INTergALACTIC PHOTON SPECTRA FROM THE FAR IR TO THE UV LYMAN LIMIT FOR 0 < Z < 6 AND THE OPTICAL DEPTH OF THE UNIVERSE TO HIGH ENERGY GAMMA-RAYS

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ABSTRACT

We calculate the intergalactic photon density as a function of both energy and redshift for 0 < z < 6 for photon energies from .003 eV to the Lyman limit cutoff at 13.6 eV in a ΛCDM universe with ΩΛ = 0.7 and Ωm = 0.3. The basic features of our backwards evolution model for galaxies were developed in Malkan and Stecker (1998 and 2001). With a few improvements, we find that this evolutionary model gives predictions of new deep number counts from Spitzer as well as a calculation spectral energy distribution of the diffuse infrared background which are in good agreement with the data. We then use our calculated intergalactic photon densities to extend previous work on the absorption of high energy γ-rays in intergalactic space owing to interactions with low energy photons and the 2.7 K cosmic microwave background radiation. We calculate the optical depth of the universe, τ, for γ-rays having energies from 4 GeV to 100 TeV emitted by sources at redshifts from 0 to 5. We also give an analytic fit with numerical coefficients for approximating τ(Eγ, z). As an example of the application of our results, we calculate the absorbed spectrum of the blazar PKS 2155-304 at z = 0.117 and compare it with the spectrum observed by the H.E.S.S. air Cherenkov γ-ray telescope array.

1. INTRODUCTION

The potential importance of the photon-photon pair production process in high energy astrophysics was first pointed out by Nikishov (1962) before the discovery of the CMB (2.7 K cosmic microwave background). However, his early paper overestimated the energy density of intergalactic starlight radiation by three orders of magnitude. With the discovery of the CMB, Gould & Schrader (1966) and Jelly (1966) showed that the universe would be opaque to γ-rays of energy above 100 TeV at extragalactic distances. Stecker (1969) and Fazio & Stecker (1970) included cosmological and redshift effects, showing that photons from a γ-ray source at a redshift zγ above an energy ~ 100(1 + zγ)−2 TeV would be significantly absorbed by pair production interactions with the CMB.

Following the CGRO (Compton Gamma-Ray Observatory) discovery of the strongly flaring γ-ray blazar 3C279 at redshift 0.54 (Hartman et al. 1992), and based on earlier calculations by Stecker, Puget & Fazio (1977) estimating the CIB (cosmic infrared background), Stecker, de Jager & Salamon (1992) proposed that one can use the predicted pair production absorption features in blazars to determine the intensity of the CIB, provided that the intrinsic spectra of blazars extend to TeV energies. Subsequent work along these lines used observations of TeV spectra of blazars to place upper limits on the CIB (Stecker & de Jager 1993, 1997; Dwek & Slavin 1994; Biller et al. 1998; Funk et al. 1998; Vassiliev 2000; Stanev & Franceschini 1998; Schroedter 2005).

With the advent of the COBE (Cosmic Background Explorer) observations (Dwek & Arendt 1998; Fixsen et al. 1997, 1998; Hauser et al. 1998) real data on the CIB became available. Lower limits from galaxy counts help in determining the spectral energy distribution of the CIB at wavelengths where no COBE data are available. In addition, the upper limits from TeV γ-ray observations and from CIB fluctuations help to determine the CIB at wavelengths where no direct measurements are available (see Hauser & Dwek 2001 for a review of the CIB measurements). More detailed theoretical models of the spectral energy distribution (SED) of the CIB produced by cool stars and dust reradiation in galaxies were subsequently constructed (MacMinn & Primack 1996; Franceschini et al. 1998; Malkan & Stecker 1998, 2001; MS98, MS01; Kneiske et al. 2002). Such models of the CIB can be used to invert the original approach and to calculate the expected opacity of the universe to high energy γ-rays (Stecker et al. 1992; MacMinn & Primack 1996; Stecker & de Jager 1998; Totani & Takeuchi 2002; Kneiske et al. 2004). One can then use these results to derive the unabsorbed intrinsic emission spectra of TeV γ-ray sources.

The empirically based approach of MS98 and MS01 yields CIB SEDs which are consistent with the most reli-

1There was a reported large CIB flux at 100 µm by Finkbeiner, Davis & Schlegel (1999) that was most probably contaminated by local solar system dust emission and is now considered to be an upper limit (Finkbeiner talk at IAU Symp. No. 204.) A reported near-IR excess (Matsumoto et al. 2005) conflicts with upper limits from TeV blazar spectra (Schroedter 2005) and is also inconsistent with galaxy counts and theoretical models of early star formation. Other theoretical problems with this reported near-IR excess are discussed by Madau & Silk (2005). This near-IR radiation may be reflected sunlight from interplanetary dust (Dwek, Arendt & Krennrich 2005). We do not consider these
able data and limits on the CIB\textsuperscript{1}, although it should be noted that these data have large error bars. Malkan \& Stecker (2001) also used this approach to derive galaxy LFs and source counts at various infrared wavelengths which are found to be in general agreement with present data. These results have then been used to determine intrinsic (unabsorbed) source spectra of well-observed TeV blazars which can be shown to be consistent with synchrotron self-Compton emission models (De Jager \& Stecker 2002; Konopelko \textit{et al.} 2003; Georgopanos \& Kazanas 2003; Konopelko, Mastichiadas \& Stecker 2005). In this way, a synoptic approach to both the γ-ray and infrared observations can lead to knowledge of both blazar emission and the low energy intergalactic photon background (Dwek \& Krennrich 2005).

It was pointed out by Madau \& Phinney (1996) that the optical and ultraviolet radiation produced by stars in galaxies at redshifts out to ∼ 2 would make the universe opaque to photons above an energy of ∼ 30 GeV emitted by sources at a redshift of ∼ 2, again owing to pair production interactions. Salamon \& Stecker (1998) (SS98) made detailed calculations of the opacity of γ-rays from such interactions down to energies of 10 GeV and out to a redshift of 3. We continue and expand this approach here using recent data from the Spitzer infrared observatory and 	extit{Hubble} deep survey data. We determine the IR-UV photon density from 0.03 eV to the Lyman limit at 13.6 eV for redshifts out to 6 using very recent results from deep surveys. We will refer to this as the “intergalactic background light” (IBL). We then use our results on the density of the IBL as a function of redshift, together with the opacity of the CMB as a function of redshift, to calculate the opacity of the universe to γ-rays for energies from 4 GeV to 100 TeV and for redshifts from ∼ 0 to 5.

As an example of the application of our results, we calculate the absorbed spectrum of the blazar PKS 2155-304 at z = 0.117 and compare it with the spectrum observed by the H.E.S.S. (High Energy Stereoscopic System) air Cherenkov γ-ray telescope array. We also give an analytic approximation to our opacity results for τ(E\textsubscript{γ}, z).

2. Calculation of the Intergalactic Background Light

In order to calculate intergalactic IR photon fluxes and densities, we again use the same method described in detail by Malkan \& Stecker (MS98, MS01). This method, a "backwards evolution" scheme, is an empirically based calculation of the SED of the CIB by using (1) the luminosity dependent galaxy SEDs based on observations of normal galaxy IR SEDs by Spinoglio \textit{et al.} (1995), (2) observationally based luminosity functions (LFs) starting with the work of Saunders \textit{et al.} (1990) and (3) the latest redshift dependent luminosity evolution functions.\textsuperscript{2} Since MS98 and MS01, new observations have allowed us here to make improvements to our model calculations as well as further detailed tests.

2.1. Galaxy IR SEDs as a Function of Luminosity

The key assumption we make, as in MS98 and MS01, is that the luminosity of a galaxy at all wavelengths,\textit{viz.}, its SED, can be predicted statistically from its observed luminosity in one infrared waveband, here chosen to be 60\textmu m. This is founded on the well-established fact that galaxies are more luminous (now and in the past) when they have higher rates of recent star formation. Empirically, it is found that for the more luminous galaxies, relatively more of the energy from these young stars is absorbed by dust grains and re-radiated in the thermal IR. This results in the observational facts that more luminous galaxies have higher IR flux relative to optical flux and warmer IR spectra. These clear luminosity-dependent trends in galaxy SEDs were well determined locally from the combination of IRAS (Infrared Astronomy Satellite) and ground based photometry for large (e.g., all sky) samples. Following our previous work, we use the quantitative measurements of these trends determined by Spinoglio \textit{et al.} (1995) and Spinoglio, Andreani and Malkan (2002). The resulting SEDs as a function of galaxy luminosity are based on broadband photometry of IRAS selected samples. Since then, other computations of IR backgrounds and source counts have used different sets of SEDs, based on somewhat different combinations of data and models, in some cases estimated in more spectral detail. We have therefore checked whether these new SEDs might differ from ours in either overall colors, or in detail around the 7–12\textmu m region, where the strongest spectral features are found.

The best example of these new galaxy template SEDs has been published by Xu \textit{et al.} (2001) in their Table 2. Many luminosity bins could be compared with our corresponding SEDs calculated with the scaling formulae from Spinoglio \textit{et al.} (1995). For simplicity, we consider two luminosity ranges near the knee of the galaxy luminosity function at z = 0 and z = 1. So long as the agreement for SEDs near the knee is reasonable, the final computed IR backgrounds will also agree, because they are dominated by galaxies around the knee.

Figures 1 and 2 compare our computed SED (solid line) with the ranges given by Xu \textit{et al.} (shown by 1σ error bars) for 10\textsuperscript{9} and 10\textsuperscript{10} solar luminosities at 25\textmu m. The dashed line shows the Xu \textit{et al.} SED smoothed to the resolution of a typical broad-band filter, such as those used for \textit{Spitzer} photometry. All SEDs are normalized at 25\textmu m. For the latter more luminous galaxies, we plot the two SEDs Xu \textit{et al.} give for their two populations of galaxies, normal late-type spirals and starbursts. Since our simpler computation includes only one average type of galaxy, it could be expected to straddle those two templates from Xu \textit{et al.} (2001).

The agreement between our SEDs and those of Xu \textit{et al.} (2001) is virtually perfect for all wavelengths longward of 15\textmu m. The most significant disagreement is in the 12\textmu m region, where our broadband photometry averages over the two peaks at higher spectral resolution produced by PAHs (polycyclic aromatic hydrocarbon) molecular emission bands (Peeters \textit{et al.} 2005) and the 10 \textmu m silicate absorption feature (Chiar \& Tielens 2006). Even in that region, the deviations hardly ever exceed the 1σ dispersion among Xu \textit{et al.} galaxy templates. In any computation which averages over redshifts, such as number counts and

\textsuperscript{2} These are empirically derived curves giving the universal star formation rate (Madau \textit{et al.} 1996) or luminosity density (Lilly \textit{et al.} 1996) as a function of redshift which are sometimes referred to as Lilly-Madau plots.
especially in diffuse background calculations, these SED wiggles, with peak amplitudes of about 40%, will make no observable difference in the results.

2.2. The Local Infrared Luminosity Function

The foundation of our backwards evolution calculation is an accurately determined local infrared luminosity function of galaxies. As in MS01, we started with the local luminosity function at 60 µm, the wavelength where it is best determined. But, instead of the Lawrence et al. (1986) LF used in MS01, we adopted the LF from Saunders et al. (1990), because it is based on an extensive analysis of a larger data sample. However, we made an update to the Saunders LF based on the even more thorough local IR LF determined by Takeuchi, Yoshikawa and Ishii (2003).

As in MS98 and MS01, we took an analytic function for the local 60 µm LF of the form

\[ \Phi(L, z = 0)_{60} \propto x^{-a}(1 + \frac{x}{b})^{-b}, \quad x \equiv L/L_\ast \]

which fits the observational data at 60 µm. LFs at other wavelengths were obtained by using the average template SED appropriate for each luminosity as is discussed in MS01. The only difference in this paper was that we used an asymptotic low-luminosity power-law index of \( a = 1.35 \) in the differential LF which then steepens by \( b = 2.25 \) at high luminosities. This LF takes better account of the large number of fainter galaxies that are now known (Blanton et al. 2005 and references therein.) The 60 µm LF was normalized to \( 8.9 \times 10^{-3} \) Mpc\(^{-3}\) dex\(^{-1}\) at the knee luminosity \( L_\ast = 10^{23.93} \) W Hz\(^{-1}\), as derived from the LF of Saunders et al. (1990) after rescaling to \( h = 0.7 \). In addition, in this new calculation, we adopted a ΛCDM cosmology with \( \Omega_\Lambda = 0.7 \) and \( \Omega_m = 0.3 \). Figure 3 compares our adopted analytic luminosity function for \( z = 0 \) with the data summarized by Takeuchi et al. (2003). As expected, the agreement is perfect.

As in MS01, the four luminosity relations obtained by Spinoglio et al. (1995) at 12, 25, 60 and 100 µm (and our estimates at 2.2 and 3.5 µm) were inverted so that a luminosity at any given rest wavelength could be determined from the 60 µm luminosity, \( L_{60} \). This allowed us to make a mapping of the 60 µm LF shown in Figure 3 to an LF at any infrared wavelength using the transformation relation

\[ \Phi_\lambda(\log L_\lambda) = \Phi_{60}(\log L_{60})(d\log L_{60}/d\log L_\lambda) \]

which MS01 showed were in good agreement with local LFs at other wavelengths.

2.3. Evolution of the IBL SED with Redshift

It is now well known that galaxies had a brighter past owing to their higher rates of star formation and the fading of stellar populations as they age. The simplest resulting evolution of the galaxy luminosity function is a uniform shift in either the vertical axis (number density evolution), or in the horizontal axis (luminosity evolution.) For a pure power-law luminosity function, number and luminosity evolution are mathematically equivalent. In reality, however, to avoid unphysical divergences in the total number or luminosity of galaxies, the luminosity function must steepen at high \( L \) and flatten at low \( L \). Thus real LF’s will
Fig. 2.— SED, relative to flux at 25μm, for a galaxy with 25μm luminosity of $10^{10}L_\odot$. The solid line shows our model, while the error bars show the 1σ range of fluxes from Xu et al. (2001), which are also shown smoothed to broadband photometry resolution by the dotted lines. The upper set of points shows the “normal late-type spiral” SED, while the lower set of points shows the “starburst galaxy” SED of the same 25μm luminosity, both sets of points as given by Xu et al. (2001).

have at least one characteristic “knee” separating the steep high-L portion from the flatter low-L slope (see Figure 3. For typical LF’s this results in most of the luminosity being emitted by galaxies within an order of magnitude of this knee. Thus large uncertainties and errors in the LF far from this knee will hardly change most of the results (e.g., number counts and integrated diffuse backgrounds).

Strong luminosity evolution of galaxies, i.e., a substantial increase in the luminosity of this knee with redshift, is consistently found by many observations relating IR luminosity to the much higher star formation rate at $z \sim 1$ and to the recent determination that most UV-selected galaxies at $z \sim 1$ are also luminous infrared galaxies (Burgarella et al. 2006).

In addition to the evolution of galaxy luminosity, some increase in galaxy number density is expected owing to the hierarchical clustering predicted by cold dark matter models. However, luminosity evolution is so strongly dominant that it is difficult to identify a component of density evolution. MS98 and MS01 therefore assumed pure luminosity evolution for their backwards evolution calculations. Even five years later, this is still an excellent description of the latest observations. The most recent galaxy luminosity functions at higher redshifts show weak evidence for a small number evolution, combined with very strong luminosity evolution. However, the number evolution is still sufficiently small (an increase in space density of only a factor of 1.5 to 1.9 times the local value), that pure luminosity evolution (PLE) is nearly as good a fit. The PLE model will be adopted here because it simplifies the calculation and it is quite adequate for the purposes of deriving intergalactic low energy photon densities and spectra. We base our calculations on two plausible cases of pure luminosity evolution very similar to what MS98 and MS01 assumed:

1. In the more conservative scenario, all galaxy 60μm luminosities evolved as $(1 + z)^{3.1}$. This is the same as in the ”baseline case” of MS01 and MS98 (with their luminosity evolution parameter $q = 3.1$), but with evolution stopped at $z_{flat} = 1.4$ and galaxy luminosities assumed constant (nonevolving) at the higher redshifts $1.4 < z < 6$, with negligible (assumed zero) emission for $z > 6$. This later assumption is supported by the recent Hubble deep survey results (Bunker et al. 2004 and references therein; Bouwens, R.J., Illingworth, G.D., Blakeslee, J.P. & Franx, M. 2005) which indicate that the average star formation rate is dropping off significantly at a redshift of 6. Independent evidence from luminosity functions of Lyman α-emitting objects at redshifts from 3 to 6 shows a similar decrease (Kashikawa et al. 2005).  

$^3$According to Bouwens et al. (2005), the star formation rate at $z = 6$ is only about 70% of that at $z = 1.5$. We have run the case where this is simulated by a negative evolution in the galaxy number density $\propto (1 + z)^{-0.637}$. As expected, this only lowers our results by $\sim 15\%$, an uncertainty which is somewhat counterbalanced by our assuming no star formation at redshifts greater than 6. This overall uncertainty is less than that arising from the uncertainty in the stellar metallicity at these redshifts.
The "fast evolution" case where galaxy luminosities evolved as \((1 + z)^4\) for \(0 < z < 0.8\) and evolved as \((1 + z)^2\) for \(0.8 < z < 1.5\) with no evolution (all luminosities assumed constant) for \(1.5 < z < 6\) and zero luminosity for \(z > 6\). This evolution model is based on the mid-IR luminosity functions recently determined out to \(z = 2\) by Perez-Gonzalez et al. (2005).

The "fast evolution" picture is favored by recent Spitzer observations (Le Floc’h et al. 2005, Perez-Gonzalez et al. 2005). It provides a better description of the deep Spitzer number counts at 70 and 160\(\mu\)m than the "baseline" model. However, GALEX observations indicate that the evolution of UV radiation (see next section) for \(0 < z < 1\) may be somewhat slower and more consistent with the "baseline" model within errors (Schiminovich et al. 2005). And the 24\(\mu\)m Spitzer source counts are closer to the baseline model than the fast evolution one. The Spitzer IRAC (Infrared Array Camera) counts lie in between these two models. In any case, we shall see that the possible small difference in evolution has only a small effect on the \(\gamma\)-ray opacity in the 10-100 GeV range, as can be seen from our results in Section 3.2. In any case, we have not used a simple evolution model for the optical-UV, but rather adopted the results of SS98 (see next section). We also note that dust extinction effects at the higher redshifts in principal may help account for the differences between the GALEX and Spitzer results (see Section 4.2).

Fazio et al. (2004) have compared our source count predictions as given in MS01 with the source count data from Spitzer in the 3-8 \(\mu\)m range. Their paper shows that our model, although not giving a perfect fit, fits these data as well as other models which have been proposed. We will present our new source count calculations (which are not substantially different from those given in MS01) for the 24\(\mu\)m, 70\(\mu\)m and 160\(\mu\)m Spitzer IRAC bands in a separate IR paper (Malkan & Stecker, in preparation).

2.4. The Intergalactic Optical and Ultraviolet Photon Spectra

Throughout the substantial evolution of galaxy IR luminosities, backwards evolution assumes that the same local monotonic relation between galaxy luminosity and SED continues to hold. In effect, the relation between evolved stars (and stellar mass) and their thermally reradiated luminosity from dust grains is assumed to remain the same. The rest-frame optical and UV continuum has a far larger contribution from more massive stars, which fade rapidly over cosmic times. Therefore stellar evolution is expected to produce redshift evolution in the optical-UV SEDs of galaxies, further justifying the observationally-based PLE models discussed in the previous section. This is reflected in the fact that our assumed PLE models, when combined with the library of galaxy SEDs as a function of luminosity (given explicitly in MS98) results in an automatic increase in the ratio of FIR (dust) to NIR (stellar) emission from galaxies with redshift.

Our calculation of the diffuse IR background as described earlier extends up to a rest frequency of \(\log \nu_{Hz} = 14.1\) corresponding to an energy of \(\sim 0.5\ eV\). This is the location of the peak in the spectral energy distributions of most galaxies and is produced by the light of red giant stars. The spectrum (in energy density units) then curves downward rapidly to higher frequencies, with modest dependence on galaxy luminosity.
SEDs have a peak at this energy, this peak, as opposed to the far IR peak in galaxy SEDs, only manifests itself as an inflection point in the photon density spectrum. At wavelengths shortward of this near IR-optical “peak” the photon density spectra drop steeply (see Figures 4 and 5 which plot $en(\nu)$ for the case of the fast evolution model.) To estimate the redshift-dependence of stellar optical-UV SEDs, we employed an analytic approximation to the more sophisticated near IR, optical and UV SEDs used in SS98. These SEDs were based on the Bruzal & Charlot (1993) stellar population synthesis models for galaxy evolution. The assumptions made by SS98 for SEDs at various redshifts are now supported by various observational results on galaxy evolution in the near IR-UV (Cowie et al. 1996, Pozzetti et al. 2003, Malkan, Webb & Konopacky 2003, Havens et al. 2004, Yee et al. 2005). We adopt here SEDs which are roughly halfway between the “with” and “without” metallicity correction cases given in SS98. This assumption is supported by the recent results of Yan et al. (2005) who find that the metallicity of stars in high redshift galaxies (out to $z = 6$) is not extremely low and that some heavy element production has already occurred by this time. In addition, a recent detection of the 158 $\mu$m CII fine structure line in a quasar at $z = 6.4$ suggests a significant stellar metallicity existed at redshifts as high as $\sim 6$ (Maiolino et al. 2005). Yan et al. (2005, 2006) found that galaxies at $z \approx 6$ have a similar blue color to those shown by the spectral evolution of the population synthesis models of Bruzal & Charlot (1993), with some even bluer than the models predict. We therefore take the galaxy SEDs given for $z = 3$ and extend them unchanged to $z = 6$. This will allow us to calculate the optical depth of the universe to $\gamma$-rays out to a redshift of 5.

We normalized the near infrared end of our full-spectrum SEDs to the near IR parts of our IR SEDs which were calculated as described in Section 2.1. For redshifts $0 < z < 1$ we extended them to optical and ultraviolet using a parabolic approximation to the energy density SEDs $\log u_{\nu}$. The SEDs used by SS98 in this redshift range can be approximated by a function whose logarithmic slope $d\log u_{\nu}/d\log \nu$ steepens from 0 at $\log \nu = 14.1$ to -2 at $\log \nu = 15.0$. For $0 < z < 1$ one can use such a parabolic approximation to the SED given by

$$\log [u_{\nu}/u_{\nu_0}] = \beta [\log (\nu/\nu_0)]^2$$

where $\log \nu_0 = 14.1$. The curvature parameter $\beta$ drops smoothly from -1.1 at $z = 0$ to 0 at $z = 1$. This is a good approximation to the more sophisticated model calculations of SS98, adequate for the purposes of calculating photon densities and $\gamma$-ray optical depths. At higher redshifts we take account of the shift in galaxy colors toward the blue by making power-law approximations to the galaxy SEDs. Denoting the power-law spectral index by the parameter $\alpha$, we take $\alpha = -0.23(2 - z)$ for $1 < z < 2$ and $\alpha = 0$ for $z > 2$.

These approximations to galaxy SEDs in the optical and UV reflect both the stellar population synthesis models (Bruzal & Charlot 1993) and the direct Hubble space telescope observations that indicate that star forming galaxies are bluer at $z > 0.7$ (De Mello et al. 2005). At all redshifts, because there is a steep drop in galaxy SEDs at the Lyman limit of 13.6 eV ($\log \nu \approx 15.5$) as shown in the spectra given in SS98, we cut off our spectra entirely at this energy. Such a marked absence in photons at wavelengths shortward of the Lyman limit in the spectra of galaxies at redshifts $\sim 1$ was observed by Malkan, Webb & Konopacky (2003).

The IBL photon density, $en(\nu) = \epsilon n(\nu)/d\epsilon$ for photon energies from the far IR to the Lyman limit, given as a function of energy and redshift is shown in Figures 4 and 5 assuming the far-IR fast evolution evolution model. As a check on the two models, Figure 6 shows the predicted background SEDs from our model calculations for $z = 0$ compared with the data and empirical limits. Most of the data shown in Figure 6 can be found in the review paper by Hauser and Dwek (2001). The inverted triangle shows the $\gamma$-ray upper limit from Stecker and De Jager (1997). The new lower limits in the far-IR $\log \nu = 12.63$ (70 $\mu$m) and $\log \nu = 12.27$ (160 $\mu$m) are from Dole et al. (2006).

3. THE OPTICAL DEPTH OF THE UNIVERSE TO GAMMA-RAYS

3.1. The Optical Depth from Interactions with CMB Microwave Photons

The optical depth of the universe to the CMB is given by

$$\tau_{CMB} = 5.00 \times 10^5 \left( \frac{1.11 \text{PeV}}{E_{\gamma}} \right) \int_0^{\infty} dz' (1 + z') e^{-\frac{1.11 \text{PeV}}{E_{\gamma}/(1+z')^3}} \frac{\Omega_\Lambda + \Omega_m (1 + z')^3}{\Omega_0 + \Omega_m (1 + z')^3}$$

for the condition $E_{\gamma} \ll 1.1/(1 + z)^2$ PeV where the interactions involve CMB photons on the Wien tail of the blackbody spectrum. This is an update of the formula given in Stecker (1969) using $T_{CMB} = 2.73$ K and we have taken a ΛCDM universe with $h = 0.7$. In all of our calculations we use $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$.

3.2. The Optical Depth from Interactions with IBL Photons

To this result, we add the optical depth of the universe to the IBL as a function of $z$ as calculated using the methods described in SS98 and using our IBL photon spectra as derived in the previous section. Figure 7 shows the relative contributions to the optical depth from the IBL and the CMB and the total optical depth for a source at a redshift of 3.

Our results on the optical depth as a function of energy for various redshifts out to a redshift of 5 are shown in Figure 8 and Figure 9. Our new results predict that the universe will become opaque to $\gamma$-rays for sources at the higher redshifts at somewhat lower $\gamma$-ray energies than those given in SS98. This is because the newer deep surveys have shown that there is significant star formation out to redshifts $z \geq 6$ (Bunker et al. 2004; Bouwens, Illingworth, Blakeslee and Franz 2005), greater than the value of $z_{\max} = 4$ assumed in SS98.

Figure 11 shows the energy-redshift relation giving an optical depth $\tau = 1$ based on our calculations of $\tau(E_{\gamma}, z)$.  

4 We note that the energy dependence of the differential photon energy spectrum, $dn_{\nu}/d\epsilon$, is obtained by dividing the SED by the square of the photon energy ($\nu^2$) so that the starlight “peak” in the SED has very few photons compared to the dust reradiation peak in the far infrared.
This curve is generated by the intersection of the function \( \tau(E_\gamma, z) \) shown in Figure 10 with the plane defined by the condition \( \log \tau = 0 \). At energies and redshifts above and to the right of this curve the universe is optically thick to \( \gamma \)-rays. Similarly, at energies and redshifts below and to the left of this curve the universe is optically thin. The first inflection point in the curve is caused by the far-IR rollover in the metagalactic photon density as shown in Fig. 4 and the second inflection point is caused by the rollover in the optical photon density, also as shown in Fig. 4.

The function shown in Figure 11 is quite different from that produced by Fazio & Stecker (1970) which was based on interactions with the CMB alone. This illustrates the importance of the IBL in determining the opacity of the universe to high energy \( \gamma \)-rays at higher redshifts as first pointed out by Stecker et al. (1992). This figure also illustrates the extremely large optical depths at the higher
Fig. 6.— Spectral energy distribution of the diffuse background radiation at $z = 0$. Error bars show data points, triangles show lower limits from number counts and the inverted triangle is an upper limit from $\gamma$-ray observations (see text). The upper and lower solid lines show our fast evolution and baseline evolution predictions, and the dotted lines show our extensions into the optical–UV, as described by SS98. The steeply dropping solid line near $10^{12}$ Hz is the spectrum of the CMB.

Fig. 7.— The optical depth of the universe from the IBL (fast evolution case) and the CMB as well as the total optical depth as a function of energy for a $\gamma$-ray source at a redshift of 3. It can be seen that the contribution to the optical depth from the IBL dominates at lower $\gamma$-ray energies and that from the CMB photons dominates at the higher energies. The dashed curve is for the IBL contribution alone and the dotted curve is for the CMB contribution alone.

energies due to interactions with the CMB. We find that the function $\tau(E_{\gamma}, z)$ can be approximated by the analytic form...
Fig. 8.— The optical depth of the universe to $\gamma$-rays from interactions with photons of the IBL and CMB for $\gamma$-rays having energies up to 100 TeV. This is given for a family of redshifts from 0.03 to 5 as indicated. The solid lines are for the fast evolution IBL cases and the dashed lines are for the baseline IBL cases.

\[ \log \tau = Ax^4 + Bx^3 + Cx^2 + Dx + E \]

over the range $0.01 < \tau < 100$ where $x \equiv \log E_\gamma$ (eV). The coefficients A through E are given in Table 1 for various redshifts. This analytic approximation can be used in comparing our results with other work.

4. IMPLICATIONS OF RESULTS

4.1. The TeV Spectrum of PKS 2155-304

Our results for $\tau(E_\gamma, z)$ can be used to derive the intrinsic $\gamma$-ray spectra of extragalactic sources. Based on the earlier results of De Jager & Stecker (2002) for low redshifts, the spectra of the best observed extragalactic TeV sources, viz. the BL Lac objects Mkn 501 and Mkn 421, were analysed by Konopelko et al. (2003). As an example here, we pick the next best observed source, the blazar
PKS 2155-304, which is situated at a redshift of 0.117 and for which there are good recent TeV spectral data obtained by the *H.E.S.S.* air Cerenkov γ-ray telescope array (Aharonian et al. 2005). This source had earlier been reported by the Durham group to have a flux above 0.3 TeV of \( \sim 4 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \), (Chadwick et al. 1999), close to that predicted by Stecker, de Jager & Salamon (1996) using a simple synchrotron self-Compton (SSC) model.

Using absorption results obtained by Stecker and de Jager (1998) and assuming an approximate \( dn/dE \propto E^{-2} \) photon source spectrum (corresponding to a flat SED), which would apply near the very high energy γ-ray Compton “peak” in the quasi-parabolic log-log SED of a typical SSC model (Stecker, de Jager & Salamon 1996), Stecker (1999) predicted that this PKS 2155-304 would have its spectrum steepened by \( \sim 1 \) in its spectral index between \( \sim 0.3 \) and \( \sim 3 \) TeV and would show a pronounced absorption turnover above \( \sim 6 \) TeV. The recent *H.E.S.S.* observations (Aharonian et al. 2005) bear out these predictions.
Table 1: Coefficients for the Baseline Model Fits

| z    | A    | B    | C    | D    | E    |
|------|------|------|------|------|------|
| 0.03 | -0.0151449 | 1.02602 | -24.2313 | 243.652 | -893.883 |
| 0.112 | -0.0107295 | -9679.05 | -138.498 | 3518.31 | -21256.9 |
| 0.2  | -0.0149538 | 1.02341 | -24.2282 | 243.291 | -888.586 |
| 0.5  | -0.0389542 | 2.12529 | -42.9679 | 382.842 | -1270.59 |
| 1    | -0.127954  | 6.22323 | -113.306 | 915.786 | -2772.64 |
| 2    | -0.192839  | 9.13298 | -161.92  | 1274.05 | -3753.66 |
| 3    | -0.143133  | 6.70614 | -117.706 | 917.64  | -2680.54 |
| 5    | -0.281498  | 12.8979 | -221.364 | 1687.01 | -4816.33 |

Energy (TeV)

| z    | A    | B    | C    | D    | E    |
|------|------|------|------|------|------|
| 0.1  | 1.0  | 10.0 |
| dN/dE (cm$^{-2}$ s$^{-1}$ TeV$^{-1}$)

1e-16

1e-15

1e-14

1e-13

1e-12

1e-11

1e-10

1e-09

1e-08

**Fig. 12.**—The γ-ray data from the H.E.S.S. for PKS2155-304 compared with the theoretical spectrum for PKS2155-304 calculated by assuming an unabsorbed source spectrum proportional to $E^{-2}$ and multiplying by $e^{-\tau}$ using $\tau(z = 0.117)$ for the fast evolution model based on Perez-Gonzalez et al. (2005) as discussed in the text.

We revisit PKS 2155-304 here, comparing the H.E.S.S. data with a photon source spectrum assumed to be approximated by an $E^{-2}$ which was then steepened by $e^{-\tau(E_\gamma)}$ with $\tau(E_\gamma; z = 0.117)$ as shown in Figure 9. The resulting spectrum is shown in Figure 12 along with the H.E.S.S. data. We also found that the best power law fit of our calculated absorbed spectrum had a spectral index of -3.35 which is in full agreement with the H.E.S.S. result on the observed spectrum of -3.32 ± 0.06 (Aharonian et al. 2005). It can therefore be seen that the steep spectum of PKS 2155-304 observed by the H.E.S.S. group can be explained by intergalactic γγ → $e^+ e^-$ absorption.

We further note that a steepening in an $E^{-2}$ power-law differential photon spectrum by one power to $E^{-3}$ would be produced by a γ-ray opacity with an energy dependence $\tau(E_\gamma) \simeq \ln(aE_\gamma)$. In fact, we find such a fit over the energy range 0.4 TeV < $E_\gamma$ < 3 TeV with an approximate relation $\tau(E_\gamma; z = 0.117) \simeq \ln(7.3E_\gamma)$ with $E_\gamma$ in TeV. An excellent fit over this energy range at $z = 0.117$ would be $\tau(E_\gamma) \simeq [\ln(5.52E_\gamma)]^{1.26}$, which is reflected in a slight flattening in our absorbed spectrum at the lower energies and a steepening at the higher energies (see Figure 12).

4.2. The Lyman Limit, UV Radiation at the Higher Redshifts, and Distant γ-ray Sources

As previously stated, our SEDs in the UV range at the higher redshifts are based on SS98 which is, in turn, based on the population synthesis models of Bruzal & Charlot (1993). They give stellar SEDs at various redshifts, but do not take account of UV extinction by dust. One way of understanding the somewhat smaller redshift evolution of the star formation rate implied by the GALEX observations (Schiminovich et al. 2005) vs. that obtained from Spitzer observations (Le Floc’h et al. 2005, Perez-Gonzalez et al. 2005) is that the effect of dust extinction followed by IR reradiation increases with redshift (Burgarella, Buat & the GALEX team 2005). Therefore, we may have overestimated the UV photon density at the higher redshifts. This uncertainty should only effect the absorption predictions in the 5 to 20 GeV energy range.

It should be noted that for γ-ray sources at the higher redshifts there is a steeper energy dependence of $\tau(E_\gamma)$ near the energy where $\tau = 1$. There will thus be a sharper absorption cutoff for sources at high redshifts. It can easily be seen that this effect is caused by the sharp drop in the UV photon density at the Lyman limit, here ap-
proximated by an absolute cutoff. Figure 10 shows the continuous function for the optical depth, $\tau(E, z)$.

4.3. Implications for GLAST

Because of the energy dependence of absorption in the blazar spectra at the higher redshifts in the multi-GeV range, GLAST, the Gamma Ray Large Space Telescope (http://glast.gsfc.nasa.gov; see also McEnery, Moskalenko & Ormes 2004), will be able to probe the IBL at these redshifts and probe the early star formation rate (Chen, Reyes & Ritz 2004). For example, GLAST should be able to detect blazars at $z \approx 2$ at multi-GeV energies and determine the critical value for $E_\gamma$ above which absorption will cut off the spectrum, thereby distinguishing between our predictions and those of the various models of Kneiske et al. (2004). More importantly, such GLAST observations at redshifts $z \geq 2$ and $E_\gamma \sim 10$ GeV may complement the deep galaxy surveys and help determine the redshift when significant star formation began. Future GLAST observations in the 5 to 20 GeV energy range may also help to clarify the uncertainty in the amount of dust extinction pointed out in the previous section by determining the mean density of UV photons at the higher redshifts through their absorption effect on the $\gamma$-ray spectra of high redshift sources.

In fact, GLAST need not have to detect $\gamma$-ray sources at high redshifts in order to aquire information about the evolution of the IBL. If the diffuse $\gamma$-ray background radiation is from unresolved blazars (Stecker & Salamon 1996), a hypothesis which can be independently tested by GLAST (Stecker & Salamon 1999), the effects of IBL absorption will steepen the spectrum of this radiation at $\gamma$-ray energies above $\sim 10$ GeV (SS98). This is a direct result of the energy and redshift dependences of the absorption coefficient as clearly indicated in Figure 11.

4.4. Implications for Fundamental Physics

Stecker & Glashow (2001) used observations of the Mkn 501 spectrum to place constraints on violations of Lorentz invariance. They concluded that the evidence for $\gamma$-ray absorption in the spectrum of Mkn 501 at an energy of 20 TeV from $\gamma \gamma \rightarrow e^+e^-$ interactions placed a strong constraint on violation of Lorentz invariance, viz. a constraint of about one part in $10^{15}$. Observing extragalactic $\gamma$-ray sources at higher energies and redshifts, where significant attenuation from $\gamma\gamma \rightarrow e^+e^-$ interactions is expected, can provide a more sensitive test of Lorentz invariance violation. This, in turn, will place constraints on some quantum gravity and extra dimension models (Stecker 2003; Jacobson, Liberati, Mattingly, & Stecker 2004).

5. COMPARISON WITH PREVIOUS WORK

Our baseline case is quite similar to the optical depths predicted by Totani & Takeuchi (2002) at low redshifts, except that their assumed galaxy SEDs had relatively less mid-IR to optical emission than ours. Our flatter SEDs result in relatively flatter $\tau(E_\gamma)$ curves than Totani & Takeuchi. However, at higher redshifts ($z = 1$ and 2), our optical depths are substantially lower than the Totani & Takeuchi models, since they assumed a very large component of far-IR emission from elliptical galaxies at $z > 3$.

Above '10 TeV, our total optical depth includes the contribution from the CMB not included by, Totani & Takeuchi and is therefore much higher.

The favored “best-fit” model of Kneiske et al. (2004) gives an optical depth $\tau = 1$ at $E_\gamma \approx 5$ TeV for $z = 0.03$, the redshift of the blazars Mrk 421 and Mrk 501. This is in good agreement with our result. The form of the function $\tau(E_\gamma; z = 0.03)$ obtained by Kneiske et al. (2004) is also in good agreement with our result. The results obtained for $z = 0.2$ both here and by Kneiske et al. are also in good agreement. Our results are also in accord with the model constraints given by Dwek & Kronrich (2005).

On the other hand, Primack, Bullock & Sommerville (2005) find a consistently smaller optical depth such that they find $\tau = 1$ at $E_\gamma \approx 17$ TeV for $z = 0.03$. At a redshift of 0.2, we find $\tau = 1$ at $E_\gamma = 0.2$ TeV and Kneiske et al. (2004) find $\tau = 1$ at $E_\gamma = 0.3$ TeV. Primack et al. (2005) find $\tau = 1$ at $E_\gamma = 1$ TeV for this redshift. The reason the Primack et al. give consistently lower values for $\tau(E_\gamma)$ is because of the lower flux which they obtain for their model IR-SED. In this regard, we point out that their model flux at $15 \mu m$ is approximately a factor of 2 lower than the lower limit obtained from galaxy count observations with ISOCAM (Altieri et al. 1999). In support of our higher opacity values, we note that the spectrum of PKS2155-304 at $z = 0.117$ shows our predicted steepening from absorption at energies down to $\sim 0.3$ TeV where Primack et al. (2005) would predict no significant absorption.

At higher redshifts where there is more uncertainty, Kneiske et al. predict less absorption for their “best-fit” model. For example, at $z = 2$, their best fit model gives $\tau = 1$ at $E_\gamma \sim 50$ GeV, whereas we find $\tau = 1$ at $E_\gamma \sim 15$ GeV. It should be noted, however, that they consider a range of models with a large uncertainty in their absorption predictions at the higher redshifts. Our calculations give a higher opacity at high redshifts because we have taken account of the recent observational evidence for significant star formation out to a redshift of $\sim 6$ (Bunker et al. 2004) as discussed in Section 2.3.

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5Because of the small photon flux above the Lyman limit, this approximation has no significant effect on our predicted $\gamma$-ray opacity values.
