

## CONSTRAINTS ON THE VERY HIGH ENERGY EMISSIVITY OF THE UNIVERSE FROM THE DIFFUSE GeV GAMMA-RAY BACKGROUND

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### ABSTRACT

Very high energy (VHE,  $E \gtrsim 100$  GeV) radiation emitted at cosmological distances will pair produce on low-energy diffuse extragalactic background radiation before ever reaching us. This prevents us from directly seeing most of the VHE emission in the universe. However, a VHE  $\gamma$ -ray that pair produces initiates an electromagnetic pair cascade. At low energies, this secondary cascade radiation has a spectrum insensitive to the spectrum of the primary  $\gamma$ -radiation and, unlike the original VHE radiation, is observable. Motivated by new measurements of the extragalactic MeV–GeV diffuse  $\gamma$ -ray background, we discuss the constraints placed on cosmological VHE source populations by requiring that the cascade background they produce not exceed the observed levels. We use a new, accurate cascading code and pay particular attention to the dependence of the constraints on the diffuse cosmic background at infrared/optical wavelengths. Despite considerable uncertainty in this background, we find that robust constraints may still be placed on the integrated emissivity of potential VHE sources in the universe. The limits are tighter than those obtained by considering cascading on the microwave background alone and restrict significantly, for example, the parameter space available for the exotic particle physics scenarios recently proposed to explain the highest energy cosmic-ray events. If direct emission from blazar AGNs in fact accounts for most of the observed GeV background, the resulting stronger limits rule out AGN emission scenarios that produce significant power above  $\sim 300$  GeV.

*Subject headings:* diffuse radiation — galaxies: active — gamma rays: theory — radiative transfer

### 1. INTRODUCTION

Photon-photon pair production of high-energy  $\gamma$ -rays on the diffuse extragalactic background radiation (DEBRA) significantly limits the distance that such  $\gamma$ -rays can propagate (Nikishov 1962; Gould & Schröder 1966). For  $\gamma$ -rays energies above a few TeV, this distance is almost certainly  $\lesssim 100$  Mpc (Stecker, de Jager, & Salamon 1992). Thus, most of the very high energy (VHE) universe is not directly visible to us. However, we can see the lower energy, secondary radiation produced in the electromagnetic cascades initiated by the absorbed VHE photons. In principle, this radiation may be detected as a halo about an individual source (Aharonian, Coppi, & Völk 1994; Phinney & Madau 1997), but an easier way to detect or constrain VHE emission is to look for the diffuse cascade background produced by the ensemble of all VHE sources in the universe. The spectrum of this background is rather insensitive to the spectrum of the original VHE radiation, and thus the total level of the cascade background acts as a particle detector calorimeter, allowing us to measure the total VHE energy input into the universe. This was first noted in the context of detecting an extragalactic population of high-energy cosmic rays (Wdowczyk, Tkaczyk, & Wolfendale 1972).

However, cosmic rays are not the only possible sources of VHE radiation. The physical conditions in powerful, extragalactic sources like active galactic nuclei (AGN) could lead to efficient acceleration of particles to large energies (e.g., see the review of Hillas 1984) and the subsequent emission of VHE  $\gamma$ -rays. Indeed, the blazar AGNs Mrk 421 and 501 do emit

TeV  $\gamma$ -rays (Punch et al. 1992; Quinn et al. 1996). Also, several “exotic” particle physics/early universe scenarios have been proposed that lead to the generation of extremely high energy charged particles and photons at late times (e.g., from decaying GUT-scale particles and topological defects). These scenarios can produce a large VHE cascade background. Tight constraints on the scenarios result from requiring that (i) the level of the cascade background today not exceed the observed extragalactic  $\gamma$ -ray background, and (ii) the level of the background at high redshifts not be enough to alter primordial nucleosynthesis (see, e.g., Ellis et al. 1992).

In this paper we reexamine and quantify the constraints placed on a cosmological VHE source population by requiring that its cascade background not exceed the  $\gamma$ -ray background observed today. EGRET has now measured the diffuse extragalactic background at 1–10 GeV (Fichtel 1995), the energy range in which the expected cascade backgrounds are typically most insensitive to model parameters. Also, prior work either does not accurately compute the cascade radiation spectrum or only considers cascading on the microwave (MBR) portion of the DEBRA. The inclusion of an infrared/optical (IR/O) DEBRA component leads to much tighter cascading constraints. Unfortunately, our knowledge of the IR/O DEBRA is limited, and in § 2, we show how the current uncertainties lead to significant uncertainties in our understanding of VHE photon propagation. In § 3, we calculate cascade backgrounds for different IR/O DEBRA and VHE source population models. Using AGNs and decaying particles from topological defects as example populations, we show how interesting and straightforward astrophysical source constraints can be de-

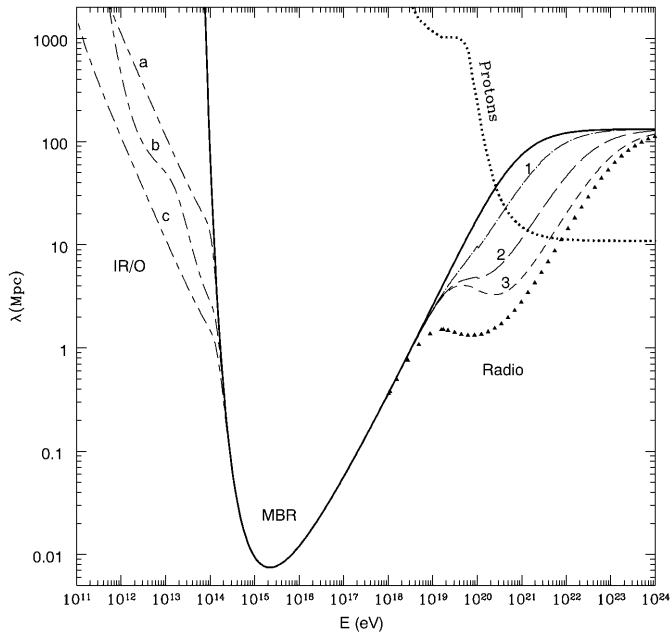


FIG. 1.—Local pair-production mean free path,  $\lambda$ , for VHE photons of energy,  $E$ , at redshift  $z = 0$  (no cosmological effects included). Below  $10^{14}$  eV, VHE photons interact primarily with IR/O photons; above  $10^{19}$  eV, they interact with radio photons; between  $10^{14}$  and  $10^{19}$  eV, they interact with MBR photons. Curves a, b, and c, respectively, show  $\lambda$  for the IR/O backgrounds of curves (i), (iv), and (vi) in Fig. 2. Curves 1, 2, and 3 show, respectively,  $\lambda$  for the extragalactic radio background estimate of Sironi et al. (1990) (see also Simon 1977) with a low-frequency cutoff at 5, 2, and 1 MHz. The triangles give the lower limit on  $\lambda$  obtained assuming the total observed radio background (e.g., Ressel & Turner 1991) is extragalactic. The heavy dotted line shows the energy-loss mean free path for energetic protons.

rived, despite the uncertainties in the DEBRA. We summarize our results in § 4.

## 2. VHE PHOTON PROPAGATION THROUGH THE COSMIC BACKGROUND RADIATION

The distance a VHE photon propagates in the universe is determined by the intensity of the intervening DEBRA. For small emission redshifts, the photon propagation length at energy  $E$  is  $\lambda(E) \approx 2.5\epsilon_s\sigma_T^{-1} [\epsilon_s U_\epsilon(\epsilon_s)]^{-1}$ , where  $\epsilon_s(E) \approx 0.25(E/1 \text{ TeV})^{-1}$  eV,  $\epsilon_s U_\epsilon(\epsilon_s)$  is the DEBRA energy density at  $\epsilon_s(E)$ , and  $\sigma_T$  is Thomson cross section (e.g., Herterich 1974). Hence, there is a rough mapping between  $\lambda(E)$  and the background intensity at  $\epsilon_s(E)$ . Measuring  $\lambda(E)$  via the detection of cutoffs in VHE spectra thus measures the DEBRA at  $\epsilon_s(E)$  [and only  $\epsilon_s(E)$ !], a possibility that has aroused much interest. Conversely, to model VHE photon propagation and cascading, we need to understand the DEBRA, especially at IR/O energies. Unfortunately, direct measurements (Puget et al. 1996) are at best preliminary, while theoretical estimates (e.g., Franceschini et al. 1994) vary considerably. Thus, estimates for the propagation lengths of VHE photons emitted today are actually quite uncertain (see Fig. 1). To calculate how far a VHE photon emitted at higher redshifts propagates, we need the DEBRA intensity over a range of energies and also redshifts. A common approximation assumes the entire DEBRA was produced in a burst at  $z_{\text{burst}} = \infty$  so that, like the MBR, the DEBRA photon density at redshift  $z$  scales from its value today as  $n(\epsilon, z) = (1+z)^3 n[\epsilon/(1+z), 0]$ . However, galaxy emission, the likely origin of the IR/O DEBRA respon-

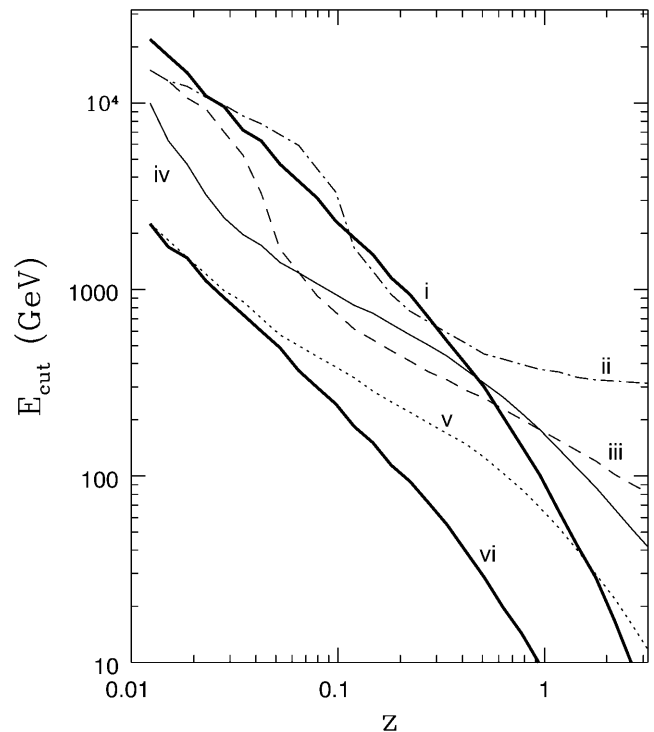


FIG. 2.—The cutoff energy,  $E_{\text{cut}}$ , as a function of source redshift,  $z$ , for different IR/O DEBRAs in an  $\Omega = 1$  universe with  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .  $E_{\text{cut}}$  is given by  $\tau_{\gamma\gamma}[(1+z)E_{\text{cut}}, z] = 1$ , where  $\tau_{\gamma\gamma}$  is the optical depth for photon absorption via pair production. Curves (i) and (vi) show  $E_{\text{cut}}$  for roughly the minimum (Tyson 1995) and maximum (Dwek & Slavin 1994) allowed IR/O levels today:  $\epsilon^2 n(\epsilon, 0) = 1 \times 10^{-3} \text{ eV cm}^{-3}$  for (i) and  $\epsilon^2 n(\epsilon, 0) = 1 \times 10^{-2} \text{ eV cm}^{-3}$  for (vi). The DEBRA evolves as  $n(\epsilon, z) = (1+z)^3 n[\epsilon/(1+z), 0]$ , and  $n(\epsilon, 0)$  has no optical/UV cutoff. Curve (v) is the same as (vi), except the IR/O DEBRA is formed in a burst at  $z = 5$  with no photons emitted above the Lyman limit (13.6 eV). Curves (ii)–(iv) show  $E_{\text{cut}}$  for more realistic DEBRA scenarios: (ii) late galaxy formation at  $z_{\text{form}} \lesssim 1$ , (iii) continuous galaxy formation at intermediate redshifts  $1 \lesssim z_{\text{form}} \lesssim 3$ , and (iv) early galaxy formation at  $z_{\text{form}} \sim 5$ . The galaxy emission components (see text) were adjusted to match, respectively, the HCDM and CDM calculations of MacMinn & Primack (1995) and those of Franceschini et al. (1994).

sible for TeV  $\gamma$ -ray absorption, evolves continually in time, and galaxies still emit strongly today.

The exact epoch of galaxy formation is highly controversial, but formation redshifts as low as  $z_{\text{form}} \sim 1$ –3 are commonly considered, i.e., the IR/O DEBRA's evolution could differ significantly from that of the MBR. Hence, the impact of DEBRA uncertainties is actually greater than implied by Figure 1. We show this in Figure 2 by plotting as a function of redshift and for several DEBRA evolutionary scenarios the characteristic energy,  $E_{\text{cut}}$ , at which an observed VHE spectrum cuts off due to pair production. To model DEBRA evolution more realistically, we follow Mazzei, Xu, & De Zotti (1992) and assume galaxy emission has two characteristic spectral components: optical/UV light from stars and IR emission from dust. We fix the spectral shapes of the components, but allow their luminosities to vary with redshift. While simple, this prescription can reproduce fairly well more detailed calculations. (For examples of such calculations and a discussion of the issues involved, see MacMinn & Primack 1995; Franceschini et al. 1994; Madau & Phinney 1996). As emphasized by MacMinn & Primack (1995) and as can be seen in Figure 2, the range of possibilities is large. One should be wary of, say, extrapolating a determination of  $E_{\text{cut}}$  at one

redshift to other redshift without extra information (the curves intersect).

### 3. THE CASCADE BACKGROUND FROM A POPULATION OF VHE SOURCES

As large as the IR/O DEBRA uncertainties are, in almost all cases cascading takes less than a few hundred megaparsecs to reprocess an absorbed VHE photon's energy into that of many photons with individual energies below  $\sim 1$  TeV. This is the primary reason VHE cascading is such a powerful diagnostic: essentially all energy emitted above 1 TeV by a cosmological population (spanning gigaparsec distances) re-emerges below 1 TeV where we can detect it. The second reason is that for VHE photon energies above  $\sim 1$  TeV the cascade spectrum at lower energies is very insensitive to the initial VHE photon spectrum and depends weakly on the DEBRA (which determines exactly where below 1 TeV the energy ends up, i.e.,  $E_{\text{cut}}$ ). The latter point, recognized as early as Strong, Wdowczyk, & Wolfendale (1973), is key but not widely appreciated. The spectrum for a cascade started at redshift  $z_{\text{emit}}$  goes roughly as  $dN/dE \propto E^{-1.5}$  for  $E < E_b$  and as  $E^{-\alpha_\gamma}$  for  $E_b < E < E_{\text{cut}}(z_{\text{emit}})$ , where  $E_b \sim [E_{\text{cut}}(z_{\text{emit}})/1\text{TeV}]^2$  GeV and typically  $\alpha_\gamma \sim 1.8-2$  (Coppi & Königl 1997). The part of this spectrum containing most of the cascade energy (and relevant to EGRET) is the  $\sim E^{-2}$  component, not the  $E^{-1.5}$  one. Changing the DEBRA changes  $E_{\text{cut}}$  but not the total observed cascade energy. Hence, the cascade spectrum amplitude goes (roughly) as  $\sim \ln(E_{\text{cut}}/E_b)$ , i.e., a weak function of  $E_{\text{cut}}$  and thus the DEBRA. Now the spectrum from a population of sources is simply the sum of cascade spectra for a range of  $z_{\text{emit}}$ , so that below  $\sim \bar{E}_{\text{cut}}$ , the cutoff energy at the typical source redshift, the total spectrum is similarly insensitive to the DEBRA. (Above  $\bar{E}_{\text{cut}}$  it does depend strongly on the DEBRA.) If we measure or constrain the  $\gamma$ -ray background below  $\bar{E}_{\text{cut}}$ , we robustly constrain the typical VHE luminosity of the source population. Below we present two sample numerical examples demonstrating the power of this VHE cascade constraint. We use a new code that solves the exact cascade kinetic equations implicitly (see Coppi & Königl 1997). The main advantages of the new code over past ones are that (i) it is not a Monte Carlo code and is typically much faster and (ii) because it is implicit, it can seamlessly and efficiently follow the cascade into the Thomson regime where pairs cool in very small steps. This allows us to accurately compute the cascade spectrum in the low-energy ( $\lesssim 1$  GeV) range required for comparison to  $\gamma$ -ray background observations. The cosmological (redshift) terms in the cascade equations are handled as in Protheroe & Stanev (1993).

Our first example considers the possibility that the highest energy cosmic rays ( $E \gtrsim 10^{20}$  eV) are produced in the decay of massive ( $\sim 10^{15}$  GeV) primordial particles/topological defects (e.g. see Sigl, Schramm, & Battacharjee 1994). Typical scenarios assume a hard decay spectrum,  $dN/dE \propto E^{-1.5}$ , extending to energy  $E_{\text{max}} \sim 10^{23-25}$  eV. To explain a cosmic-ray flux above  $3 \times 10^{20}$  eV of  $4 \times 10^{-21}$  cm $^{-2}$  s $^{-1}$  sr $^{-1}$  (Bird et al. 1994; Yoshida et al. 1995), such scenarios require a current ( $z = 0$ ) VHE energy release rate  $\dot{Q}_{\text{em}} \approx 1.5 \times 10^{-22} [(\pi^0/p)/10][E_{\text{max}}/10^{24} \text{ eV}]^{1/2}$  eV cm $^{-3}$  s $^{-1}$  if the observed cosmic rays are protons, and  $\dot{Q}_{\text{em}} \approx 6.5 \times 10^{-23} [E_{\text{max}}/10^{24} \text{ eV}]^{1/2} [\lambda_\gamma/10 \text{ Mpc}]^{-1}$  if they are photons. Here  $(\pi^0/p)$  is the number ratio of  $\pi^0$  particles to protons produced in a decay (usually  $\sim 10$ ), and  $\lambda_\gamma$  is the photon absorption mean free path at  $3 \times 10^{20}$  eV (probably  $\sim 3-20$  Mpc; see Fig. 1). Figure 3

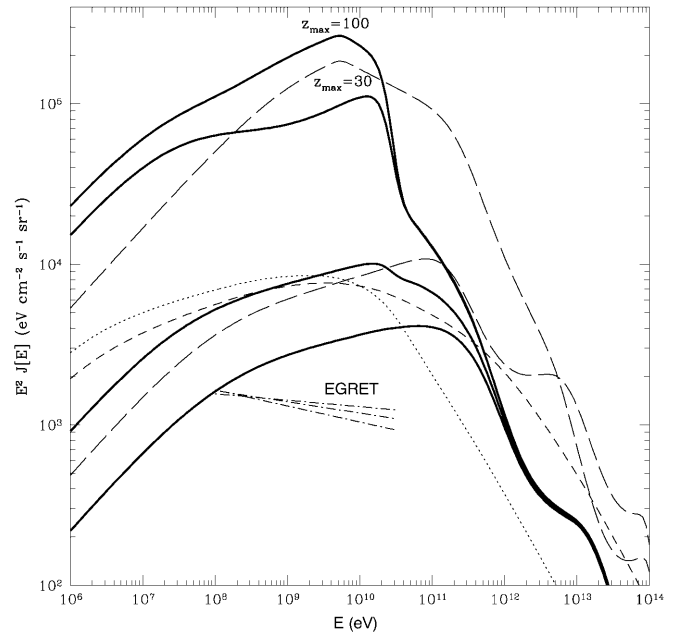


FIG. 3.—The VHE cascade background produced for different IR/O DEBRAs and topological defect/particle decay rates in a flat  $\Omega = 1$  universe with  $H_0 = 75$ . From bottom to top, the heavy, solid lines show the backgrounds normalized to a current VHE decay luminosity density of  $\dot{Q}_{e-m} = 1 \times 10^{-22}$  eV cm $^{-3}$  s $^{-1}$  that increases with redshift as  $(1+z)^3$ ,  $(1+z)^{3/2}$  (the currently favored scenario), and  $(1+z)^6$ . The  $(1+z)^6$  case does not converge, and we truncate the integration at two different  $z_{\text{max}}$ . The IR/O DEBRA of curve (iv) in Fig. 2 was used. The dotted, dashed, and long-dashed curves, respectively, show the effects of changing the IR/O background to that of curves (vi), (i), and (ii) in Fig. 2. The dot-dashed curves depict the range of uncertainty in the current EGRET background measurements.

shows the calculated background cascade spectra for a range of DEBRA and decay rate evolutionary scenarios. The dependence on the IR/O DEBRA increases with stronger decay rate evolution, but below the  $\sim$  TeV spectral break at  $\bar{E}_{\text{cut}}$ , it is remarkably small, especially in the 1–10 GeV range. Comparing to the observed EGRET flux, we see that  $\dot{Q}_{\text{em}}$  must be  $\lesssim 3 \times 10^{-23}$  eV cm $^{-3}$  s $^{-1}$ . Hence if the cosmic-ray events are protons, we can rule out typical primordial particle/defect scenarios. If the events are photons, we also find strong constraints but with caveats concerning the intergalactic magnetic field (IGMF). For a weak IGMF  $\lesssim 10^{-11}$  G, the initial cascading effectively increases  $\lambda_\gamma$  at  $3 \times 10^{20}$  eV to  $\sim 100$  Mpc, and a decay scenario is not ruled out (see Lee 1996; Sigl, Lee, & Coppi 1996). For a stronger IGMF, typical scenarios are at best marginally allowed (in overall agreement with Chi et al. 1992, although they significantly overestimated the expected cascade backgrounds).

VHE constraints of this type tighten if the observed GeV background proves to be dominated by direct (nonscatter) GeV emission from discrete sources. The constraints may be quite interesting when applied to the discrete sources themselves. For example, AGNs are prime candidates for producing the background. While EGRET has shown most AGNs are not strong  $\gamma$ -ray emitters, they still could have low-level emission extending to quite high energies (e.g.,  $\sim 10^{16}$  eV in Mastichiadis & Protheroe 1990). Assume all AGNs isotropically emit a  $dN/dE \propto E^{-2}$  spectrum to some maximum energy, and that, as speculated, this emission explains the GeV background. If AGN  $\gamma$ -ray emission scales with AGN optical emission, then using the Boyle et al. (1990) quasar luminosity

function, we find that for every decade quasar emission extends above  $\sim 300$  GeV, cascading overproduces the background by a factor of  $\sim 0.25$ : either AGNs as a whole cannot make up the background, or they are weak VHE sources. A more likely background candidate is the blazar subclass of AGNs, which does show strong GeV emission. This emission can be rapidly variable, and EGRET has not seen that many blazars, so it is still unclear what the typical time-averaged  $\gamma$ -ray blazar luminosity is (this is the relevant quantity since the EGRET background is an integration over several years) and how it relates to other properties of blazars, i.e., if blazars dominate the background. If they do, it is crucial to consider cascading since the weakest blazars, at least, emit at VHE (TeV) energies. As an illustration, we repeat (Fig. 4) the GeV background calculation of Stecker & Salamon (1996), making the same assumptions for the blazar  $\gamma$ -ray luminosity function but allowing for VHE photon absorption and cascading and considering different values for the typical maximum blazar emission energy and the blazar  $\gamma$ -ray spectral index (hardness) distribution. Again, typical blazar spectra must break strongly by  $\sim 100$  GeV (depending exactly on  $\bar{E}_{\text{cut}}$ , i.e., the IR/O DEBRA, and the blazar spectral hardness), or blazars do not explain the GeV background. Spectral breaks at  $\sim 100$  GeV are not implausible since the centers of most blazars have UV photon densities high enough to absorb any VHE  $\gamma$ -rays emitted there and possibly quench VHE acceleration mechanisms.

#### 4. CONCLUSION AND DISCUSSION

Since the cascade energy flux falls in the EGRET range (Fig. 3), we can estimate the maximum average VHE emissivity of the universe by equating the cascade background energy flux accumulated over a cosmological distance scale ( $\frac{1}{4}\pi\dot{Q}_{c-m}d$ , with  $d \sim 1$  Gpc) to the observed EGRET energy flux above 100 MeV,  $\sim 8 \times 10^3 \text{ eV cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ . This gives  $\dot{Q}_{\text{em}}^{\text{max}} \approx 5 \times 10^{-23} \text{ eV cm}^{-3} \text{ s}^{-1}$ , while the calculation of Fig. 3 gives  $\dot{Q}_{\text{em}}^{\text{max}} \sim 1-3 \times 10^{-23} (H_0/75)^{-1} \text{ eV cm}^{-3} \text{ s}^{-1}$  for moderately evolving source populations. In a Hubble volume  $V_H \sim (4\pi/3)(c/H_0)^3$ , this implies a maximum VHE source luminosity  $\sim 1-3 \times 10^{50} \text{ ergs}^{-1}$ —not a large number (the bolometric luminosity of a single powerful quasar is  $\sim 10^{48} \text{ ergs}^{-1}$ .) This limit is not very sensitive to the IR/O DEBRA and applies to any cosmological population with significant VHE emission above  $\sim 1$  TeV. It will be interesting to see how much of the GeV background a future instrument like GLAST (Bloom

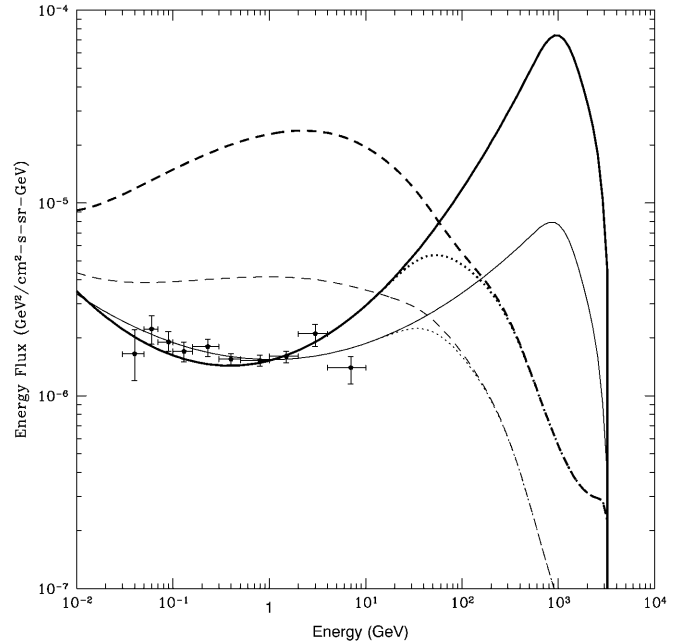


FIG. 4.—The diffuse  $\gamma$ -ray background produced by blazars. The solid lines show the same blazar  $\gamma$ -ray background calculation as Fig. 3 of Stecker & Salamon (1996), but assuming that blazar spectra are unbroken power laws to 3 TeV and that the distribution of blazar spectral indices  $\alpha$  (where photon number  $dN/dE \propto E^{-\alpha}$ ) is a Gaussian centered at  $\bar{\alpha} = -2.05$ , with width  $\sigma_{\alpha} = 0.25$  (regular weight lines) and  $\bar{\alpha} = -2.1$ , with  $\sigma_{\alpha} = 0.35$  (heavy lines). The dotted lines show the effects of VHE  $\gamma$ -ray absorption on the expected background. The dashed lines show the result when the VHE cascade contribution is included. The IR/O background of curve (iv) in Fig. 2 was used, but with  $H_0 = 50$  in order to compare with Stecker & Salamon (1996).

1996) can resolve. If the background is mainly noncascade blazar emission, this limit tightens and, for example, may imply that typical blazar spectra show an intrinsic break at  $\approx 100$  GeV. Any residual background surviving a fluctuation/point source analysis could well be from VHE cascades. (A few AGNs are VHE sources.) Detection of a cascade background, especially in the cutoff region  $\approx 10$  GeV, provides combined information on the evolution of the underlying VHE source population and the IR/O DEBRA (i.e., galaxies).

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