

# Constraints on the VHE Emissivity of the Universe from the Diffuse GeV Gamma-Ray Background

Paolo S. Coppi

Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101

Felix A. Aharonian

Max-Planck-Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany

(Shortened version submitted to *Ap.J. Lett.*)

## ABSTRACT

VHE (Very High Energy,  $E \gtrsim 100$  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 AGN in fact accounts for most of the observed GeV background, these limits strengthen and rule out AGN emission scenarios which produce significant power above  $\sim 300$  GeV.

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

## 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, DeJager, & Salamon 1992). Thus, most of the VHE Universe is not visible to us. Nevertheless, we can detect the presence of VHE emission via the lower-energy, secondary radiation produced in the cascades initiated by the VHE photons. (The energy carried by absorbed VHE  $\gamma$ -rays is not lost; the electron-positron pairs produced create new  $\gamma$ -rays by inverse Compton scattering on background field photons and can trigger an electromagnetic pair cascade.) In principle, this radiation could be detected from an individual source as a halo about the source (Aharonian, Coppi, & Völk 1994, Phinney & Madau 1996), 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. In particular, the spectrum of this secondary cascade radiation is rather insensitive to the spectrum of the primary VHE radiation, and therefore 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 pointed out 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, non-thermal extragalactic sources like Active Galactic Nuclei (AGN) and Radio Galaxies could lead to the acceleration of particles to very high energies (e.g., see the review of Hillas 1984), and depending on exactly where acceleration occurs, AGN can easily contain enough target matter (e.g., strong photon fields) to convert efficiently this particle energy into high energy radiation. Indeed, the nearby blazar AGN Mrk 421 and 501 do emit TeV  $\gamma$ -rays. 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 primordial black holes or GUT-scale particles and topological defects) . These scenarios can produce a large VHE cascade background, and tight constraints on them 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 (e.g., see the review by Ellis *et al.* 1992).

In this paper, we re-examine 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. We are motivated by two considerations. First, EGRET has provided us with a determination of the diffuse extragalactic background at 1 – 10 GeV (Fichtel 1995). This is the energy range where the expected cascade backgrounds

are typically most insensitive to model parameters and from which we thus obtain the most robust constraints. Second, the prior work we are aware of either does not accurately compute the cascade radiation spectrum or only considers cascading on the microwave portion of the DEBRA. The use of a realistic DEBRA, i.e., one that includes an infrared/optical (IR/O) component, is key as it leads to much tighter cascading constraints. Except for the microwave background (MBR), our current knowledge of the DEBRA and its evolution in time is limited. In §2 of the paper, we illustrate the uncertainties in the propagation of VHE photons corresponding to these uncertainties in the DEBRA. These can be significant and should not be forgotten when evaluating claims based on calculations of VHE photon absorption and cascading. In §3, we calculate the cascade backgrounds expected for different IR/O background fields and VHE source population models. Using decaying particles from topological defects (hypothesized as a possible source for the highest energy cosmic rays) and AGN as example populations, we show how interesting and straightforward astrophysical source constraints can be derived – *despite* the uncertainties in the DEBRA. We summarize our results in §4 and discuss their implications for future high energy  $\gamma$ -ray experiments.

## 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  $\lambda(E) \approx 2.5\epsilon_s[\epsilon_s U_\epsilon(\epsilon_s)]^{-1}$  where  $\epsilon_s(E) \approx 0.25(E/1 \text{ TeV})^{-1}$  eV and  $\epsilon_s U_\epsilon(\epsilon_s)$  is the background energy density at energy  $\epsilon_s(E)$  (e.g., Herterich 1974). In other words, there is a rough one-to-one mapping between  $\lambda(E)$  and the background intensity at  $\epsilon_s(E)$ . A determination of  $\lambda(E)$  via the detection of an absorption cutoff in a spectrum thus measures the background at  $\epsilon_s(E)$  (and *only*  $\epsilon_s(E)$ !) – a possibility that has aroused much interest given the observational difficulties in extracting the extragalactic IR/O background from the galactic/solar system foregrounds. Conversely, to understand VHE photon propagation, we require accurate knowledge of the DEBRA, in particular at IR/O energies. Unfortunately, direct measurements of the IR/O background (Puget *et al.* 1996) are at best preliminary. Theoretical estimates for the DEBRA exist (e.g., Franceschini *et al.* 1994) but are also rather uncertain. Consequently, our estimates for the propagation lengths of VHE photons emitted today are similarly uncertain. We summarize these uncertainties in Fig. 1. They are not small. In the ultra-high photon energy range ( $\epsilon \gtrsim 10^{20}$  eV), they arise from problems in determining the low-frequency cutoffs of extragalactic radio sources. In the GeV-TeV range, the uncertainties reflect our poor understanding of galaxy formation and evolution ( e.g., see MacMinn & Primack 1995, Madau & Phinney 1996 for detailed

discussions).

For a VHE photon emitted at redshifts  $z_{\text{emit}} \gtrsim 0.1$ , an added complication arises. As it propagates, the photon’s energy is redshifted and at any given redshift  $z'$ , the photon interacts most strongly with local background photons of energy  $\epsilon_s \propto \frac{(1+z')}{(1+z_{\text{emit}})} E_{\text{emit}}^{-1}$  where  $E_{\text{emit}}$  is the energy of the VHE photon at  $z_{\text{emit}}$ . Therefore, to estimate the probability for this photon to be absorbed, we need good estimates for the DEBRA over a range of energies *and* over a range of redshifts. A common assumption is that the DEBRA was produced in a burst at  $z_{\text{burst}} = \infty$  like the MBR, so that the DEBRA photon density also scales as  $n(\epsilon, z) = (1+z)^3 n[\epsilon/(1+z), 0]$  (e.g., Stecker, DeJager, & Salamon 1992, Biller 1995). However, galaxy emission, the likely source of the IR/O DEBRA, evolves in time as galaxy stellar populations evolve, and galaxies still emit significant amounts of light today (i.e., their emission burst is not over). The exact epoch of galaxy formation is highly controversial, but formation redshifts as low as  $z_{\text{form}} \sim 1 - 3$  are commonly considered. In other words, the evolution of the non-MBR DEBRA could deviate considerably from the  $(1+z)^3$  law. Consequently, uncertainties in the DEBRA actually have a greater impact on  $\gamma$ -ray propagation than implied by Fig. 1. This is not always appreciated. In Fig. 2, we show for several DEBRA evolutionary scenarios the observed cutoff energy,  $E_{\text{cut}}$ , in the spectrum of a VHE source located at redshift  $z$ . In curves (i) and (vi) of Fig.2, we 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), where for an order of magnitude estimate, we assume the background goes as  $n(\epsilon) \propto \epsilon^{-2}$ . In both cases, we scale the DEBRA back in redshift as  $n(\epsilon, z) = (1+z)^3 n[\epsilon/(1+z), 0]$ , and we assume  $n(\epsilon, 0)$  has *no* optical/UV cutoff (e.g., a Lyman limit). While convenient, note that obtaining the DEBRA at high redshifts in this way, i.e., extrapolating it from the DEBRA today, can be dangerous. Most likely, the today’s DEBRA is a complicated superposition of light emitted at various redshifts. By extrapolating from the current DEBRA, we make an implicit, but often unrealistic and unphysical assumption about the spectra of the sources contributing to the DEBRA, especially when the source spectra contain sharp cutoffs, e.g., a Lyman limit. As an example, assume that because of the Lyman limit, the current DEBRA cuts off sharply above, say, 5 eV. Extrapolating to  $z = 2$ , we now find a DEBRA that cuts off sharply only above 15 eV, and we could conclude that the DEBRA at that epoch was due to sources with strong emission above the Lyman limit (13.6 eV) – rather unlikely if the sources are galaxies. Now, the absorption cutoff in distant sources like AGN depends critically on the DEBRA intensity at optical/UV energies (i.e., near the Lyman limit), so one must be very careful about the optical/UV DEBRA evolution. In curve (v), we compute  $E_{\text{cut}}$  for the DEBRA of curve (vi) except that we assume the DEBRA was produced in a burst at  $z_{\text{burst}} = 5$  and that no photons were emitted above the Lyman limit

during the burst. In this case, the DEBRA at  $z < z_{\text{burst}}$  still scales as  $(1+z)^3$ , but there are no photons present above  $13.6(1+z)/(1+z_{\text{burst}})$  eV. Note the large discrepancy between curves (v) and (vi) at high  $z$ .

Curves (i) and (vi) are probably fairly good as absolute upper and lower bounds for  $E_{\text{cut}}$  at a given  $z$ , but the assumptions underlying them are not very realistic. To give better examples of the effects of DEBRA evolution, we assume that the IR/O DEBRA is the integrated light from galaxies, and that galaxies have two distinct spectral components: direct/optical UV emission from stars, and IR emission from dust which reprocesses the starlight. We allow the component luminosities to vary (independently) with redshift, but we keep their spectral shapes fixed and choose them to match the intermediate age spectra in Mazzei, Xu, & DeZotti (1992). This prescription can reproduce fairly well more sophisticated calculations and allows one to efficiently explore a variety of galaxy evolutionary scenarios. In curve (iv), we show the results for a scenario of the type proposed in Franceschini *et al.* (1994) where galaxies and stars form very early in the universe, and the DEBRA is dominated by light produced during the initial burst of star formation. The calculation shown assumes most stars/galaxies were formed at a formation redshift  $z_{\text{form}} \sim 5$ , and the intensity and evolution of the spectral components were adjusted to give roughly the IR/O DEBRA spectrum (for  $z = 0$ ) shown in Franceschini *et al.* 1994. In curves (ii) and (iii), we show what might happen if galaxies are instead formed at later times, as suggested by cosmological numerical simulations and as discussed by MacMinn & Primack (1995). In curve (ii), we assume galaxies form late, at  $z_{\text{form}} \lesssim 1$ , and adjust the spectral component intensities and intensity evolution to roughly match those in the HCDM (Hot-Cold Dark Matter)-based calculation of MacMinn & Primack (1995). In curve (iii), we assume galaxies form at intermediate redshifts  $1 \lesssim z_{\text{form}} \lesssim 3$  and adjust the component intensity evolution to match the CDM (Cold Dark Matter)-based calculation of MacMinn & Primack (1995). Although the models shown probably do not produce enough UV light (e.g., as compared to Madau & Phinney 1996) and  $E_{\text{cut}}$  could be somewhat lower at high  $z$ , the curves in Fig. 2 should be indicative of the large range of possibilities due to the current uncertainties in the DEBRA. Consequently, one should be wary of extrapolating a determination of  $E_{\text{cut}}$  at one redshift to other redshifts without extra information (the curves in Fig. 2 intersect!). For example, an exact measurement of the IR/O DEBRA today would not be sufficient to allow a precise determination of the Hubble constant via the absorption cutoffs in distant ( $z > 0.1$ ) sources. Finally, one should be careful when claiming an unidentified source, e.g., a  $\gamma$ -ray burst, is closer than a certain redshift because it shows no VHE absorption.

### 3. The Cascade Background from a Population of VHE Sources

While the IR/O DEBRA uncertainty is significant, it is not enough to allow VHE photon emitted above  $\sim 1$  TeV to propagate more than a few hundred Mpc (see Fig. 1; and note that the DEBRA intensity generally increases with redshift). Similarly, cascading typically takes less than a few hundred Mpc to reprocess an absorbed VHE photon’s energy into that of many photons with individual energies well below a TeV. Thus, for cosmological source populations like AGN that span Gpc distance scales, it is a reasonable approximation to assume a VHE photon is transformed instantaneously into sub-TeV photons. This is the primary reason VHE cascading is such a powerful diagnostic: essentially *any* energy emitted above 1 TeV re-emerges below 1 TeV, where we can detect it. The second is that for VHE photon energies above  $\sim 1$  TeV, the cascade spectrum at lower energies is very insensitive to the initial VHE photon energy distribution and only weakly sensitive to the details of the IR/O background distribution (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 has not been widely appreciated. The spectrum for a cascade started at  $z_{\text{emit}}$  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 1996) The portion of this spectrum which is relevant to 100 MeV-GeV observations and also contains most of the cascade energy is the  $\sim E^{-2}$  component, and not as usually believed, the  $E^{-1.5}$  component. Changing the IR/O background changes  $E_{\text{cut}}$  but not the total observed cascade energy. Hence, the cascade photon spectrum amplitude goes (roughly) as  $\sim \ln(E_{\text{cut}}/E_b)$ , i.e., it is rather insensitive to  $E_{\text{cut}}$  and thus the IR/O background. Now, the spectrum from a population of sources is simply the sum of cascade spectra for a range of  $z_{\text{emit}}$ . Below  $\bar{E}_{\text{cut}}$ , the cutoff energy for the average  $z$  of the VHE source population, the summed cascade spectrum then goes roughly as  $\sim E^{-2}$  and is similarly insensitive to the IR/O background. (However, the spectrum above  $\bar{E}_{\text{cut}}$  *does* depend strongly on the background.) If we can measure or constrain the  $\gamma$ -ray background below  $\bar{E}_{\text{cut}}$ , we can robustly constrain the VHE source population luminosity.

The preceding arguments need to be backed up by a rigorous calculation. We have developed a new code that solves the exact cascade kinetic equations implicitly (see Coppi & Königl 1996). The main advantages of our code over past ones are: (i) it does not have to confront problems of Monte Carlo particle statistics and is typically much faster, and (ii) because it is implicit, it can efficiently follow the cascade into the Thomson regime where cascade electrons lose energy in very small steps and thus accurately compute the low-energy ( $\lesssim 1$  GeV) cascade spectrum. The accuracy in this energy range – the range needed to compare with  $\gamma$ -ray observations – has been a problem in past work (e.g., Chi, X. *et al.* 1992), especially given that small errors at high energies extrapolate to large errors

at low energies. The cosmological (redshift) terms in the kinetic equations are handled in the same manner as Protheroe & Stanev (1993).

We present two sample numerical calculations which demonstrate the power of the VHE cascade constraint. The first, shown in Fig. 3, is motivated by the possibility that the highest energy cosmic rays ( $E \gtrsim 10^{20}$  eV) might be explained as decay products of massive ( $\sim 10^{15}$  GeV) primordial particles/topological defects (e.g., see Sigl, Schramm, & Battacharjee 1994 for a recent review). For this calculation, we assume the intergalactic magnetic field (IGMF) exceeds  $\sim 10^{-11}$  G, so that the initial cascading is suppressed by synchrotron losses, and we can approximate the initial decay products as photons of energy  $\sim 10^{15-16}$  eV (e.g., see Aharonian, Bhattarjee, & Schramm 1992). Taking the integral cosmic ray flux above  $3 \times 10^{20}$  eV to be  $\approx 4 \times 10^{-21} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$  (Bird *et al.* 1994, Yoshida *et al.* 1995), one can easily show that the current energy release rate required to explain such a flux is  $\dot{Q}_{e-m} \approx 1.5 \times 10^{-22} [(\pi^0/p)/10] [E_{\text{max}}/10^{24} \text{eV}]^{1/2} \text{eV cm}^{-3} \text{s}^{-1}$  if the observed cosmic rays are protons, and  $\dot{Q}_{e-m} \approx 6.5 \times 10^{-23} [E_{\text{max}}/10^{24} \text{eV}]^{1/2} [\lambda_\gamma/10 \text{Mpc}]^{-1}$  if they are photons. Here  $(\pi^0/p)$  is the number ratio of  $\pi^0$  particles to protons produced in a decay,  $\lambda_\gamma$  is the photon absorption mean free path at  $E = 3 \times 10^{20}$  eV (probably between 3 – 20 Mpc, see Fig. 1), and we assume the decay product energy spectrum is  $dN/dE \propto E^{-1.5}$  extending to energy  $E_{\text{max}}$ . (For most models,  $E_{\text{max}}$  lies in the range  $10^{23} - 10^{25}$  eV.) The dependence of the cascade background on the IR/O DEBRA increases with stronger decay rate evolution, but below  $\bar{E}_{\text{cut}}$  is remarkably small, between 1-10 GeV. For the optimal case of constant comoving decay rate, the EGRET measurement constrains the local energy release rate to be  $\lesssim 3 \times 10^{-23} \text{eV cm}^{-3} \text{s}^{-1}$ . Thus, if the cosmic ray events above  $10^{20}$  eV are caused by protons, we can firmly rule out a primordial particle/defect scenario as their origin. This conclusion does not depend strongly on the details of the IR/O DEBRA or the IGMF strength. If the high energy events are instead due to  $\gamma$ -rays, we also find strong constraints, but with some caveats concerning the IGMF. If the IGMF exceeds  $\sim 10^{-11}$  G, then Fig. 3 shows the standard scenarios are at best marginally allowed. (This agrees with the conclusions of Chi *et al.* 1992, even though they appear to have significantly overestimated the expected cascade background.) However, if the IGMF is weak ( $\lesssim 10^{-11}$  G), the initial cascading effectively increases the mean free path of  $3 \times 10^{20}$  eV photons to  $\lambda_\gamma \sim 100$  Mpc and in this case a decay scenario is *not* ruled out (see Lee 1996; Sigl, Lee, & Coppi 1996).

Blazar AGN are known to emit at GeV energies and, in fact, may dominate the observed GeV background (e.g., see Stecker & Salamon 1996 and references therein). If this were the case, the VHE source luminosity constraints would of course tighten considerably. In fact, they appear rather interesting when applied to radio-loud AGN, the parent population of blazars, and to AGN in general. As an illustration, we repeated

(see Fig. 4) the background calculation of Stecker & Salamon (1996), making exactly the same assumptions about the blazar luminosity function. However, we also took into account VHE photon absorption and cascading and considered various values for the typical maximum blazar emission energy. The level of the expected cascade background depends on the value of the IGMF and the exact relation between the apparent luminosity  $\gamma$ -ray of blazars measured by EGRET (which is enhanced by relativistic beaming) and the intrinsic (unbeamed)  $\gamma$ -ray luminosity of blazars, and their parent population, radio-loud quasars. When the IGMF exceeds  $\sim 10^{-15}$  G, the pairs in a VHE cascade are deflected sufficiently that the VHE luminosity of a blazar is effectively “debeamed.” The contribution from an individual blazar to the cascade background is then dramatically reduced, by a currently unknown factor between  $\delta^2$  (if the typical EGRET blazar luminosity corresponds to quasi-steady emission) and  $\delta^4$  (if it corresponds to strong, flaring emission). Here,  $\delta$  is the typical Doppler boost factor for blazars, probably  $\sim 10$ . In the high IGMF case, this decrease in the contribution from individual blazars can be partially or completely compensated by the  $\delta^2$  times larger number of radio-loud AGN (blazars pointing away from us) that are now visible in  $\gamma$ -rays via their cascade radiation. The cascade backgrounds shown in Fig. 4 apply to the cases when the IGMF is very low (the cascade is essentially rectilinear) or when the boost in the apparent blazar luminosity is  $\sim \delta^2$ . If one of these cases holds and the assumptions of Stecker & Salamon (1996) are correct, then typical blazar spectra must break strongly at  $\sim 100$  GeV or blazars do not explain the GeV background. (Note that the precise value of the break energy depends strongly on the IR/O DEBRA, the blazar luminosity function, and the distribution of blazar  $\gamma$ -ray spectral indices, all of which are poorly known.) Ignoring blazars and beaming effects, we can play a similar game with quasars as a whole. Assume all quasars isotropically emit  $\gamma$ -rays with a  $dN/dE \propto E^{-2}$  spectrum up to some maximum energy, and that, as speculated, their direct emission explains the 100MeV-GeV background. If quasar  $\gamma$ -ray emission scales with optical emission, then using the Boyle *et al.* (1991) quasar luminosity function, we find that for every decade quasar emission extends above  $\sim 300$  GeV (e.g., Mastichiadis & Protheroe 1990 predict spectra extending to  $\sim 10^{16}$  eV for radio-quiet AGN), cascading overproduces the background by a factor of  $\sim 0.25$ ; cascading should *not* be ignored in a GeV background calculation involving blazars or quasars.

#### 4. Conclusion and Discussion

Since the cascade energy flux falls in the same range as the EGRET observations (Fig. 3), we can make a quick estimate of the maximum average VHE emissivity allowed in the Universe by equating the cascade background energy flux accumulated over a cosmological



distance scale ( $\frac{1}{4\pi}\dot{Q}_{e-m}d$  where  $d \sim 1$  Gpc) with the observed EGRET energy flux above 100 MeV,  $\sim 8 \times 10^3$  eV cm<sup>-2</sup>sr<sup>-1</sup>s<sup>-1</sup> :  $\dot{Q}_{em}^{max} \approx 5 \times 10^{-23}$  eV cm<sup>-3</sup>s<sup>-1</sup>. For source populations with no or moderate cosmological evolution, the more exact calculation of Fig. 3 gives an upper limit  $\sim 1 - 3 \times 10^{-23}$  eV cm<sup>-3</sup>s<sup>-1</sup> for  $H_0 = 75$  ( $\dot{Q}_{em}^{max} \propto H_0^{-1}$ ). This is not a large number. In a Hubble volume  $V_H \sim \frac{4\pi}{3}(c/H_0)^3$ , this represents a total VHE source luminosity  $\sim 1 - 3 \times 10^{50}$ erg s<sup>-1</sup>. This can be compared, say, to the bolometric luminosity of a single powerful quasar  $\sim 10^{48}$ erg s<sup>-1</sup>, which as discussed, implies that AGN do not emit much of their luminosity at VHE energies. As we have shown, this limit is rather insensitive to details of the IR/O background and applies to *any* cosmological population with significant VHE emission above  $\sim 1$  TeV, e.g., any galaxy or cluster population with strong cosmic ray production at some stage in its history. It will be interesting to see how much of the GeV  $\gamma$ -ray background future instruments like GLAST can resolve. If, as suspected, most of the background is non-cascade blazar emission, the VHE cascade limits tighten and become even more interesting. In particular, depending on the IGMF and the details of blazar beaming, they could imply that typical blazar AGN show an *intrinsic* spectral break (not due to DEBRA absorption) at  $\gtrsim 100$  GeV – which would be an important constraint for blazar models. At the same time, though, a few AGN (e.g., Mkn 421) *are* effective VHE emitters, and there is no shortage of ideas for producing VHE emission by other means (e.g., the decaying topological defects discussed here). Any residual background surviving a fluctuation/point source analysis could well be VHE cascade emission. Detection of a cascade background, especially in the cutoff region  $\gtrsim 10$  GeV, provides combined information on the evolution of the underlying VHE source population and the IR/O background (i.e., galaxies). For a low IR/O background, the cascade background is quite hard. A GLAST detector with sufficient sensitivity to the diffuse  $\gamma$ -ray background up to 100 GeV could set even tighter limits on VHE source populations (or more easily detect a cascade background).

## 5. Acknowledgments

PSC would like to thank the Max-Planck-Institut für Kernphysik for its generous hospitality.

## REFERENCES

- Aharonian, F.A., Bhattacharjee, P., & Schramm, D.N. 1992, Phys. Rev. D, 46,1448  
 Aharonian, F.A., Coppi, P.S., & Völk, H.J. 1994, ApJ, 423, L5

- Biller, S. 1995, *Astropar. Phys.*, 3, 385
- Bird, D. J., *et al.* 1994, *ApJ*, 424, 491
- Chen, A., Dwyer, J., & Kaaret, P. 1996, *ApJ*, 463, 169
- Chi, X., *et al.* 1992, *Astropar. Phys.*, 1, 129
- Coppi, P.S., & Königl, A. 1996, submitted to *ApJ*
- Dwek, E. & Slavin, J. 1994, *ApJ*, 436, 696
- Ellis, J. *et al.* 1992, *Nucl. Phys. B*, 373, 399
- Fichtel, C., 1995, in *Proc. 3rd Compton Observatory Symposium*, A&AS, in press
- Franceschini, A., *et al.* 1994, *ApJ*, 427, 140
- Gould, R.J. & Schréder, G. 1966, *Phys. Rev. Lett.*, 16, 252
- Halzen, F., *et al.* 1990, *Phys. Rev. D*, 41
- Herterich, K. 1974, *Nature*, 250, 311
- Lee, S. 1996, astro-ph/9604098, submitted to *Phys. Rev. D*
- MacMinn, D. & Primack, J.R. 1995, *Space Sci. Revs.*, 75, 413.
- Madau, P. & Phinney, E. 1996, *ApJ*, **456**, 124
- Mannheim, K., Biermann, P., & Kruells, W.M. 1991, *A&A*, 251, 723
- Mastichiadis, A. & Protheroe, R.J. 1990, *MNRAS*, 246, 279
- Mazzei, P., Xu, C., De Zotti, G. 1992, *Astronomy and Astrophysics*, vol 256, p. 45]
- Nikishov, A.I. 1962, *Sov. Phys. JETP*, 14, 393
- Phinney, E.S. & Madau, P. 1996, submitted to *ApJ*
- Puget, J.-L. *et al.* 1996, *A&A*, 308, L5
- Protheroe, R.J. & Stanev, T. 1993, *MNRAS*, 264, 191
- Protheroe, R.J. & Biermann, P. 1996, *Astropar. Phys.*, in press
- Ressell, T. & Turner, M. 1991, *Comm. Astrophys.*, 14, 323

- Sigl, G., Lee, S., & Coppi, P. 1996, astro-ph/9604093, submitted to Phys. Rev. Lett.
- Sigl, G., Schramm, D.N., & Battacharjee, P. 1994, *Astropar. Phys.*, 2, 401
- Simon, A.J.B 1977, *MNRAS*, 180, 429
- Sironi, G., *et al* 1990, *ApJ*, 357, 301
- Stecker F.W., De Jager, O.C., & Salamon, M.H. 1992, *ApJ*, 390, L49
- Stecker, F.W. & Salamon, M.H. 1996, *ApJ*, 464,600
- Strong, A.W., Wdowczyk, J., Wolfendale, A.W. 1973, *Nature*, 241, 109
- Tyson, J.A. 1995, in *Extragalactic Background Radiation*, ed. D. Calzetti, M. Livio, & P. Madau (Cambridge: Cambridge University Press), p. 103
- Wdowczyk, J., Tkaczyk, W., Wolfendale, A.W. 1972, *J. Phys A.*, 5, 1419
- Yoshida, S., *et al.* 1995, *Astropar. Phys.*, 3, 151

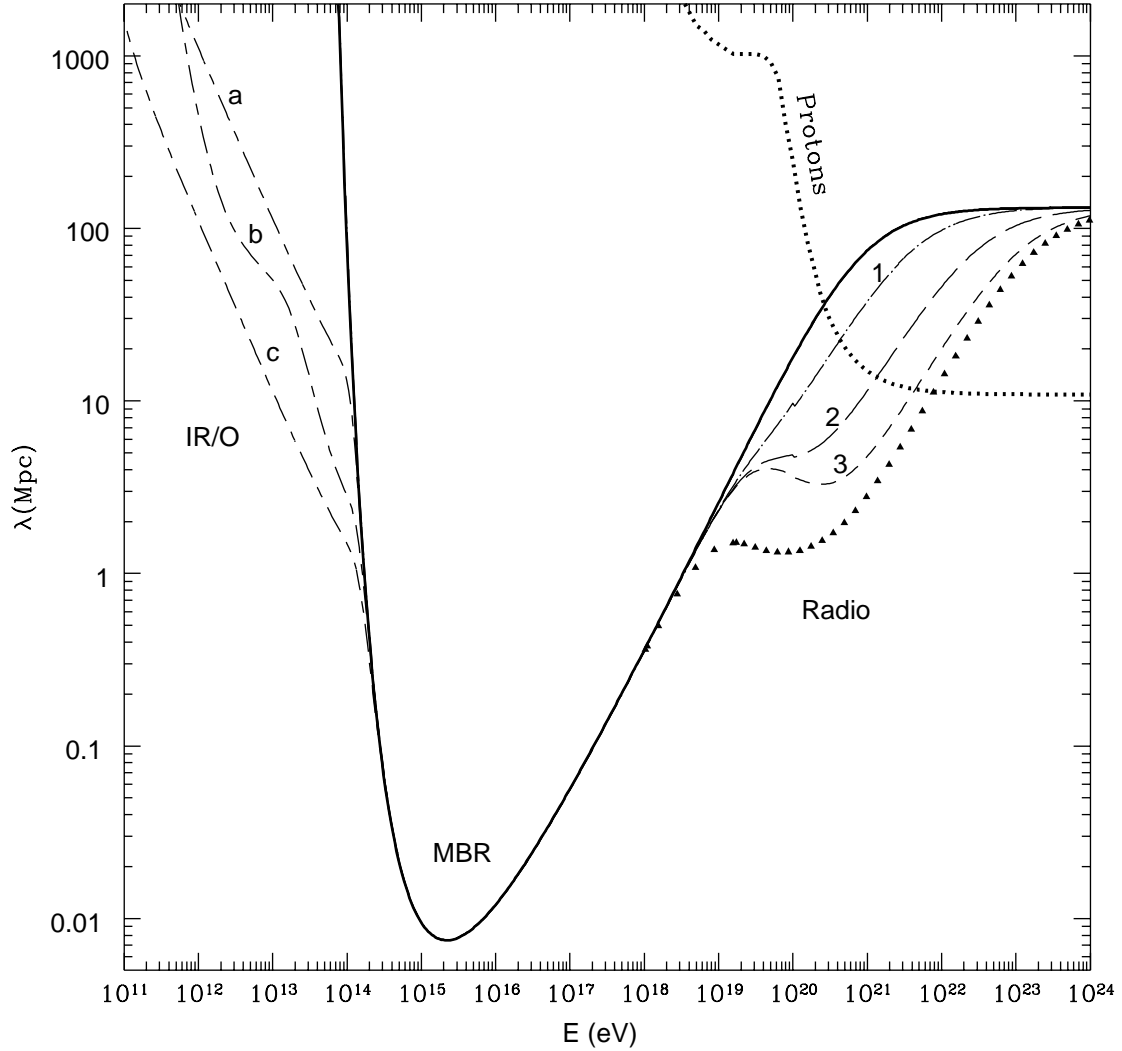


Fig. 1.— The current ( $z = 0$ ) pair-production mean free path,  $\lambda$ , for VHE photons of energy,  $E$ . Below  $10^{14}$  eV, VHE photons interact primarily with IR/O photons; above  $10^{19}$  eV they interact with radio photons, and in between, with MBR photons. Curves (a), (b), (c) respectively show  $\lambda$  for the IR/O backgrounds of curves (i), (iv), (vi) in Fig. 2. Curves (1),(2),(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 MHz, 2 MHz, 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.

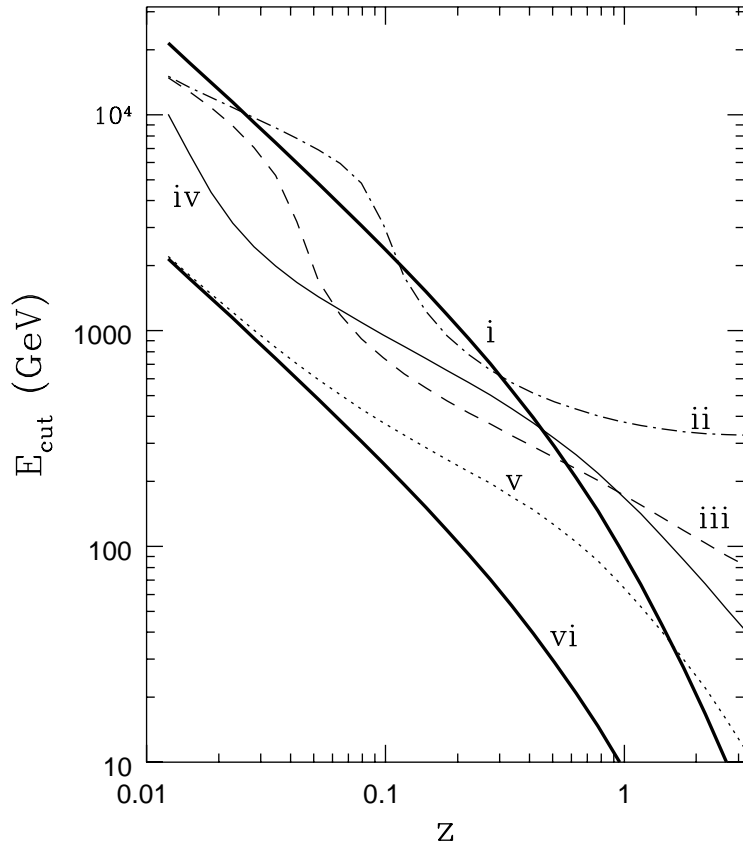


Fig. 2.— The absorption cutoff energy,  $E_{cut}$ , as a function of source redshift,  $z$ , for different IR/O background models.  $E_{cut}$  is defined by the condition  $\tau_{\gamma\gamma}[(1+z)E_{cut}, z] = 1$ , where  $\tau_{\gamma\gamma}$  is the optical depth for photon absorption via pair production. See text for a discussion of the specific DEBRA models shown. A flat universe with  $H_0 = 75$  was assumed for all calculations.

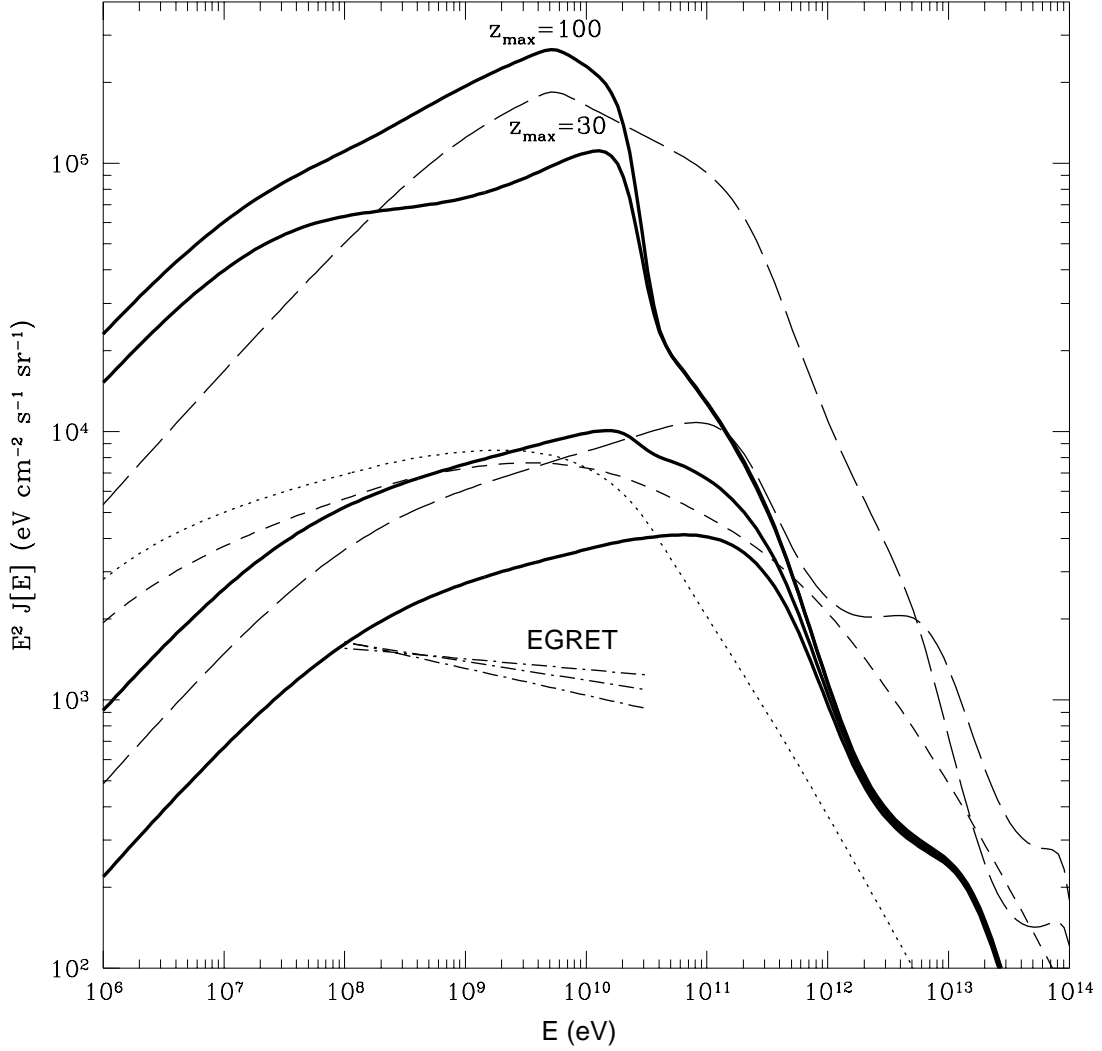


Fig. 3.— The VHE cascade background produced for different IR/O backgrounds and topological defect/particle decay rates. From bottom to top, the *heavy, solid* lines show the backgrounds normalized to a current VHE decay luminosity density of  $\dot{Q}_{e-m} = 1 \times 10^{-22} \text{ eVcm}^{-3}\text{s}^{-1}$  that increases with redshift as  $(1+z)^3$ ,  $(1+z)^{9/2}$  (the currently favored scenario), and  $(1+z)^6$ . The  $(1+z)^6$  case does not converge, and we truncate the integration at two different  $z_{\max}$ . The IR/O background 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.

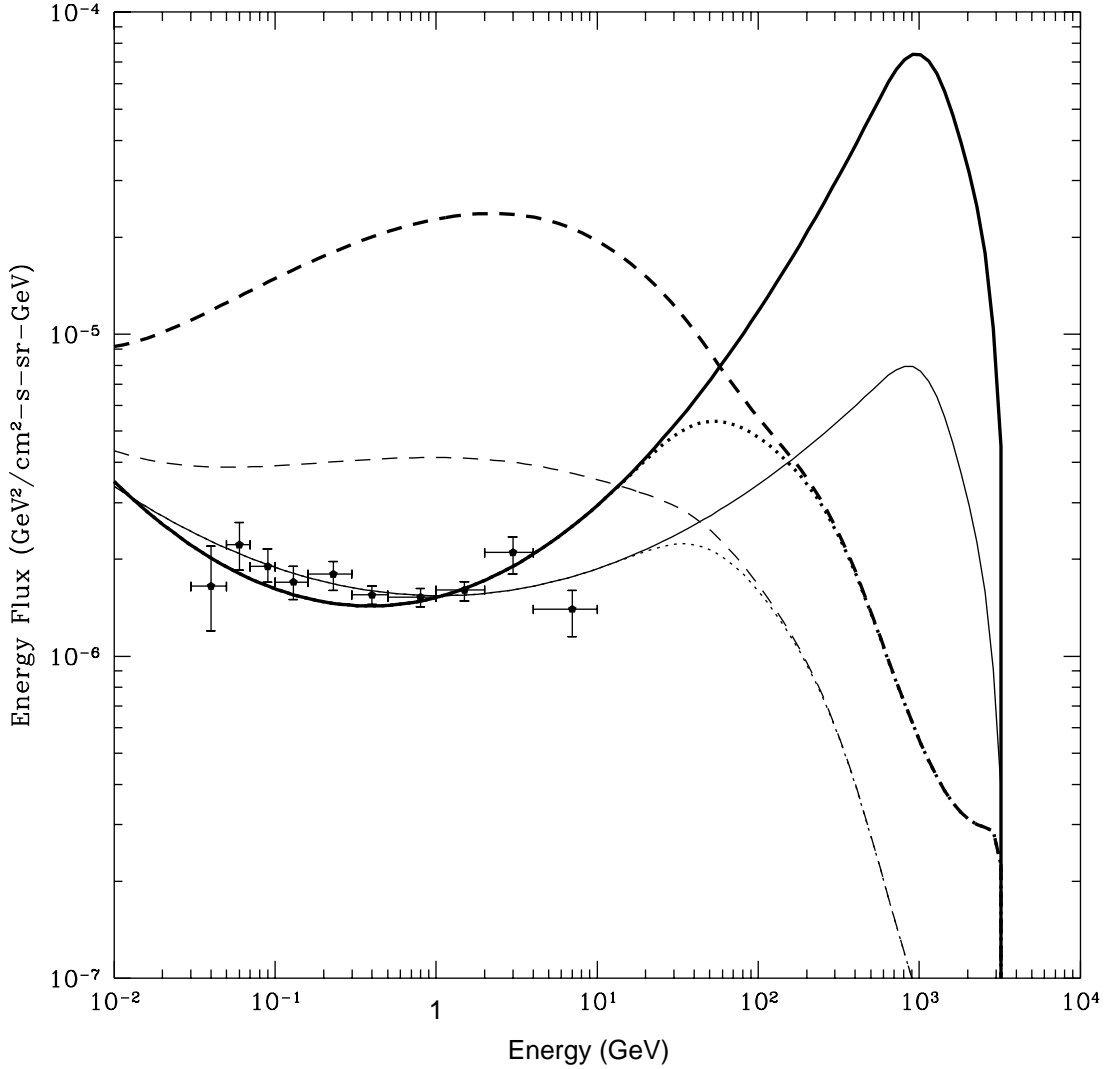


Fig. 4.— The diffuse  $\gamma$ -ray background produced by blazars. The *solid* lines show the same blazar  $\gamma$ -ray background calculation as Fig. 3 of Stecker & Salamon (1996), but assuming that a blazar spectrum is an unbroken power law up to 3 TeV and that the blazar spectral index distribution is a gaussian centered at  $\bar{\alpha} = -2.05$  with  $\sigma_{\alpha} = 0.25$  (*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).