The Extragalactic Infrared Background and its Cosmological Implications
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TeV Gamma-Ray Absorption and the Intergalactic Infrared Background

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Abstract.

In this paper, I will take a synoptic approach to determining the intergalactic infrared radiation field (IIRF). This approach draws on both the multi-TeV γ-ray observations and the infrared background observations and relates them *via* the semi-empirical modelling method of Malkan & Stecker. I discuss the evidence for an intergalactic infrared background obtained by an analysis of the *HEGRA* observations of the high energy γ-ray spectrum of Mrk 501 and from constraints from Mrk 421 deduced from the Whipple air Cherenkov telescope results. I will show that this evidence is in accord with the predictions made by Malkan & Stecker (1998) for the intergalactic infrared spectral energy distribution produced by galaxies. The Malkan-Stecker predictions are also in excellent agreement with mid- and far infrared galaxy counts. However, there may be potential problems relating these predictions with the results of the analysis of *COBE-DIRBE* far infrared data. The γ-ray and *COBE-DIRBE* observations may also need to be reconciled. I will discuss possible ways to resolve this situation including a partial nullification of the γ-ray absorption process which can hypothetically occur if Lorentz invariance is broken.

1. Introduction

Shortly after the discovery that blazars can be strong sources of high energy γ-rays, we suggested 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 (Stecker, De Jager & Salamon 1992). In recent years, this concept has been used successfully to place upper limits on the the intergalactic IR field (IIRF) (Stecker & De Jager 1993; Dwek & Slavin 1994; Stecker & De Jager 1997; Stanev & Franceschini 1997; Biller *et al.* 1998). 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, 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.

On the other hand, by modelling the intergalactic infrared and optical radiation fields as a function of redshift, one can calculate the expected γ-ray opacity as a function of redshift and comparison of predicted absorption with the data can yield important new information about the evolution of the IIRF (Stecker & De Jager 1998; Salamon & Stecker 1998).

Exploring the IIRF with high energy γ-rays has both advantages and disadvantages over direct infrared observations. An important advantage is that since the absorption process only acts effectively in intergalactic space over large distances, the γ-ray approach does not suffer from problems of subtraction of foreground emission from both zodiacal light and interstellar dust in the Galaxy. As we have seen at this meeting, these can be formidable sources of uncertainty in determining the IIRF. Also, high energy γ-ray observations of blazar and γ-ray burst spectra at high redshifts can be used to probe the past evolution of the IIRF whereas direct infrared observations can only tell us about the present IIRF.

On the other hand, the disadvantage of the γ-ray approach is the uncertainty in the unabsorbed spectrum of the source. This uncertainty is somewhat ameliorated by the strong energy dependence of the absorption effect itself. Therefore, it is my contention that using both direct infrared and high energy γ-ray observations in a "synoptic" approach can yield the most information about the IIRF.

2. The Opacity of Intergalactic Space Owing to the IIRF

The formulae relevant to absorption calculations involving pair-production are given and discussed in Stecker, De Jager & Salamon (1992), where we derived the absorption formulae with cosmological and redshift effects included. 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:

$$\lambda(E_\gamma) \simeq \lambda_e \frac{E_\gamma}{4m_e c^2} = 1.24 E_{\gamma,TeV} \ \ \mu m \tag{1}$$

where $\lambda_e = h/(m_e c)$ is the Compton wavelength of the electron. For 15 TeV γ-rays, absorption will occur primarily by interactions with mid-infrared photons having a wavelength $\sim 20\mu$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; see eq. (11)).) 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 & de Jager 1998; Salamon & Stecker 1998).

3. Absorption of Gamma-Rays at Low Redshifts

Stecker & De Jager (1998) (hereafter SD98) have calculated 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

& Stecker (1998) (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, Stecker & De Jager (1998) (SD98) applied their calculations by comparing their results with the spectral data on Mrk 421 (McEnery *et al.* 1997) and spectral data on Mrk 501 (Aharonian, *et al.* 1997).

SD98 made the reasonable simplifying assumption that the IIRF is basically in place at a redshifts < 0.3, having been produced primarily at higher redshifts (Madau 1995; Salamon & Stecker 1998). Therefore SD98 limited their calculations to $z < 0.3$.

SD98 assumed for the IIRF, two of the spectral energy distributions (SEDs) given in MS98 (shown in Figure 1). The lower curve in Figure 1 (adapted from MS98) assumes luminosity evolution proportional to $(1+z)^{3.1}$ out to $z = 1$, whereas the middle curve assumes such evolution out to $z = 2$. Evolution in stellar emissivity is expected to level off at redshifts greater than ~ 1.5 (Steidel 1999; Hopkins, Connolley & Szalay 2000) Using these two SEDs for the IIRF, SD98 obtained parametric expressions for the optical depth $\tau(E_\gamma, z)$ for $z < 0.3$, taking a Hubble constant of $H_o = 65$ km s^{-1}Mpc^{-1} (Gratton 1997).

The double-peaked form of the SED of the IIRF requires a third order polynomial to approximate the opacity τ in a parametric form. SD98 give the following approximation:

$$log_{10}[\tau(E_{\rm TeV}, z)] \simeq \sum_{i=0}^{3} a_i(z)(\log_{10} E_{\rm TeV})^i \ \text{ for } \ 1.0 < E_{\rm TeV} < 50, \tag{2}$$

where the z-dependent coefficients are given by

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

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 Figure 1; The numbers in the brackets are obtained using the middle IIRF SED. Equation (2) approximates $\tau(E, z)$ to within 10% for all values of z and E considered. Figure 2 shows the results obtained by SD98 for $\tau(E_\gamma, z)$.

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)

The advantage of using empirical data to construct the SED of the IIRF, as done in MS98, is particularly indicated in the mid-infrared range. In this region of the spectrum, galaxy observations indicate more flux from warm dust in galaxies than that taken account of in more theoretically oriented models (*e,g,* MacMinn & Primack (1996)). As a consequence, the mid-infrared "valley"

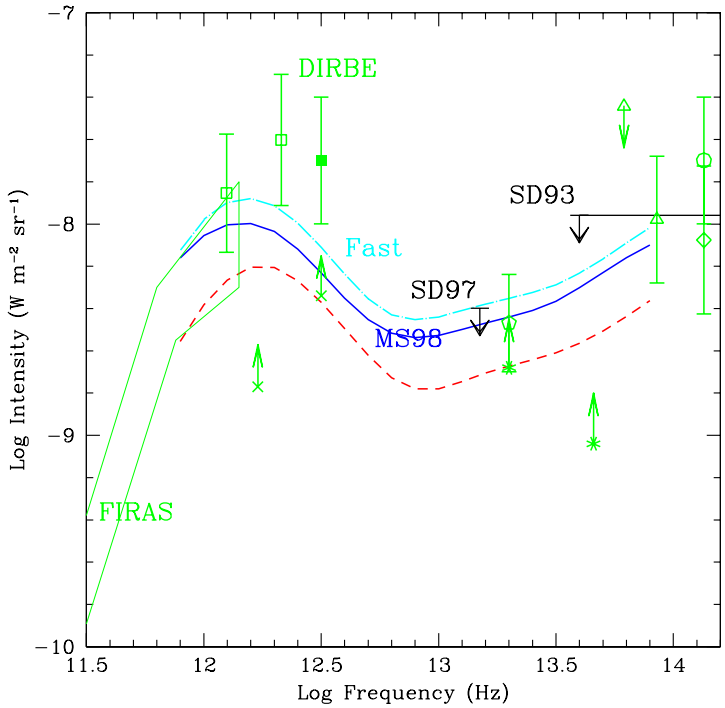

Figure 1. The spectral energy distribution (SED) of the extragalactic infrared radiation calculated by Malkan & Stecker (1998, 2000) The dashed line (lower IIRF curve) and the solid line (middle IIRF curve) correspond to the middle and upper curves calculated by Malkan & Stecker (1998) with redshift-evolution assumptions as described in the text. The dot-dashed line (Malkan & Stecker 2000) corresponds to a "fast evolution" case with $Q = 4.1$ and $z_{flat} = 1.3$. Representative data are also shown *with 2σ error bars* as follows. From left to right, *FIRAS* polygon: Fixsen *et al.* 1998, open squares: Hauser *et al.* (1998), solid square: Lagache *et al.* (2000), pentagon: Altieri *et al.* (1999), open triangles: Dwek and Arendt (1998), open circle: Gorjian, Wright & Chary (2000), diamond: Totani, *et al.* (2000) (see also Pozzetti *et al.* (2000). The lower limits with crosses are from *ISOPHOT* (Puget *et al.* 1999) and the lower limits with asterisks are from *ISOCAM* (Elbaz *et al.* (1999). The upper limits are from Stecker & de Jager (1993)(SD93) and Stecker & de Jager (1997)(SD97).

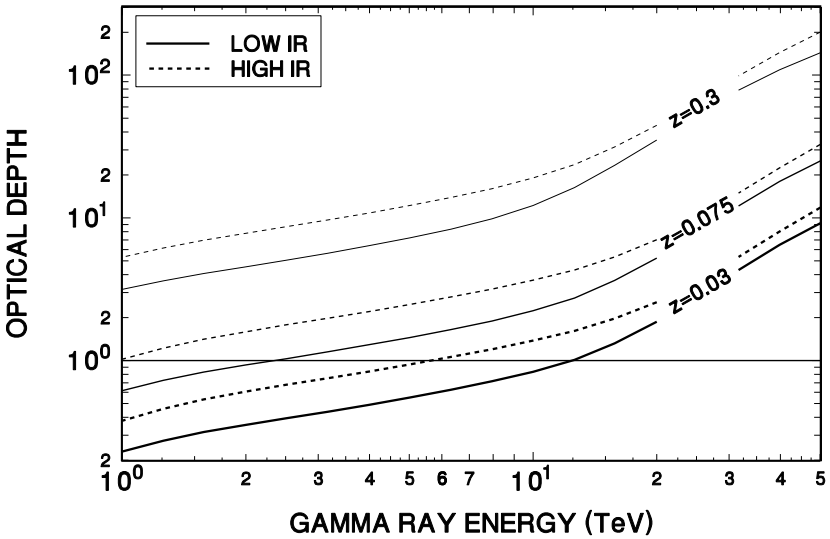

Figure 2. Optical depth versus energy for γ-rays originating at various redshifts obtained using the SEDs corresponding to the lower IIRF (solid lines) and middle IIRF (dashed lines) levels shown in Fig. 1 (from SD98). Note that the line styles in this Figure are the *reverse* of those in Figure 1.

between the cold dust peak in the far-infrared and cool star peak in the near IR is filled in more in the MS98 results and is not as pronounced as in previously derived models of the IR background SED. As can be seen in Figure 1, the background SED predicted in MS98 is in excellent agreement with the results obtained from ultradeep *ISOCAM* galaxy count observations at 15 μm (Altieri *et al.* 1999).

The SD98 calculations predict that intergalactic absorption should only slightly steepen the spectra of Mrk 421 and Mrk 501 below $\sim$ 7 TeV, which is consistent with the data in the published literature The SD98 calculations further predict that intergalactic absorption should turn over the spectra of these sources at energies greater than $\sim$ 15 TeV.

4. The Multi-TeV Spectrum of Mrk 501 and its Interpretation

The *HEGRA* group has observed the BL Lac object Mrk 501 in the flaring phase, obtaining an energy spectrum for this source up to an energy of 24 TeV (Aharonian *et al.* 1999). The Mrk 501 spectrum obtained by the *HEGRA* group are well fitted by a source spectrum power-law of spectral index $\sim$ 2 steepened

at in the multi-TeV energy range by intergalactic absorption, with the optical depth calculated by SD98 (Konopelko, *et al.* 1999). Figure 3 clearly shows this.

5. Reconciling the Infrared and Gamma-Ray Observations

Malkan & Stecker (2000) have used their empirically based model (MS98) to predict infrared luminosity functions and deep infrared galaxy counts at various wavelengths. They have also examined their predictions for the IIRF for comparison with the subsequent determinations from the *COBE-DIRBE* data analysis. Using the formalism of luminosity evolution proportional to $(1+z)^Q$ out to a redshift of z_{flat} and constant (no evolution) for $z_{flat} < z < z_{max} = 4$, they find that a comparison of their predictions with current *ISO* galaxy counts at 15 and 175μm favor their "Baseline Model" with $Q = 3.1$ and $z_{flat} = 2$ (the middle curve in Figure 1). The γ-ray limits (SD97) also favor $Q \sim 3$.

On the other hand, the *COBE-DIRBE* far infrared determinations seem to favor a stronger evolution with $Q > 4$ up to $z_{flat} = 1$. For example, the upper curve in Figure 1 (Malkan & Stecker 2000) assumes $Q = 4.1$ and $z_{flat} = 1.3$. This curve gives a flux in the mid-infrared which is a factor of $\sim$1.8 above the "Baseline Model" and would imply a corresponding increase in the opacity of the Universe to multi-TeV γ-rays. (Thus, one should multiply the appropriate bracketed numbers in Table 1 by a factor of 1.8) Therefore, τ(15 TeV) would increase from ~ 2 to ~ 4 in the case of Mrk 501 and Mrk 421 ($z \simeq 0.03$).

This *prima facie* conflict can be resolved in two ways: either (a) the *COBE-DIRBE* far-infrared estimates may suffer from undersubtraction of foreground emission and therefore are too high, or (b) the *ISOPHOT* galaxy counts may be missing a significant fraction of sources. In this later case, one may also have require that the γ-ray results are wrong in that the *HEGRA* energy determinations have been overestimated, mimicing the effect of absorption which would be produced by a lower IIRF. Another possibility is one involving new physics, *viz.* that Lorentz invariance may be broken, allowing the Universe to be transparent to multi-TeV photons (Coleman & Glashow 1999; Kifune 1999). This "new physics"scenario presents problems in that the Mrk 501 spectrum does exhibit exactly the characteristics expected for high-energy γ-ray absorption from pair-production (Konopelko *et al.* 1999). However, we will discuss this possibility more quantitatively in the next section (Glashow & Stecker 2000).

Possibility (a) finds support in the independent analysis of the *COBE* data by Lagache et al. (1999) who obtain a flux at 140 μm which is only 60% of the flux obtained by Hauser *et al.* (1998) shown in Figure 1. Lagache *et al.* (2000) also obtained a smaller flux at 240 μm. In this regard, one should also note that the results reported by Hauser *et al.* (1998) were at the 4σ level.

If the far-infrared galaxy counts are incomplete (possibility (b)), this would imply stronger evolution in the far-infrared emission of galaxies than in the mid-infrared. Although the MS98 model already includes some differential evolution of this type, based on the data of Spinoglio *et al.* (1995), it is conceivable that starburst galaxies at redshifts at ~ 1 might produce an even higher ratio of $\sim$ 60μm to $\sim$ 7μm rest-frame fluxes than their present-day counterparts. Radiation at these widely separated wavelengths is known to be emitted by quite different dust grains which could have different evolutionary development, particularly for

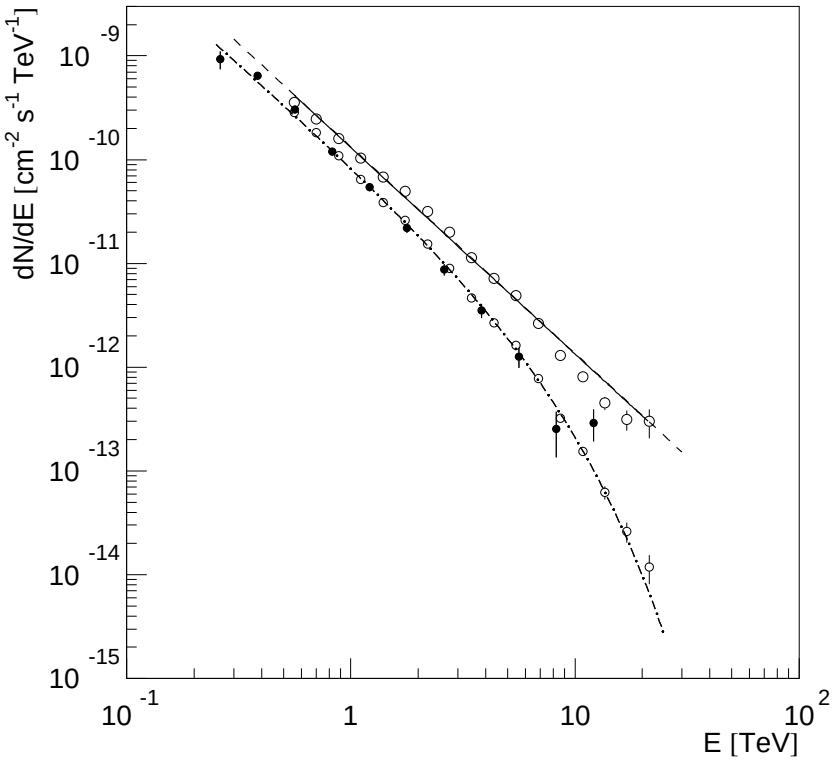

Figure 3. The *HEGRA* and Whipple telescope data on Mrk 501 in the flaring state is indicated by the lower line. The upper line and points show the intrinsic spectrum of the source with the effect of extragalactic absorption removed. The absorption is calculated using the middle line IIRF spectrum shown in Figure 1 (see also Figure 2) (From Konopelko *et al.* 1999).

ULIRGs (ultraluminous infrared galaxies) and AGN (active galactic nuclei). One should note that *this possibility can make the γ-ray and infrared data compatible*, since absorption of $\sim$ 15 TeV γ-rays is caused by interactions with mid-infrared ($\sim 20\mu$m) photons and not 140μm far-infrared photons.

6. Breaking Lorentz Invariance

With the idea of spontaneous symmetry breaking in particle physics came the suggestion that Lorentz invariance (LI) might be weakly broken at high energies (Sato & Tati 1972). Although no real quantum theory of gravity exists, it was suggested that LI might be broken as a consequence of such a theory (Amelino-Camilia *et al.* 1998). A simpler formulation for breaking LI by a small first order perturbation in the electromagnetic Lagrangian which leads to a renormalizable treatment has been given by Coleman & Glashow (1999). The breaking of LI at high energies is one way of avoiding the predicted, but unseen, "GZK" cutoff in the ultrahigh energy cosmic-ray spectrum owing to photomeson interactions with 2.7K cosmic background photons (Greisen 1966; Zatsepin & Kuz'min 1966), which produces an effective absorption mean-free-path for ultrahigh energy cosmic rays in intergalactic space of < 100 Mpc (Stecker 1968).

It has recently been suggested that LI breaking could also make the universe transparent to high energy γ-rays (Kifune 1999). Such LI breaking implies a perferred frame of reference in the Universe which would naturally be associated with a rest frame for the 2.7K cosmic background radiation. We follow here the formalism proposed by Coleman & Glashow (1999) for LI breaking. Within this scenario, the maximum attainable velocity of an electron, $c_e \neq c_\gamma$, the velocity of the photon. Let us consider the case where $c_e > c_\gamma$ and we define

$$c_e \equiv c_\gamma(1+\delta) \ , \qquad \delta \ll 1 \tag{4}$$

In this case, electrons above an energy $E_{max} = \gamma_{max} m_e$ will be superluminal. They will radiate Cherenkov light if their velocity is large enough, *i.e.*, if $\beta > (c_\gamma/c_e)$ which implies that $\gamma_e^2 > [1-(c_\gamma/c_e)^2]^{-1}$. This determines the maximum electron energy above which electrons would rapidly lose energy by Cherenkov radiation:

$$E_{max} = m_e(2\delta)^{-1/2} \tag{5}$$

(In this section, we adopt the standard paticle physics convention $c = 1$.) Since electrons are seen in the cosmic radiation up to an energy $\sim$ 1 TeV, this implies that $E_{max} > 1$ TeV which gives an upper limit on δ of 1.3×10^{-13}.

If LI is broken so that $\delta > 0$, the threshold energy for the pair production process is altered because the square of the four-momentum becomes

$$2\epsilon E_\gamma(1-\cos\theta) - 2E_\gamma^2\delta = 4\gamma^2 m_e^2 > 4m_e^2 \tag{6}$$

where ϵ is the energy of the low energy (infrared) photon and θ is the angle between the two photons. The second term on the left-hand-side comes from the fact that $c_\gamma = \partial E_\gamma/\partial p_\gamma$.

For head-on collisions ($\cos\theta = -1$) the minimum low energy photon energy for pair production becomes

$$\epsilon_{min} = m_e^2/E_\gamma + (E_\gamma \delta)/2 \tag{7}$$

It follows that the condition for a significant increase in the energy threshold for pair production is

$$(E_\gamma \delta)/2 \geq m_e^2/E_\gamma \tag{8}$$

or, equivalently, δ must be greater than $2m_e^2/E_\gamma^2$.

Thus, for a significant decrease in the optical depth to Mrk 501 for $E_\gamma = 15$ TeV, we must have $\delta \geq 2.4 \times 10^{-15}$.

The effect of breaking LI is to exclude photons of energy below ϵ_{min} from pair producing, thus reducing the number of target photons. In this way, one can exclude the high flux of far-infrared photons implied by the *COBE-DIRBE* analysis from participating in the absorption process while still allowing mid-infrared photons to produce an absorption feature.

One can rule out this hypothesis is if one observes electrons with energies $\gg 1$ TeV. This would reduce the upper limit on δ to the point where there will be no significant reduction in absorption by pair-production interactions with infrared photons.

On the other hand, if one observes γ-rays above 100 TeV from an extragalactic source, this would be strong evidence for LI breaking. This is because the very large density ($\sim$ 400 cm^{-3}) of 3K cosmic microwave photons would otherwise absorb $>$ 100 TeV γ-rays within a distance of $\sim$ 10 kpc (see eq. (1)).

Finally, we note that even if absorption is reduced in Mrk 501, one can still have absorption in sources at higher redshifts owing to interactions with higher energy photons (see next section).

7. Absorption of Gamma-Rays at High Redshifts

We now discuss the absorption of 10 to 500 GeV γ-rays at high redshifts. In order to calculate such 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.

Conversely, observations of high-energy cutoffs in the γ-ray spectra of blazars as a function of redshift, which may enable one to separate out intergalactic absorption from redshift-independent cutoff effects, could add to our knowledge of galaxy formation and early galaxy evolution. In this regard, it should be noted that the study of blazar spectra in the 10 to 300 GeV range is one of the primary goals of a next generation space-based γ-ray telescope *GLAST* (Gamma-ray Large Area Space Telescope) (Bloom 1996) as well as *VERITAS* and other future ground based γ-ray telescopes.

Salamon and Stecker (1998) (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 SED and emissivity of galaxies with redshift. In order to accomplish this, they adopted the recent analysis of Fall *et al.* (1996)

and also included the effects of metallicity evolution on galactic SEDs. Their results indicate that the extragalactic γ-ray background spectrum from blazars should steepen significantly above 20 GeV, owing to extragalactic absorption. Future observations of such a steepening would thus provide a test of the blazar origin hypothesis for the γ-ray background radiation.

7.1. Redshift Dependence of the Intergalactic Low Energy SED

Pei and Fall (1995) 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 Lyman 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.

Damped Lyman α systems are high-redshift clouds of gas whose neutral hydrogen surface density is large enough ($> 2\times10^{20}$ cm^{-2}) to generate saturated Lyman α absorption lines in the spectra of background quasars that happen to lie along and behind common lines of sight to these clouds. These gas systems are believed to be either precursors to galaxies or young galaxies themselves, since their neutral hydrogen (HI) surface densities are comparable to those of spiral galaxies today, and their co-moving number densities are consistent with those of present-day galaxies (Worthy 1986; Pei & Fall 1995). It is in these systems that initial star formation presumably took place, so there is a relationship between the mass content of stars and of gas in these clouds; if there is no infall or outflow of gas in these systems, the systems are "closed", so that the formation of stars must be accompanied by a reduction in the neutral gas content. Such a variation in the HI surface densities of Lyman α systems with redshift is seen, and is used by Pei and Fall (1995) to estimate the mean cosmological rate of star formation back to redshifts as large as $z = 5$.

Following Fall, Charlot & Pei (1996), SS98 used the Bruzual-Charlot model (Charlot & Bruzual 1991; Bruzual & Charlot 1993) corresponding to a Salpeter stellar initial mass function, $\phi(M)\,dM \propto M^{-2.35}\,dM$, where $0.1M_\odot < M < 125M_\odot$. The mean co-moving emissivity $\mathcal{E}_\nu(t)$ was then obtained by convolving over time t the specific luminosity with the mean co-moving mass rate of star formation. SS98 also obtained metallicity correction factors for stellar radiation at various wavelengths. Increased metallicity gives a redder population spectrum (Worthy 1994; Bertelli, *et al.* 1994).

SS98 calculated stellar emissivity as a function of redshift at 0.28 μm, 0.44 μm, and 1.00 μm, both with and without a metallicity correction. Their results agree well with the emissivity obtained by the Canada-French Redshift Survey (Lilly, *et al* 1996) over the redshift range of the observations ($z \leq 1$).

The stellar emissivity in the universe is found to peak at $1 \leq z \leq 2$, dropping off steeply at lower reshifts and more slowly at higher redshifts. Indeed, Madau, Pozzetti & Dickinson (1998) have used 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.

The co-moving radiation energy density $u_\nu(z)$ is the time integral of the co-moving emissivity $\mathcal{E}_\nu(z)$,

$$u_\nu(z) = \int_z^{z_{\max}} dz'\, \mathcal{E}_{\nu'}(z') \frac{dt}{dz}(z') e^{-\tau_{\rm eff}(\nu,z,z')}, \tag{9}$$

where $\nu' = \nu(1+z')/(1+z)$ and $z_{\max}$ is the redshift corresponding to initial galaxy formation. The extinction term $e^{-\tau_{\rm eff}}$ accounts for the absorption of ionizing photons by the clumpy intergalactic medium (IGM) that lies between the source and observer. Although the IGM is effectively transparent to non-ionizing photons, the absorption of photons by HI, HeI and HeII can be considerable (Madau 1995).

7.2. The Gamma-Ray Opacity at High Redshifts

SS98 evaluated the co-moving energy density $u_\nu(z)$ using equation (9) above. They then calculated the optical depth for γ-rays owing to electron-positron pair production interactions with photons of the stellar radiation background. This can be determined from the expression (Stecker, De Jager & Salamon 1992)

$$\tau(E_0, z_e) = c \int_0^{z_e} dz\, \frac{dt}{dz} \int_0^2 dx\, \frac{x}{2} \int_0^\infty d\nu\, (1+z)^3 \left[\frac{u_\nu(z)}{h\nu}\right] \sigma_{\gamma\gamma}(s) \tag{10}$$

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, $x = (1-\cos\theta)$, θ being the angle between the γ-ray and the soft background photon, h is Planck's constant ($\epsilon = h\nu$), 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,

$$\sigma_{\gamma\gamma}(s) = \frac{3}{16}\sigma_{\rm T}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right], \tag{11}$$

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

Figure 4, based on the results of SS98, shows the predicted critical energy for a 1/e absorption by pair production versus redshift obtained for the cases of correction for metallitcity evolution and no correction. Absorption of γ-rays of energies below $\sim$15 GeV is negligible.

The weak redshift dependence of the opacity at the higher redshifts, as shown in Figure 4, indicates that the opacity is not very sensitive to the initial epoch of galaxy formation, contrary to the speculation of MacMinn and Primack (1996). In fact, the uncertainty in the metallicity correction (see Figure 4) would obscure any dependence on z_{max} even further.

7.3. The Effect of Absorption on the Spectra of Blazars and the Gamma-Ray Background

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. The left graph in Figure 5, from SS98, shows the effect of the intergalactic radiation background on a few of the blazars observed

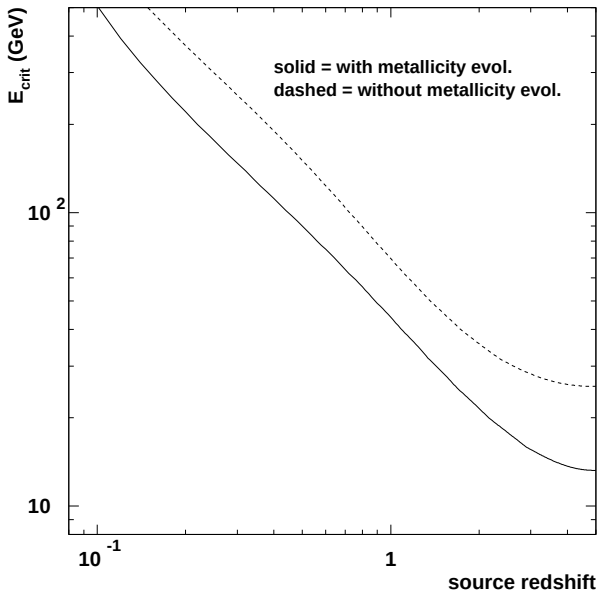

Figure 4. The critical energy for γ-ray absorption above which the optical depth is predicted to be greater than 1 as a function of the redshift of the source (obtained from the results of SS98).

by *EGRET*, *viz.*, 1633+382, 3C279, 3C273, and Mrk 421, assuming that the mean spectral indices obtained for these sources by *EGRET* extrapolate out to higher energies attenuated only by intergalactic absorption. (Observed cutoffs in blazar 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.)

The right hand graph in Figure 5 shows the background spectrum predicted from unresolved blazars (Stecker & Salamon 1996; Salamon & Stecker 1998) compared with the *EGRET* data (Sreekumar, *et al.* 1998). Note that the predicted spectrum steepens above 20 GeV, owing to extragalactic absorption by pair-production interactions with intergalactic optical and infrared photons, particularly at high redshifts.

8. Conclusions

Studies of the absorption of high energy γ-rays in the spectra of extragalactic objects can be used to probe both the present intergalactic infrared background and the infrared and optical radiation that existed in intergalactic space at higher redshifts. The results of such observations are free of the effects of solar system and galactic foreground contamination. Such studies are most effective when combined with direct infrared observations in a synoptic approach.

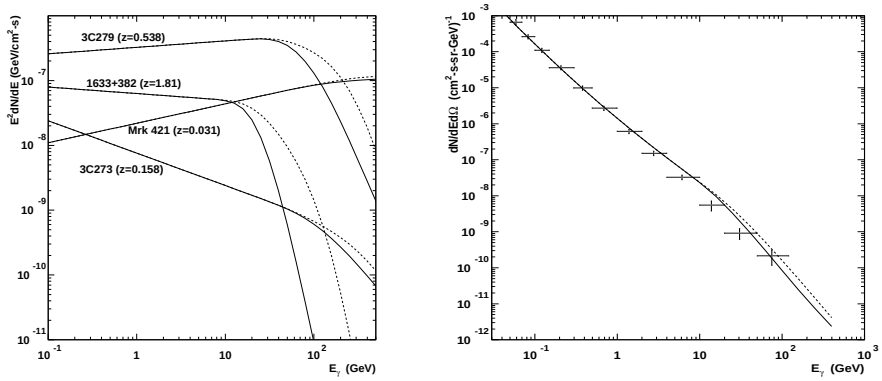

Figure 5. The left graph shows the effect of intergalactic absorption by pair-production on the power-law spectra of four prominent blazars: 1633+382 ($z = 1.81$), 3C279 ($z = 0.54$), 3C273 ($z = 0.15$), and Mrk 421 ($z = 0.031$); The right graph shows the extragalactic γ-ray background spectrum predicted by the unresolved blazar model of Stecker & Salamon (1996) with absorption included, calculated for a mean *EGRET* point-source sensitivity of 10^{-7} cm^{-2}s^{-1}, compared with the *EGRET* data on the γ-ray background (Sreekumar *et al.* 1998). The solid (dashed) curves are calculated with (without) the metallicity correction function (from SS98).

High energy γ-ray observations have already provided the best constraints on the mid-infrared background and they support a galaxy evolution scenario where emissivity evolution in the mid-infrared evolved as $\sim (1+z)^Q$ with $Q \sim 3$. This is consistent with observations of galaxy counts using *ISOCAM*. On the other hand, the analysis of *COBE-DIRBE* observations favors a stronger evolution in far-infrared emissivity with $Q > 4$.

There are various possible interpretations of these results; among them is the possibility that special relativity is modified at high energies. Future γ-ray and infrared observations will be needed to resolve this situation.

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References

Aharonian, F. *et al.* 1997, A&A 327, L5

Aharonian, F. *et al.* 1999, A&A 342, 69

Altieri, B. *et al.* 1999, A&A 343, L65

Amelino-Camilia, G., *et al.* 1998, Nature 393, 763

Bertelli, G. *et al.* 1994, A&AS 106, 275.

Bertin, E., Dennefeld, M. & Moshir M. 1997, A&A 323, 685

Biller, S.D. *et al.* 1998, Phys. Rev. Lett. 80, 2992

Blain, A.W. & Natarajan, P. 2000, MNRAS, 312, L39

Bloom, E.D. 1996, Space Sci.Rev. 75, 109

Bruzual, A.G. & Charlot, S. 1993, ApJ 457, 538

Charlot, S. & Bruzual A.G. 1991, ApJ 405, 625

Coleman, S. & Glashow, S.L. 1999, Phys.Rev.D59, 116008

Dwek, E. & Arendt, R. 1998, ApJ 508, L9

Dwek, E. & Slavin, J. 1994, ApJ 436, 696.

Elbaz, D. *et al.* 2000, A & A Letters, in press, e-print astro-ph/9910496

Fall, S.M., Charlot, S. & Pei, Y.C., 1996 ApJ , 464, L43

Fixsen, D.J. *et al.* 1998, ApJ 508, 123

Franceschini, A., *et al.* 1998, MNRAS 296, 709

Glashow, S.L. & Stecker, F.W. 2000, in preparation

Gorjian, V., Wright, E.L. & Chary, R.R. 2000, ApJ, 536, 550

Gratton, R.G. *et al.* 1997, PASP 402, 651

Greisen, K. 1966, Phys.Rev.Lett 16, 148

Hauser, M., *et al.* 1998, ApJ 508, 25

Hopkins, A.M., Connelly, A.J. & Szalay, A.S. 2000, AJ, in press, e-print astro-ph/0009073

Kifune, T. 1999, ApJ 518, L21

Konopelko, A.K. Kirk, J.G., Stecker, F.W. & Mastichiadas, A. 1999, ApJ 518, L13

Lagache, G., Haffner, L.M., Reynolds, R.J. & Tufte, S.L. 2000, A & A 354, 247

Lawrence, A. *et al.* 1986, MNRAS 219, 687

Lilly, S.J. *et al.* 1996, ApJ 460, L1

MacMinn, D. & Primack, J.R. 1996, Space Sci.Rev. 75, 413

Madau, P. 1995, ApJ 441, 18

Madau, P. Pozzetti, L. & Dickinson, M. 1998, ApJ 498, 106

Malkan, M.A. & Stecker, F.W. 1998, ApJ 496, 13 (MS98)

Malkan, M.A. & Stecker, F.W. 2000, e-print astro-ph/0009500, submitted to ApJ

McEnery, J.E. *et al.* 1997, Proc. 25th Intl. Cosmic Ray Conf., Durban, S.A. 3, 257

Pei, Y.C. & Fall, S.M. 1995, ApJ 454, 69

Pozzetti, L. *et al.* 2000, in *The Extragalactic Background and its Cosmological Implications*, IAU Symp. Vol. 204, ed. M. Harwit and M.G. Hauser, in press

Puget, J.L. *et al.* 1999, A & A 354, 29

Salamon, M.H. & Stecker, F.W. 1998, ApJ 493, 547 (SS98)

Sato, H. & Tati, T. 1972, Prog. Theor. Phys. 47, 1788

Sreekumar, P. *et al.* 1998, ApJ 494, 523

Spinoglio, L. *et al.* 1995, ApJ 453, 616

Stanev, T. & Franceschini, A. 1998, ApJ 494, 159

Stecker, F.W. 1968, Phys.Rev.Lett 21, 1016

Stecker, F.W. & De Jager, O.C. 1993, ApJ 415, L71

Stecker, F.W. & De Jager, O.C. 1997, in *Towards a Major Atmospheric Cerenkov Detector V*, Proc. Kruger National Park Workshop on TeV Gamma Ray Astrophysics, ed. O.C. De Jager (Potchefstroom: Wesprint) pg. 39

Stecker, F.W. & De Jager, O.C. 1998, A&A 334,L85 (SD98)

Stecker, F.W., O.C. De Jager, O.C. & Salamon, M.H. 1992, ApJ 390, L49

Stecker, F.W., O.C. De Jager, O.C. & Salamon, M.H. 1996, ApJ 473, L75

Stecker, F.W. & Salamon, M.H. 1996, ApJ 464, 600

Steidel, C.C. *et al.* 1999, ApJ 519, 1

Totani, T. *et al.* in *The Extragalactic Background and its Cosmological Implications*, IAU Symp. Vol. 204, ed. M. Harwit and M.G. Hauser, in press

Worthey, G. 1994, ApJS 95, 107.

Xu, C. *et al.* 1998, ApJ 508, 576

Zatsepin, G.T. & Kuz'min, V.A. 1966, JETP Lett 4, 78