Extragalactic Absorption of High Energy Gamma-Rays

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The pair-production absorption of high-energy γ-rays by intergalactic low-energy photons is expected to produce a high-energy cutoff in the spectra of sources which is a sensitive function of redshift. We first discuss the expected absorption coefficient as a function of energy and redshift derived by Stecker and De Jager by making use of a new empirically based calculation of the spectral energy distribution of the intergalactic infrared radiation field as given by Malkan and Stecker. We then discuss the fact that new data on the high energy γ-ray source Mrk 501 appear to show the amount of intergalactic absorption predicted. The implications of this new HEGRA data, should they be confirmed, are significant for the astrophysics of this source, implying that (1) there is no significant intrinsic absorption inside the source, and (2) the physics of the emission spectrum produces a power-law to energies above 20 TeV. As a further test for intergalactic absorption, we give a predicted spectrum, with absorption included, for PKS 2155-304. This XBL lies at a redshift of 0.12, the highest redshift source yet observed at an energy above 0.3 TeV. We also discuss the determination of the γ-ray opacity at higher redshifts (out to $z = 3$), following the treatment of Salamon and Stecker.

I. INTRODUCTION

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 [1]. In recent years, this concept has been used successfully to place upper limits on the the intergalactic IR field (IIRF) [2] - [6]. Determining the (IIRF), 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 [7], cutoffs 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 [8], [9].

There are now 66 "grazars" (γ-ray blazars) which have been detected by the *EGRET* team [10]. These sources, optically violent variable quasars and BL Lac objects, have been detected out to a redshift greater that 2. Of all of the blazars detected by *EGRET*, only the low-redshift BL Lac, Mrk 421 ($z = 0.031$), has been seen by the Whipple telescope [11]. The fact that the Whipple team did not detect the much brighter *EGRET* source, 3C279, at TeV energies [12], [13] is consistent with the predictions of a cutoff for a source at its much higher redshift of 0.54 [1]. So too are the further detections of three other close BL Lacs ($z < 0.12$), *viz.*, Mrk 501 ($z = 0.034$) [14], 1ES2344+514 ($z = 0.044$) [15], and PKS 2155-304 ($z = 0.117$) [16] which were too faint at GeV energies to be seen by *EGRET*[1].

The formulae relevant to absorption calculations involving pair-production are given and discussed in Ref. [1]. 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:

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

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 (2.2μm). (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; see eq. (3).) If the emission spectrum of an extragalactic source extends beyond 20 TeV, then the extragalactic infrared field

[1] PKS 2155-304 was seen in one observing period by *EGRET* as reported in the Third EGRET Catalogue [10]

should cut off the *observed* spectrum between ~ 20 GeV and ~ 20 TeV, depending on the redshift of the source [8], [9].

II. ABSORPTION OF GAMMA-RAYS AT LOW REDSHIFTS

Stecker and De Jager [17] (hereafter SD98) have recalculated the absorption coefficient of intergalactic space using a new, empirically based calculation of the spectral energy distribution (SED) of intergalactic low energy photons by Malkan and Stecker [18] (hereafter MS98) obtained by integrating luminosity dependent infrared spectra of galaxies over their luminosity and redshift distributions. After giving their results on the γ-ray optical depth as a function of energy and redshift out to a redshift of 0.3, SD98 applied their calculations by comparing their results with the spectral data on Mrk 421 [19] and spectral data on Mrk 501 [20].

SD98 make the reasonable simplifying assumption that the IIRF is basically in place at a redshifts < 0.3, having been produced primarily at higher redshifts [21]. Therefore SD98 limited their calculations to $z < 0.3$. (The calculation of γ-ray opacity at higher redshifts [8], [9] will be discussed in the next section.)

SD98 assumed for the IIRF, two of the SEDs given in MS98 [18]. Their upper curve now appears to be in better agreement with lower limits from galaxy counts, with Keck telescope, *HST. NICMOS*, *ISO* and *SCUBA* studies of galaxies at high redshifts (Ref. [21] and references therein) and with *COBE* data [22] - [27] (see Figure 1).

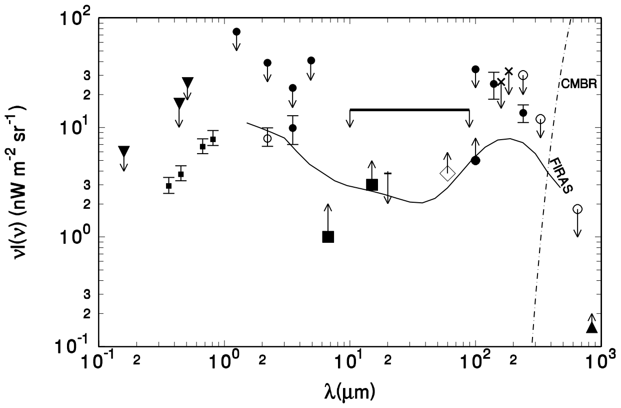


FIG. 1. The upper infrared SED from Malkan and Stecker compared with observational data and other constraints (courtesy O.C. De Jager).

The results of MS98 are also in agreement with upper limits obtained from TeV γ-ray studies [2] - [6]. This agreement is illustrated in Figure 1 which shows the upper SED curve from MS98 in comparison with various data and limits.

The SD98 results for the absorption coefficient as a function of energy do not differ dramatically from those obtained previously [28], [29]; however, 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 60μm luminosity function of galaxies and, (3) the redshift distribution of galaxies.

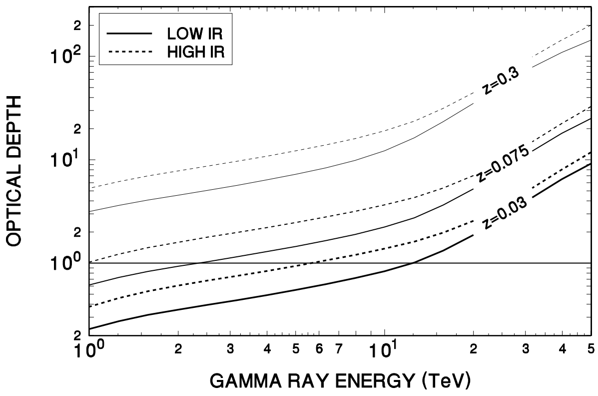


FIG. 2. Optical depth versus energy for γ-rays originating at various redshifts obtained using the SEDs corresponding to the lower IIRF (solid lines) and higher IIRF (dashed lines) levels shown in a Figure taken from SD98. As discussed in the text, the higher IIRF curves (dashed lines) are more in line with recent data.

The advantage of using empirical data to construct the SED of the IIRF, as done in MS98, is particularly indicated in the mid-ir range where galaxy observations indicate more flux from warm dust in galaxies than that taken account of in more theoretically oriented models. As a consequence, the mid-IR "valley" between the cold dust peak in the far IR and cool star peak in the near IR is partially filled in (see Figure 1). For a source at low redshift, it follows from eq. (1) that γ-rays of energy $\sim$ 20 TeV will be absorbed preferentially by photons in the wavelength range of this "valley", *i.e.*, near 50 μm. In this range, significant lower limits now exist which are near the predicted IIRF flux (see Figure 1).

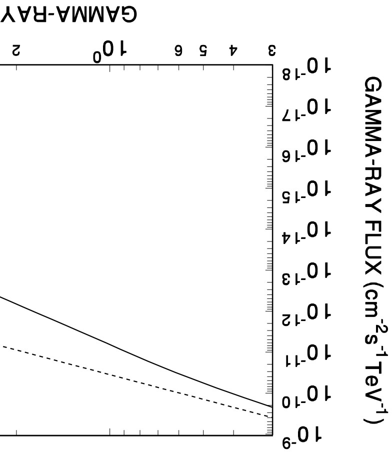
In fact, the observed flaring spectrum of Mrk 501 has been newly extended to an energy of 24 TeV by observations of the *HEGRA* group [30]. The new *HEGRA* data are well fitted by an E^{-2} source spectrum steepened at energies above a few TeV by intergalactic absorption with the optical depth calculated by SD98 [31]. Figure 3, taken from Ref. [31], clearly shows this. The philosophy behind Ref. [31] is that the existing lower limits on the mid-ir background flux predict a minimum expected absorption. The derived unabsorbed source spectrum then tells us (1) that there is negligible intrinsic absorption in the source, and (2) the physics of the emission mechanism should give a power-law spectrum with a spectral index of $\sim$2 up to an energy of at least $\sim$ 20 TeV.

Consider the source PKS 2155-304, an XBL located at a moderate redshift of 0.117, which has been reported by the Durham group to have a flux above 0.3 TeV of $\sim 4 \times 10^{-11}$ cm^{-2} s^{-1} [16]. We predict that this source should have its spectrum steepened by $\sim$ 1 in its spectral index between $\sim$ 0.3 and $\sim$ 3 TeV and should show an absorption turnover above $\sim$ 6 TeV as shown in Figure 4. Observations of the spectrum of this source should provide a further test for intergalactic absorption.

III. ABSORPTION OF GAMMA-RAYS AT HIGH REDSHIFTS

In order to calculate high-redshift absorption properly, it is necessary to determine the spectral distribution of the intergalactic low energy photon background radiation as a function of redshift as realistically as possible out to frequncies beyond the Lyman limit. This calculation, in turn, requires observationally based information on the evolution of the spectral energy distributions (SEDs) of IR through UV starlight from galaxies, particularly at high redshifts.

Salamon and Stecker [9] (hereafter SS98) have calculated the γ-ray opacity as a function of both energy and redshift for redshifts as high as 3 by taking account of the evolution of both the stellar population spectra and emissivity of galaxies with redshift. In order to accomplish this, they adopted the recent analysis of Fall, *et al.* [32] and also included the effects of metallicity evolution on galactic stellar population spectra. They then gave predicted γ-ray spectra for selected blazars and extend our calculations of the extragalactic γ-ray background from blazars to an energy of 500 GeV with absorption effects included.



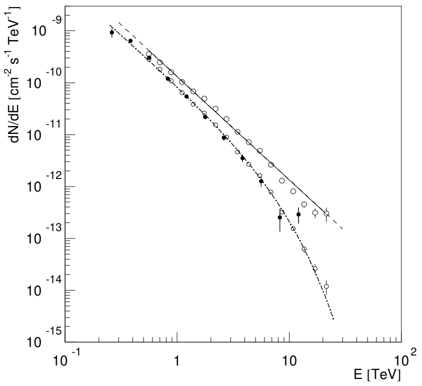


FIG. 3. The bottom curve and points show the new HEGRA data on Mrk 501 in the flaring state [30]; the upper line and points show the intrinsic spectrum of the source with the effect of the predicted extragalactic absorption removed [31].

FIG. 4. Predicted differential absorbed spectrum, for PKS 2155-304 (solid line) assuming an E^{-2} differential source spectrum (dashed line) normalized to the integral flux given in Ref. [16] (see text).

Fall, *et al.* [32] have devised a method for calculating stellar emissivity which bypasses the uncertainties associated with estimates of poorly defined luminosity distributions of evolving galaxies. The core idea of their approach is to relate the star formation rate directly to the evolution of the neutral gas density in damped Ly α systems, and then to use stellar population synthesis models to estimate the mean co-moving stellar emissivity $\mathcal{E}_\nu(z)$ of the universe as a function of frequency ν and redshift z.

The SS98 calculation of stellar emissivity closely follows this elegant analysis, with minor modifications. SS98 also obtained metallicity correction factors for stellar radiation at various wavelengths. Decreased metallicity at high redshifts gives a bluer stellar population spectrum [33], [34].

The stellar emissivity in the universe is found to peak at $1 \leq z \leq 2$, dropping off steeply at lower redshifts and more slowly at higher redshifts. Indeed, observational data from the Hubble Deep Field to show that metal production has a similar redshift distribution, such production being a direct measure of the star formation rate (see, *e.g.*, Ref. [21]).

With the co-moving energy density $u_\nu(z)$ evaluated [9] (SS98), the optical depth for γ-rays owing to electron-positron pair production interactions with photons of the stellar radiation background can be determined from the expression [1]

$$\tau(E_0, z_e) = c \int_0^{z_e} dz \, \frac{dt}{dz} \int_0^2 dx \, \frac{x}{2} \int_0^\infty d\nu \, (1+z)^3 \left[\frac{u_\nu(z)}{h\nu}\right] \sigma_{\gamma\gamma}(s) \tag{2}$$

where $s = 2E_0 h\nu x(1+z)$, E_0 is the observed γ-ray energy at redshift zero, ν is the frequency at redshift z, z_e is the redshift of the γ-ray source, $x = (1 - \cos\theta)$, and the pair production cross section $\sigma_{\gamma\gamma}$ is zero for center-of-mass energy $\sqrt{s} < 2m_e c^2$, m_e being the electron mass. Above this threshold,

$$\sigma_{\gamma\gamma}(s) = \frac{3}{16}\sigma_{\rm T}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right], \tag{3}$$

where $\beta = (1 - 4m_e^2 c^4/s)^{1/2}$.

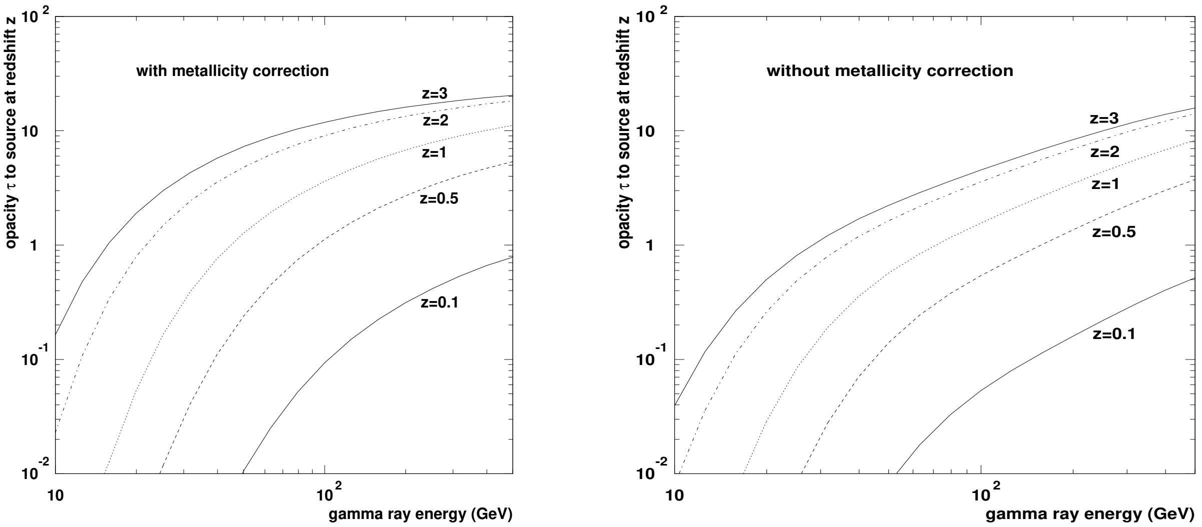


FIG. 5. The opacity τ of the universal soft photon background to γ-rays as a function of γ-ray energy and source redshift (from SS98) [9]. These curves are calculated with and without a metallicity correction.

Figure 5 shows the opacity $\tau(E_0, z)$ for the energy range 10 to 500 GeV, calculated by SD98 both with and without a metallicity correction. Extinction of γ-rays is negligible below 10 GeV. The weak redshift dependence of the opacity at the higher redshifts as shown in Figure 5 indicates that the opacity is not very sensitive to the initial epoch of galaxy formation, z_{max}. In fact, the uncertainty in the metallicity correction (see Figure 5) would obscure any dependence on z_{max} even further.

IV. THE EFFECT OF ABSORPTION ON THE SPECTRA OF BLAZARS AND GAMMA-RAY BURSTS

With the γ-ray opacity $\tau(E_0, z)$ calculated out to $z = 3$, the cutoffs in blazar γ-ray spectra caused by extragalactic pair production interactions with stellar photons can be predicted. Figure 6, based on the results given in Ref. [9] (SS98), shows the expected effect of the intergalactic radiation grazar and γ-ray burst spectra. This figure plots the critical energy for absorption (*i.e.*, for $\tau = 1$) versus redshift. For energies much above the critical energy, the optical depth is greater than 1, leading to a predicted cutoff in the spectrum of the extragalactic source.

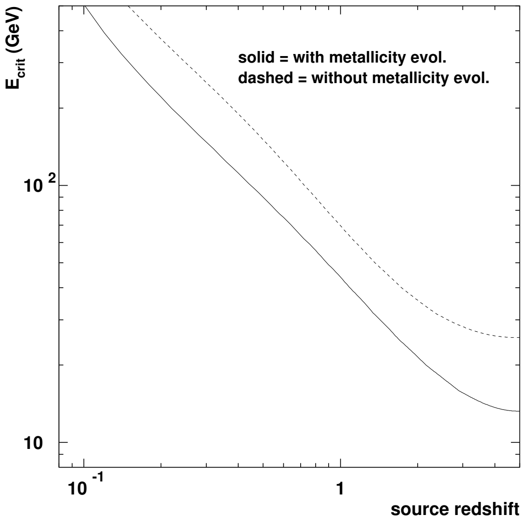


FIG. 6. The critcal energy for γ-ray absorption above which the optical depth is predicted to be greater than 1 as a function of the redshift of the source (from the results of SS98) [9] (see text).

The discovery of optical and X-ray afterglows of γ-ray bursts and the identification of host galaxies with measured redshifts (see, *e.g.*, Refs. [35] and [36]) has lead the accumulation of evidence that these bursts are highly relativistic fireballs originating at cosmological distances [37] and may be associated primarily with early star formation [38].

As indicated in Figure 6 γ-rays above an energy of $\sim$ 15 GeV will be attenuated if they at emitted at a redshift of $\sim$ 3. On 17 February 1994, the *EGRET* telescope observed a γ-ray burst which contained a photon of energy $\sim$ 20 GeV [39]. As an example, if one adopts the opacity results which include the metallicity correction, the highest energy photon in this burst would be constrained probably to have originated at a redshift less than $\sim$2. Future detectors such as *GLAST* Ref. [40], may be able to place better redshift constraints on bursts observed at higher energies. Such constraints may further help to identify the host galaxies of γ-ray bursts.

Observed cutoffs in grazar spectra may be intrinsic cutoffs in γ-ray production in the source, or may be caused by intrinsic γ-ray absorption within the source itself. In fact, models of quasar emission can predict natural cutoffs in quasar emission spectra in the relevant energy range above $\sim$ 10 GeV. Whether or not cutoffs in grazar spectra are primarily caused by intergalactic absorption can be determined by observing whether the grazar cutoff energies have the type of redshift dependence predicted here.

V. ACKNOWLEDGMENT

The work presented here was a result of extensive collaboration with O.C. De Jager, M.A. Malkan, and M.H. Salamon, as indicated in the references cited.

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