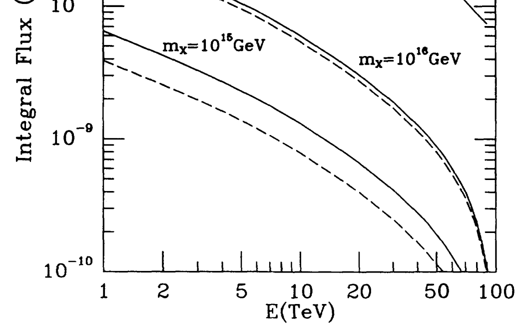

FIG. 4. The expected γ-ray fluxes below 100 TeV for the TD model. The value of m_X is as indicated near the curves. The solid curves are for $B=0$ and the dashed curves are for $B=10^{-10}$ G. The integral CR flux is also shown for comparison.

rays in this energy interval is determined mainly by the properties of cascade development in the MBR and hence has a standard shape which may be approximated as $I(E) \propto E^{-1.5}$ for $E \lesssim 10$ TeV, and $I(E) \propto E^{-1.75}$ for $E > 10$ TeV with a sharp cutoff above $E \sim 100$ TeV [20]. The absolute flux of these γ rays is determined by the total energy of the electromagnetic radiation above 100 TeV initiating the cascade in the MBR. For the A model, the flux of these γ rays is expected only at a level $\lesssim 10^{-5}$ of the CR background, which makes the detection of this component of γ rays by modern air-shower detectors rather problematic. However, in the TD model, due to the high production rate of γ rays and electrons, the integral γ-ray fluxes at $E \leq 100$ TeV are expected at the level of 10^{-3}–10^{-2} of the CR (see Fig. 4). Detection of this component seems very difficult even by the large UMC (Utah-Michigan-Chicago) air-shower detector facility [21]. It requires a rather high efficiency for rejection of cosmic ray background ($\leq 10^{-3}$) at energies $E \leq 100$ TeV, which perhaps may be provided by a new generation of future ground-based detectors such as CRT [22], MILAGRO [23], and HEGRA-AIROBICC [24]. Note that the γ-ray fluxes in this energy range depend weakly on the value of the magnetic field, but they are sensitive to m_X. Thus it may be possible to probe m_X by measuring the γ/p ratio at energies $E \leq 100$ TeV.

It should be noted also that the γ-ray fluxes shown in Fig. 4 were obtained taking into account cascading only in the field of MBR. What about the interaction of ≤ 100 TeV γ rays with other (apart from MBR intergalactic fields? It seems rather unclear due to the absence of certain information about the level of the universal *far* IR radiation. If the density of this radiation is not essentially below the upper limits obtained by the Infrared Astronomy Satellite (IRAS) and the Cosmic Background Explorer (COBE), then the electromagnetic cascade in this radiation field would strongly (two or three orders of magnitude) shift the spectra in Fig. 4 to lower energies, providing much higher fluxes at energies $E \leq 100$ GeV. This component of the diffuse γ radiation may be probed by the Energetic Gamma Ray Experiment Telescope (EGRET) Gamma Ray Observatory (GRO).

To summarize, we are noting that GUT processes may be observed through the use of γ/p ratio in extremely high energy cosmic rays.

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