

*Letter to the Editor***Absorption of very high energy gamma-rays
by intergalactic infrared radiation: A new determination**F.W. Stecker¹ and O.C. de Jager²¹ Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA² Space Research Unit, Department of Physics, Potchefstroom University for CHE, Potchefstroom 2520, South Africa

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Abstract. We present a new calculation of the intergalactic γ -ray pair-production absorption coefficient as a function of both energy and redshift. In reexamining this problem, we make use of a new *empirically* based calculation (as opposed to previous *model* calculations) of the intergalactic infrared radiation field (IIRF). We find smaller opacities than those given previously (Stecker & De Jager 1997). We apply our results to the new observations of the flaring γ -ray spectra of Mrk 421 and Mrk 501, both at a redshift of ~ 0.03 . Our new calculations indicate that there should be no significant curvature in the spectra of these sources for energies below 10 TeV, as indicated by recent observations. However, the intrinsic spectra of these sources should be harder by amounts of ~ 0.25 to 0.45 in the spectral index (in the 1–10 TeV range), with an intergalactic absorption cutoff above ~ 20 TeV.

Key words: γ -rays: theory – infrared: general – quasars: general – quasars: individual (Markarian 421, Markarian 501)

1. Introduction

We have previously pointed out (Stecker, De Jager & Salamon 1992 (hereafter, SDS92)) that very high energy γ -ray beams from blazars can be used to measure the intergalactic infrared radiation field, since pair-production interactions of γ -rays with intergalactic IR photons will attenuate the high-energy ends of blazar spectra. Determining the intergalactic IR field, in turn, allows us to model the evolution of the galaxies which produce it. As energy thresholds are lowered in both existing and planned ground-based air Cherenkov light detectors (Cresti 1996), cut-offs in the γ -ray spectra of more distant blazars are expected, owing to extinction by the IIRF. These can be used to explore the redshift dependence of the IIRF (Stecker & Salamon 1997; Salamon & Stecker 1998). Furthermore, by using blazars for a determination of attenuation as a function of redshift, combined with a direct observation of the IR background from the *DIRBE* detector on *COBE*, one can, in principle, measure of the Hubble

constant H_0 at truly cosmological distances (Salamon, Stecker & De Jager 1994).

There are now over 50 grazars which have been detected by the *EGRET* team (Thompson et al. 1996). These sources, optically violent variable quasars and BL Lac objects, have been detected out to a redshift greater than 2. Of all of the blazars detected by *EGRET*, only the low-redshift BL Lac, Mrk 421, has been seen by the Whipple telescope. The fact that the Whipple team did not detect the much brighter *EGRET* source, 3C279, at TeV energies (Vacanti et al. 1990, Kerrick et al. 1993) is consistent with the predictions of a cutoff for a source at its much higher redshift of 0.54 (see SDS92). So too is the recent observation of two other very close BL Lacs ($z < 0.05$), viz., Mrk 501 (Quinn et al. 1996) and 1ES2344+514 (Catanese et al. 1997) which were too faint at GeV energies to be seen by *EGRET*.

In this paper, we calculate the absorption coefficient of intergalactic space using a new, empirically based calculation of the spectral energy distribution (SED) of intergalactic low energy photons (Malkan & Stecker 1998; hereafter MS98) obtained by integrating luminosity dependent infrared spectra of galaxies over their luminosity and redshift distributions. After giving our results on the γ -ray optical depth as a function of energy and redshift out to a redshift of 0.3, we apply our calculations by comparing our results with recent spectral data on Mrk 421 as reported by McEnery et al. (1997) and spectral data on Mrk 501 given by Aharonian et al. (1997). The results presented here supersede those of our previous calculations (Stecker & De Jager 1997), which were based more on theoretical models (see discussion in MS98). We consider the results presented here to be considerably more reliable than any presented previously.

2. The opacity of intergalactic space to the IIRF

The formulae relevant to absorption calculations involving pair-production are given and discussed in SDS92. For γ -rays in the TeV energy range, the pair-production cross section is maximized when the soft photon energy is in the infrared range:

$$\lambda(E_\gamma) \simeq \lambda_e \frac{E_\gamma}{2m_e c^2} = 2.4 E_{\gamma, \text{TeV}} \mu\text{m} \quad (1)$$

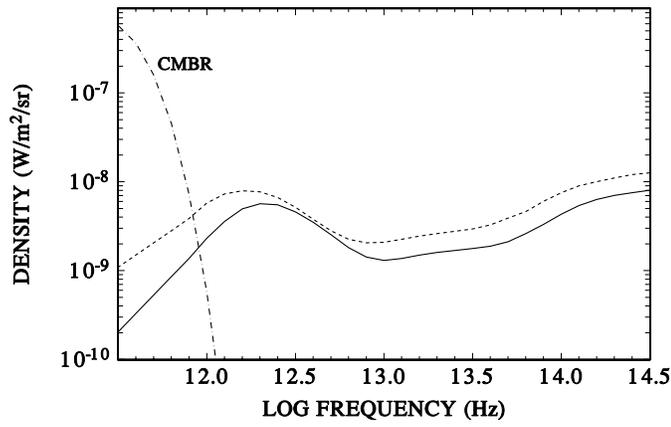


Fig. 1. The spectral energy distribution (SED) of the extragalactic IR radiation calculated by Malkan & Stecker (1997) with the 2.7 K cosmic background radiation spectrum added. The solid line (lower IIRF curve) and the dashed line (higher IIRF curve) correspond to the middle and upper curves calculated by Malkan & Stecker (1997) with redshift-evolution assumptions as described in the text.

Table 1. Polynomial coefficients a_{ij}

j	a_{0j}	a_{1j}	a_{2j}	a_{3j}
0	1.11(1.46)	-0.26(0.10)	1.17(0.42)	-0.24(0.07)
1	1.15(1.46)	-1.24(-1.03)	2.28(1.66)	-0.88(-0.56)
2	0.00(0.15)	-0.41(-0.35)	0.78(0.58)	-0.31(-0.20)

where $\lambda_e = h/(m_e c)$ is the Compton wavelength of the electron. For a 1 TeV γ -ray, this corresponds to a soft photon having a wavelength near the K-band ($2.2\mu\text{m}$). (Pair-production interactions actually take place with photons over a range of wavelengths around the optimal value as determined by the energy dependence of the cross section.) If the emission spectrum of an extragalactic source extends beyond 20 TeV, then the extragalactic infrared field should cut off the *observed* spectrum between ~ 20 GeV and ~ 20 TeV, depending on the redshift of the source (Stecker & Salamon 1997; Salamon & Stecker 1998, and this paper).

In our calculations, we make the reasonable simplifying assumption that the IIRF is basically in place at redshifts < 0.3 , having been produced primarily at higher redshifts (Madau 1996; Stecker & Salamon 1997; Salamon & Stecker 1998 and references therein). We therefore limited our calculations to $z < 0.3$. For a treatment of intergalactic absorption at higher redshifts by optical and UV photons using recent data on galaxy evolution at moderate and high redshifts, see Stecker & Salamon (1997) and Salamon & Stecker (1998).

We assume for the IIRF, two of the SEDs given in MS98 (shown in Fig. 1); the lower curve in Fig. 1 assumes evolution out to $z = 1$, whereas the upper curve assumes evolution out to $z = 2$. Evolution in stellar emissivity is expected to level off or decrease at redshifts greater than ~ 1.5 (Fall, Charlot & Pei 1996, Madau 1996), so that the two curves in Fig. 1 may be considered to be lower and upper limits, bounding the expected

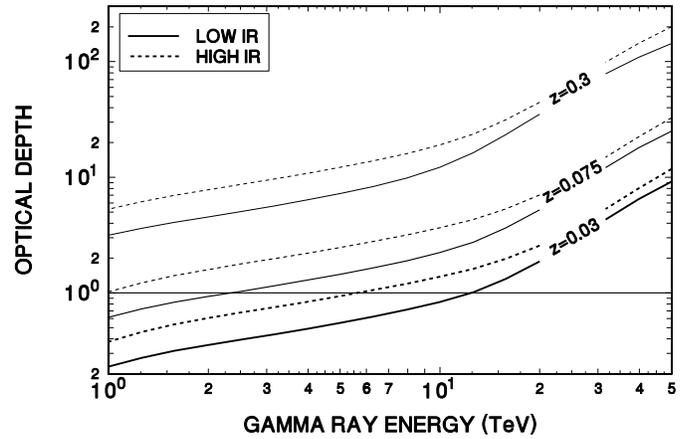


Fig. 2. Optical depth versus energy for γ -rays originating at various redshifts obtained using the SEDs corresponding to the lower IIRF (solid lines) and higher IIRF (dashed lines) levels shown in Fig. 1.

IR flux (MS98). Using these two SEDs for the IIRF, we have obtained parametric expressions for $\tau(E, z)$ for $z < 0.3$, taking a Hubble constant of $H_o = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Gratton et al. 1997). The double-peaked form of the SED of the IIRF requires a 3rd order polynomial to reproduce parametrically. It is of the form

$$\log_{10}[\tau(E_{\text{TeV}}, z)] \simeq \sum_{i=0}^3 a_i(z) (\log_{10} E_{\text{TeV}})^i$$

for $1.0 < E_{\text{TeV}} < 50$, (2)

where the z -dependent coefficients are given by

$$a_i(z) = \sum_{j=0}^2 a_{ij} (\log_{10} z)^j. \quad (3)$$

Table 1 gives the numerical values for a_{ij} , with $i = 0, 1, 2, 3$, and $j = 0, 1, 2$. The numbers before the brackets are obtained using the lower IIRF SED shown in Fig. 1; The numbers in the brackets are obtained using the higher IIRF SED. Because we are using real IRAS data to give more accurate estimates of the IIRF, we do not give values of τ for $E < 1$ TeV and for larger redshifts, which would involve interactions with starlight photons of wavelengths $\lambda \leq 1\mu\text{m}$. Eq. (2) approximates $\tau(E, z)$ correctly within 10% for all values of z and E considered.

Fig. 2 shows the results of our calculations of the optical depth for various energies and redshifts up to 0.3. Fig. 3 shows observed spectra for Mrk 421 (McEnery et al. 1997) and Mrk 501 (Aharonian et al. 1997) in the flaring phase, compared with best-fit spectra of the form $KE^{-\Gamma} \exp(-\tau(E, z = 0.03))$, with $\tau(E, z)$ given by the two appropriate curves shown in Fig. 2. Because $\tau < 1$ for $E < 10$ TeV, there is no obvious curvature in the *differential* spectra below this energy; rather, we obtain a slight steepening in the power-law spectra of the sources as a result of the weak absorption. This result implies that the *intrinsic* spectra of the sources should be harder by $\delta\Gamma \sim 0.25$ in the lower IIRF case, and ~ 0.45 in the higher IIRF case.

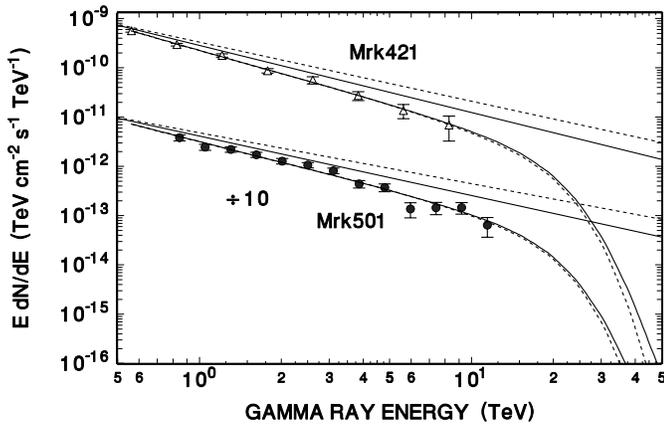


Fig. 3. The observed spectra of Mrk 421 from McEnery et al. (1997) (open triangles) and Mrk 501 from Aharonian et al. (1997) (solid circles – spectrum divided by 10). Best-fit absorbed spectra (of the form $KE^{-\Gamma} \exp(-\tau(E, z = 0.03))$) and unabsorbed spectra ($KE^{-\Gamma}$) for both sources are shown for τ corresponding to the lower IIRF SED (solid lines; $\Gamma = 2.36$ and 2.2 for Mrk 421 and Mrk 501 respectively) and higher IIRF SED (dashed lines; $\Gamma = 2.2$ and 2.03 for Mrk 421 and Mrk 501 respectively).

3. Discussion and conclusions

We have calculated the absorption coefficient of intergalactic space from pair-production interactions with low energy photons of the IIRF, both as a function of energy and redshift, using new, more reliable estimates of the SED for the IIRF which were obtained by MS98. Our results predict less absorption than we obtained previously (Stecker & De Jager 1997), because the MS98 IIRF is lower than our previous estimate. One reason for this difference is that our previous IIRF spectrum was normalized partly to reflect the estimate of Gregorich, et al. (1995) of the IIRF at $60 \mu\text{m}$. According to Bertin, Dennefeld & Moshir (1997), that estimate may have been based on the inclusion of false detections in their analysis of the IRAS data. For absorption calculations, it is important to use the most reliable estimate of the IIRF available, since the absorption effect depends exponentially on the magnitude of the IIRF. While we do not claim that our new results for the absorption coefficient as a function of energy differ dramatically from those obtained previously (MacMinn & Primack 1996; Stecker & De Jager 1997), we *do* claim that they are more reliable because they are based on the empirically derived IIRF given by MS98, whereas all previous calculations of TeV γ -ray absorption were based on theoretical modeling of the IIRF. The MS98 calculation was based on data from nearly 3000 IRAS galaxies. These data included (1) the luminosity dependent infrared SEDs of galaxies, (2) the $60 \mu\text{m}$ luminosity function of galaxies and, (3) the redshift distribution of galaxies.

We have applied our absorption calculations to recent flaring spectra of the nearby BL Lac objects Mrk 421 and Mrk 501.

The spectral calculations given here are in good agreement with the recent observations that indicate no significant curvature in the spectra of Mrk 421 and Mrk 501. The observations are also consistent with our calculated steepening of 0.25 to 0.45 in the spectral index of these sources in the 1–10 TeV range. Our new calculations predict a significant intergalactic absorption effect which should cut off the spectra of Mrk 421 and Mrk 501 at energies greater than ~ 20 TeV. Observations of these objects at large zenith angles, which give large effective threshold energies, may thus demonstrate the effect of intergalactic absorption.

Our new calculations confirm the conclusion in SDS92 that TeV spectra of sources at redshifts higher than 0.1 should suffer significant absorption. The recent detection of another XBL at a redshift below 0.1, *viz.*, 1ES2344+514 (Catanese et al. 1997), further supports the argument that nearby XBLs may be the only significant TeV sources presently detectable (Stecker, De Jager & Salamon 1996).

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