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CONSTRAINTS ON THE EXTRAGALACTIC BACKGROUND LIGHT FROM GAMMA-RAY OBSERVATIONS OF HIGH-REDSHIFT QUASARS

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ABSTRACT

We propose to use the detectability of energetic γ-rays in the 10–200 GeV range from high-redshift quasars to set limits on the energy density and era of formation of the extragalactic background light (EBL) in the near-ultraviolet, optical, and near-infrared portion of the spectrum. We study a variety of EBL models based on recent estimates of the density of starlight at the present epoch, a detailed modeling of the transfer of ionizing radiation through the intergalactic medium and of the spectral energy distribution of young galaxies, and simple parameterizations of the star formation history. We demonstrate that a cosmic background of optical photons which is comparable to the integrated EBL contributed by ordinary galaxies and originates as near-ultraviolet radiation at redshift $z \sim 2$ will make the universe optically thick to γ-ray photons above ~ 30 GeV through electron-positron pair production. We also show that a detection by the EGRET instrument aboard the *Compton Observatory* of $\gtrsim 15$ GeV photons from the quasar 1633+382 (Mattox et al. 1993) would rule out models in which a diffuse optical background with an energy density several times in excess that of known galaxies was formed at $z \sim 2$ by a new class of sources. The universe to intermediate redshifts is optically thin to pair production below ~ 10 GeV.

Subject headings: diffuse radiation — gamma rays: observations — quasars: general — quasars: individual (1633+382)

1. INTRODUCTION

The extragalactic background light (EBL) is an indicator of the integrated luminosity of the universe and can provide unique information on the origin of structures at early epochs. The great cosmological importance of measuring the EBL in the optical portion of the spectrum stems from the prospects of using it as a probe of galaxy formation and evolution, as the cumulative emission from pregalactic, protogalactic, and evolving galactic systems is expected to be recorded in this background. Upper limits to the EBL have been set by all-sky photometry (see Mattila 1990 for a recent review). It is found that $\sim 85\%$ of the current optical EBL upper limits is not accounted for by resolved galaxies with $B < 27$ mag (Toller 1983; Tyson 1995).

It has been known for more than 30 years (Nikishov 1962; Gould & Schreder 1966) that high-energy γ-rays from sources at cosmological distances will be absorbed along the way by a diffuse background of softer photons via electron-positron pair production. Recent TeV observation of the nearby BL Lac object Mrk 421 ($z_{\rm em} = 0.031$), obtained by the Whipple Observatory (Punch et al. 1992), have been used by Stecker & De Jager (1993), and De Jager, Stecker, & Salamon (1994; see also Dwek & Salvin 1994) to place constraints on the local extragalactic infrared energy density. However, the fact that Mark 421—the closest EGRET source and the only extragalactic object detected by Whipple—is a relatively weak GeV γ-ray source lends support to the suggestion that TeV γ-rays from more distant quasars are being significantly attenuated by infrared photons. If this were the case, there would be little hope to detect TeV sources at cosmological distances, and only upper limits to the cosmic background flux could be placed.

For a determination of the background energy density at early epochs, the detection of a bright quasar in the γ-ray energy range where the pair production optical depth is of order unity appears to be ideal. The main purpose of this paper is to stress the potential importance of γ-ray observations in the lower 10–200 GeV energy range for deep cosmological studies. As this spectral region barely overlap the upper energy limit, ~ 30 GeV, of the EGRET instrument aboard the *Compton Gamma-Ray Observatory*, and lies well below the lower energy limit, ~ 0.5 TeV, of the Whipple Observatory, the possibility of using γ-ray photons emitted from high-redshift quasars in this region as a probe of the intensity and evolution of the background light has not received much attention in previous work on the subject. However, a number of ground-based detectors are being designed or improved at the present time to measure γ-ray fluxes in the critical energy window between few tens and few hundreds GeV. Also, although the photon statistics is typically low close to its upper energy limit, it is conceivable that EGRET might detect a flaring, γ-ray loud distant blazar at $\gtrsim 10$ GeV. The primary motivation of this study is the realization that the detection of 10–200 GeV energetic γ-rays from quasars at cosmological distances could constrain the intensity and era of formation of the integrated EBL at near-UV, optical, and near-IR wavelengths.

The basic idea is quite simple. Gamma-ray photons emitted at $z_{\rm em} \sim 2$ with rest-frame energy, say, ~ 60 GeV are redshifted by the cosmological expansion into the EGRET window. Along their light travel path to Earth, they can produce an e^+e^- pair by

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interacting with background soft photons of rest-frame energies $\gtrsim 4.4$ eV. One might therefore use the detection of $z_{\rm em} \sim 2$ quasars at ~ 20 GeV to set limits on the energy density of the diffuse EBL at observed wavelengths $\lesssim 8500$ Å, and on its evolution as a function of redshift. The plan of the paper is as follows. We present the basic equations for calculating the cosmological optical depth to photon-photon pair production in § 2. In § 3 we review our current knowledge of the local density of starlight from the near-IR to the ultraviolet. We illustrate the potential of GeV γ-ray observations in § 4. We show, in particular, that the detection of 40 GeV photons from $z_{\rm em} \sim 2$ blazars could probe the optical EBL at a level of the integrated light contributed by ordinary galaxies. We also argue that an EGRET detection of $\gtrsim 15$ GeV photons from the quasar 1633+382 (Mattox et al. 1993) might already test models in which diffuse optical light with an energy density of a few times 10^{-3} eV cm^{-3} at the present epoch originates as near-ultraviolet radiation at intermediate results. We summarize our conclusions in § 5.

2. INTERGALACTIC ABSORPTION OF GAMMA-RAY PHOTONS

2.1. *Photon-Photon Pair Production*

Electron-positron pair creation due to the interaction of a γ-ray photon of energy $E(z) = E_0(1 + z)$ with a soft photon of energy $\epsilon(z) = \epsilon_0(1 + z)$ can take place provided that

$$E\epsilon(1 - \cos\theta) \geq 2m_e^2 c^4 \,, \tag{1}$$

where m_e is the electron mass and θ is the encounter angle of the two photons. The pair production cross section is (Heitler 1960)

$$\sigma(E, \epsilon, \theta) = \frac{3\sigma_T}{16}(1 - \beta^2)\left[2\beta(\beta^2 - 2) + (3 - \beta^4)\ln\frac{1 + \beta}{1 - \beta}\right], \tag{2}$$

where $\sigma_{\rm T}$ is the Thomson cross section, $\beta = (1 - 1/s)^{1/2}$ is the velocity of the components of the pair in the center-of-momentum (c.m.) system, and

$$s = \frac{E\epsilon(1 - \cos\theta)}{2m_e^2 c^4} \tag{3}$$

is the square of the electron (and positron) total energy in the c.m. frame. For a fixed γ-ray energy E, σ rises steeply from a threshold $\epsilon = \epsilon_{\rm th}$ given by equation (1), has a maximum value equal to $0.26\sigma_{\rm T}$ at $\epsilon = 2\epsilon_{\rm th}$, and then falls off as ϵ^{-1} for $\epsilon \gg \epsilon_{\rm th}$. Because of the peaked cross section, collisions will preferentially take place between γ-ray photons of energy $E/m_e c^2$ and soft photons with energy $\sim m_e c^2/E$, as long as the number density photon distribution is a decreasing function of energy. If we denote with $n(\epsilon, z)$ the number density of cosmic background photons with energy between ϵ and $\epsilon + d\epsilon$ at redshift z, the optical depth for attenuation between a source at redshift $z_{\rm em}$ and Earth is given by

$$\tau(E_0, z_{\rm em}) = \frac{c}{2H_0}\int_0^{z_{\rm em}} dz(1 + z)^{-2}(1 + 2q_0 z)^{-1/2}\int_{-1}^{1} d\cos\theta(1 - \cos\theta)\int_{\epsilon_{\rm th}}^{\infty} d\epsilon n(\epsilon, z)\sigma(E, \epsilon, \theta)\,, \tag{4}$$

where $H_0 = 50\,h_{50}$ km s^{-1} Mpc^{-1} is the Hubble constant, and q_0 is the deceleration parameter.

There is no uniquely predicted time evolution for the diffuse EBL, as the density of starlight at any given epoch will depend on the (unknown) cosmological history of star formation, metal production, etc. If all the background target photons are already in place at redshift z (i.e., no absorption or reemission), their specific number density, as seen by a comoving observer, satisfies the relation

$$n(\epsilon, z)d\epsilon = (1 + z)^3 n(\epsilon_0, 0)d\epsilon_0\,. \tag{5}$$

The $(1 + z)^3$ dependence roughly corresponds to the case of strong evolution of the galaxy optical emissivity. This model may approximately describe the properties of faint, $B > 25$ blue galaxies, the B and I counts of which show numbers which are well in excess of cosmological models that do not include galaxy luminosity evolution—galaxies were brighter in the past because they were forming more stars—or density evolution—galaxies are less numerous at present because of a large amount of merging at intermediate redshifts (see, e.g., Tyson 1988; Yoshii & Takahara 1988; Lilly, Cowie & Gardner 1991; Broadhurst, Ellis, & Glazebrook 1992). On the other hand, "normal," massive field galaxies selected by Mg II QSO absorption exhibit little evolution in their color, luminosity, and space density to redshifts as high as $z \sim 1.5$ (Steidel, Dickinson, & Persson 1994; Steidel & Dickinson 1995). Assuming an infinite power-law spectrum $n(\epsilon_0, 0) = n_0\,\epsilon_0^{-\alpha-1}$ and a cosmological model with $2q_0 z \ll 1$, the redshift dependence of the background photon density in a no-evolution (constant comoving emissivity) scenario becomes much shallower,

$$n(\epsilon, z)d\epsilon = (1 + z)^{2-\alpha} n(\epsilon_0, 0)d\epsilon_0 \tag{6}$$

($\alpha > -1$). Equation (4) can then be written as

$$\tau(E_0, z_{\rm em}) = \frac{c}{H_0}\left[\frac{(1 + z_{\rm em})^{2\alpha+k-1} - 1}{2\alpha + k - 1}\right]\sigma_{\rm T} n_0\left(\frac{m_e^2 c^4}{E_0}\right)^{-\alpha}\eta(\alpha)\,, \tag{7}$$

where (Gould & Schreder 1967)

$$\eta(\alpha) = \tfrac{3}{8}\int_1^{\infty} ds_0\, s_0^{-3-\alpha}\int_1^{s_0} ds s\sigma(s)\,, \tag{8}$$

$s_0 = E\epsilon/(m_e^2 c^4)$, and we have taken $n(\epsilon, z)d\epsilon \propto (1 + z)^k$. The exact analytical expression for $\eta(\alpha)$ can be found in Svensson (1987). Evaluating this function for $\alpha = 0$, 0.5, 1.0, 1.5, and 2.0 gives $\eta = 7/12$, $211\pi/2800$, $11/90$, $1623\pi/70560$, and $7/150$, respectively. When

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$\alpha > -0.5$ and $k = 3$ (strong evolution), most of the absorption of γ-ray photons occurs at high redshifts. In the no-evolution, $k = (2 - \alpha)$ case, this is only true for $\alpha > 0$. The pair production optical depth increases with increasing γ-ray photon energy E_0 for positive values of α, and it is, for a given observed EBL, larger in the case of a strongly evolving emissivity.

2.2. *Gamma Ray Observations*

The operation of the EGRET experiment and the Whipple Observatory has only recently made feasible the search for γ-ray attenuation by interaction with cosmic background radiation. During Phases I and II of the *Compton Gamma-Ray Observatory* mission, the EGRET instrument has positively detected 33 AGNs (Fichtel et al. 1994; von Montigny et al. 1995), with a number of them being sufficiently bright to provide quite accurate energy spectra over most of the EGRET energy range (from 20 MeV to ~ 30 GeV). The γ-ray flux in many of these sources completely dominates the overall energy budget. Four active galaxies are located at $z_{\rm em} \sim 2$. The closest objects, Mrk 421 ($z_{\rm em} = 0.031$), has been observed to be a TeV γ-ray source (Punch et al. 1992) by the Whipple detector. The dearth of $\gtrsim 3$ TeV photons in the Mrk 421 Whipple spectrum has been attributed by De Jager et al. (1994) to attenuation by the cosmic infrared background. A recent detailed analysis of the data by Dwek & Slavin (1994) has yielded the following fit to the spectrum of the local diffuse radiation field in the $\epsilon_0 = 0.03$–0.08 eV energy range (where the background is dominated by a thermal dust emission component):

$$\epsilon_0^2 n(\epsilon_0, 0) = 8.5 \times 10^{-4} \epsilon_0^{-0.55} h_{50}\ {\rm eV\ cm^{-3}}\ . \tag{9}$$

At shorter wavelengths, where stellar emission provides most of the target soft photons, only an upper limit can be placed,

$$\epsilon_0^2 n(\epsilon_0, 0) < 0.04\ h_{50}\ {\rm eV\ cm^{-3}} \tag{10}$$

in the $\epsilon = 0.3$–0.6 eV window. This value is a factor ~ 20 above the observed K-band energy density from galaxies (see § 3 below).

The EGRET observations suggest that the spectra of γ-ray loud blazars generally follow power laws with energy spectral indices α_γ between 0.4 and 2. The spectrum of 1633+382 ($z_{\rm em} = 1.81$), in particular, can be well fitted by a power law with $\alpha_\gamma = 0.9$ between 30 MeV and 10 GeV (Mattox et al. 1993). If these power laws extend to the 100 GeV energy region, then it is reasonable to expect such sources to be detectable by the forthcoming new generation of ground-based Cherenkov detectors. For energetic γ-rays observed at tens of GeV encountering (at an angle $\theta = \pi/2$) soft target photons which are now observed in the optical range, the pair production cross section is maximized along the path at redshift

$$1 + z_{\rm max} = 3\left(\frac{\epsilon_0}{2\ {\rm eV}}\right)^{-1/2}\left(\frac{E_0}{30\ {\rm GeV}}\right)^{-1/2}, \tag{11}$$

while the threshold condition requires $z > z_{\rm th} = 0.7(1 + z_{\rm max}) - 1$ for pair creation to occur at all. One could therefore use a lack of evidence for strong cosmological absorption in the 10–200 GeV γ-ray spectrum of a $z_{\rm em} \gtrsim 2$ quasar to set strict upper limits on the intergalactic energy density along the path. Vice versa, the presence of a sharp rollover in the observed spectrum at $E_0 \gtrsim 20$ GeV could provide, for the first time, a direct method to estimate the amount of background starlight present at early epochs. While the shape of the γ-ray spectral cutoff itself would provide information on the shape of the EBL spectrum, the observations of γ-ray sources at different redshifts would additionally constrain the EBL evolution history.

3. EXTRAGALACTIC BACKGROUND LIGHT

We can use the observed density of starlight as a check of our inventory of luminous objects in the universe. At optical frequencies, the EBL from discrete galaxies originates largely from metal-producing stellar populations in young galaxies. Deep CCD imaging surveys down to $B \sim 27$ have revealed a high surface density of weakly clustered, faint blue galaxies (Tyson 1988; Lilly et al. 1991). While the bulk of the $B \lesssim 24$ population is represented by normal dwarfs at low redshifts (Colless et al. 1993), the nature of the faintest, $B > 25$ objects remain unclear. A significant fraction of these have truly flat spectral energy distributions (Guhathakurta, Tyson, & Majewski 1990; Lilly et al. 1991), $(B-I)_{\rm AB} \sim 0$, the signature of a population of young objects undergoing a burst of star formation at early epochs, with high-mass stars producing metals and ultraviolet photons which are redshifted into the blue band. The large occurrence of gravitational lensing effects and the lack of many Lyman break candidates suggest that most of the 25–27 magnitude blue galaxies are distributed over a broad redshift range of 0.7–3. Galaxy counts versus isophototal magnitude down to $29B$ mag arcsec^{-2} have been used to calculate their contribution to the integrated mean surface brightness of the night sky. The equivalent energy density is (Tyson 1995)

$$\epsilon_0^2 n(\epsilon_0, 0) \sim 8 \times 10^{-4}\ {\rm eV\ cm^{-3}}\ , \tag{12}$$

approximately constant from 3600 to 9000 Å ($\epsilon_0 = 1.4$–3.4 eV). Galaxies fainter than $B = 24$ mag contribute $\sim 30\%$ of the EBL in the blue. At longer wavelengths, the background energy density from K-band selected galaxies to $K = 22$ is (Cowie et al. 1994)

$$\epsilon_0^2 n(\epsilon_0, 0) \sim 2 \times 10^{-3}\ {\rm eV\ cm^{-3}} \tag{13}$$

at 2.2 μm ($\epsilon_0 = 0.6$ eV). We will see in § 4 that, in the selected high-energy range, the cosmic γ-ray opacity to pair producion will not be sensitive to infrared background photons beyond few microns. At shorter wavelengths, galaxy counts down to a magnitude of 18.5 in the ultraviolet lead to a value in the range (Armand, Milliard, & Deharveng 1994)

$$\epsilon_0^2 n(\epsilon_0, 0) = 2\text{–}7 \times 10^{-4}\ {\rm eV\ cm^{-3}} \tag{14}$$

for the background at 2000 Å ($\epsilon_0 = 6.2$ eV). This must be compared to the firm upper limit set by direct background measurements,

$$\epsilon_0^2 n(\epsilon_0, 0) < 1.5 \times 10^{-3}\ {\rm eV\ cm^{-3}} \tag{15}$$

in the range from 1400 to 1900 Å (see Bowyer 1991 for a review).

The "proximity effect," which is the measured decrease in the number of Lyα-absorbing clouds induced by the UV radiation field of a QSO in its neighborhood, provides an estimate of the intensity of the metagalactic flux at the hydrogen Lyman edge, $J_L \sim 10^{-21}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at $1.7 < z < 3.8$ (Bajtlik, Duncan, & Ostriker 1988; Bechtold 1994). The attenuation at 912 Å due to the accumulated H I absorption associated with intervening Lyα clouds and Lyman-limit systems is a factor $\sim$4–6 over this redshift range (Madau 1992; Zuo & Phinney 1993; Miralda-Escudé & Ostriker 1990). The opactiy drops rapidly at longer wavelengths (see Fig. 1 of Madau 1992), and is negligible by $\sim$1200 Å in the rest frame at z. Thus we know that γ-rays at $1.7 < z < 3.8$ must see a background light of at least

$$\epsilon_0^2 n(\epsilon_0, 0) > 10^{-4} J_{-21}\left(\frac{2.5}{1+z}\right)^4 \text{ eV cm}^{-3} \tag{16}$$

at $1200(1+z)$ Å [$\epsilon_0 = 10.3/(1+z)$ eV]. We have written the inequality in this way, since this calculation assumes that the sources of ionizing radiation have no intrinsic discontinuity across the Lyman limit. Galaxies, which may be needed to account for J_L (Zuo & Phinney 1993), would have a Lyman discontinuity and thus contribute significantly more at low energies than our estimate (see model B in § 4). Finally, recent Hα surface brightness observations of an intergalactic neutral hydrogen cloud by Vogel et al. (1995) yield an upper limit of

$$\epsilon_0^2 n(\epsilon_0, 0) < 10^{-4} \text{ eV cm}^{-3} \tag{17}$$

at the Lyman limit ($\epsilon_0 = 13.6$ eV$+$). Notice that the ultraviolet background is quite constrained between equations (14) and (17).

Direct observations of the optical EBL are hampered by the much stronger foreground components of the light of the night sky. All-sky photometry has yielded upper limits to the diffuse EBL (after correction for foreground emission from airglow, the zodiacal and diffuse Galactic light) close to

$$\epsilon_0^2 n(\epsilon_0, 0) \lesssim 5 \times 10^{-3} \text{ eV cm}^{-3} \tag{18}$$

at 4400 Å (Toller 1983; Dube 1979; Mattila 1990). The difference between this value and the value in equation (12) for the EBL contributed by ordinary galaxies leaves open the possibility that a new class of objects exists with energy density at the present epoch $\sim$6 times greater than that of known $B < 27$ mag galaxies. In particular, there is room for galaxy evolution models in which a significant amount of ultraviolet light is produced at early epochs and then redshifted into the visible band. It is possible that optical surveys might have missed galaxies too compact to be distinguished from stars, or too low in surface brightness to be detected against the light of the night sky. We also know that, as the present rate of production of heavy elements in normal galaxies is too low to yield the observed element abundances, there must have been an epoch when the heavy element production rate per unit mass was considerably larger than it is now. Could an EBL at a level of the upper limit given in equation (18) be the starlight that accompanied element formation at moderate to high redshift? We recall that the energy density radiated by a population of objects at a redshift z which produce a present mass density of metals equal to $Z\rho_*$ is

$$\epsilon_0^2 n(\epsilon_0, 0) \sim \frac{Z\rho_* \eta c^2}{1+z} \sim 0.2\Omega_* h_{50}^2 \text{ eV cm}^{-3} , \tag{19}$$

where we have taken $Z = 0.03$, $z = 2$, and an efficiency of rest mass to starlight conversion of $\eta = 0.007$. Together, equations (18) and (19) bound the mass density of the heavy element producing material at $\Omega_* \lesssim 0.02\, h_{50}^{-2}$, about one-third of the baryon density derived from big bang nucleosynthesis constraints (Walker et al. 1991). Again, it is not clear where this material would finally end up, whether in dwarfs, low surface brightness galaxies, or in dark galactic halos.

4. MODEL RESULTS

We shall now illustrate the potential of using 10–200 GeV photons from high-redshift QSOs as a probe of the EBL and the history of galaxy and element formation. We will restrict our analysis to cosmological sources with $z_{\rm em} \sim 2$. In this case, only background photons with energies in the emitter's frame

$$\epsilon(z_{\rm em}) > 0.44\left(\frac{1+z_{\rm em}}{3}\right)^{-1}\left(\frac{E_0}{200 \text{ GeV}}\right)^{-1} \text{ eV} \tag{20}$$

will satisfy the threshold condition and contribute to the pair production optical depth. While polycyclic aromatic hydrocarbon molecules are responsible for some pronounced Galactic emission features at 3.3, 6.2, 7.7, 8.6, and 11.3 μm (Puget, Léger, & Boulanger 1985), the thermal dust emission contribution to the observed infrared EBL at wavelengths $\lambda_0 < 3$ μm ($\epsilon_0 > 0.4$ eV) is estimated to be negligible compared to starlight (see Figs. 1 and 12 of Franceschini et al. 1991).

As the pair production cross-section drops below 50% of the peak value for $\epsilon > 8\epsilon_{\rm th}$, and the background photon distribution is generally a decreasing function of energy, γ-rays at the low end of the energy interval under study will interact only weakly with photons above

$$\epsilon(z_{\rm em}) > 70\left(\frac{1+z_{\rm em}}{3}\right)^{-1}\left(\frac{E_0}{10 \text{ GeV}}\right)^{-1} \text{ eV} . \tag{21}$$

In the redshift range of interest, the selected γ-ray observing band will therefore probe that part of the spectrum of a star-forming galaxy, from the near-infrared to the ultraviolet, where most of the energy in normal starlight is emitted.

Below, we will compute the $\gamma\gamma \rightarrow e^+e^-$ cosmological optical depth along the line of sight to redshift $z_{\rm em} \sim 2$ for a variety of models of the cosmic background intensity and evolution. All models are constructed to satisfy the upper limits to the observed EBL given in equations (10), (15), (17), and (18). We shall assume that the redshift of formation of galaxies and the EBL is always greater than or equal to $z_{\rm em}$. It is worth mentioning that the attenuation of γ-rays by the local Galactic radiation field is indeed negligible compared with cosmological absorption. The energy density of optical/near-IR photons in the Galactic solar neighborhood is ~ 0.4 eV cm^{-3} (Mathis, Mezger, & Panagia 1983), ~ 200 (500) times larger than the energy density of the EBL from galaxies at 2.2 μm (0.36–0.9 μm). However, the look-back time to $z_{\rm em} \sim 2$ is $\sim 10^5$ times larger than the pathlength through the Galactic disk.

4.1. *EBL Models A*

In this "extreme" models the present-epoch EBL in the blue band is normalized at a level of the upper limit from all-sky photometry given in equation (18), $U_B(0) = 5 \times 10^{-3}$ eV cm^{-3}. This value implicitly requires a new class of sources with radiative energy density well in excess that of known galaxies at $B < 27$ mag. We assume a single power-law emissivity (with $\alpha > -1$) from the near-IR to the far-UV, with a large break at 1 Ry in order not to exceed the intensity of the metagalactic ionizing flux which is inferred from the proximity effect (Bajtlik et al. 1988). Beyond its pedagogical importance, these simple models provide an estimate of the *maximum* cosmological pair production opacity allowed at 10–200 GeV energies. We consider both a no-evolution (NE) and a strong-evolution (SE) scenario for the background emissivity. In the latter case, the diffuse energy density becomes

$$\epsilon^2 n(\epsilon, z) = U_B(0)(\epsilon/\epsilon_B)^{1-\alpha} a^{3+\alpha} \begin{cases} (1+z_{\rm L})^{3+\alpha} & (\epsilon < a\epsilon_{\rm L}) , \\ [U_{\rm L}/U_B(0)](\epsilon_B/\epsilon_{\rm L})^{1-\alpha} & (\epsilon \geq a\epsilon_{\rm L}) , \end{cases} \tag{22}$$

where $\epsilon_B = 2.82$ eV, $\epsilon_{\rm L} = 13.6$ eV, and $a = (1+z)/(1+z_{\rm L})$. We take a cosmic background density at the Lyman edge of $U_{\rm L} = 8.6 \times 10^{-4}$ eV cm^{-3} at $z_{\rm L} = 2$. In the case of a constant comoving emissivity, we derive instead

$$\epsilon^2 n(\epsilon, z) = U_{\rm L}(\epsilon/\epsilon_{\rm L})^{1-\alpha} a^2 \begin{cases} [1 - (\epsilon/\epsilon_{\rm L})^{1+\alpha}(1-D)]/D & (\epsilon < \epsilon_{\rm L}) , \\ 1 & (\epsilon \geq \epsilon_{\rm L}) , \end{cases} \tag{23}$$

where D measures the discontinuity in the volume emissivity across the rest-frame Lyman limit,

$$D = \frac{1 - (\epsilon_B/\epsilon_{\rm L})^{1+\alpha}}{[U_B(0)/U_{\rm L}](1+z_{\rm L})^2(\epsilon_{\rm L}/\epsilon_B)^{1-\alpha} - (\epsilon_B/\epsilon_{\rm L})^{1+\alpha}} . \tag{24}$$

For $\alpha = 2$, the break at 1 Ry is $1/D \simeq 11$. Note that the intergalactic absorption of Lyman-continuum (LyC) photons by neutral hydrogen associated with intervening Lyα forest clouds and Lyman-limit systems has been neglected in these models. We have checked that this approximation introduces only a modest error in our estimates of the cosmic opacity produced by models A.

Two representative model backgrounds are shown in Figure 1*a*, where we plot the extragalactic energy density $\epsilon^2 n(\epsilon, z)$ versus soft photon energy ϵ at $z = 0$, 1, and 2, for an SE scenario with $\alpha = 0$, and an NE scenario with $\alpha = 2$.

For illustrative purposes, we plot in Figure 1*b* the corresponding pair production optical depth along the line of sight to $z_{\rm em} = 1.8$, the redshift of quasar 1633+382, as a function of the observed γ-ray photon energy E_0. Note that, in the SE case, the transition from a transparent to an optically thick universe is quite sharp: (weakly) depending on the background spectral energy distribution (SED), the optical depth along the line of sight drops below 0.1 at $\lesssim 10$ GeV, and is already of order a few at 20 GeV. Also, due to the discontinuity at the Lyman limit in the assumed background SED, the energy dependence of $\tau(E_0)$ is different than the simple power-law scaling, $\tau \propto E_0^\alpha$, derived in equation (7). It is the lack of LyC target photons which produces the low-energy rollover. In the strong-evolution scenario, the energy density of optical/near UV photons is so high that cosmological sources at $z_{\rm em} \gtrsim 2$ will disappear altogether at $\gtrsim 20$ GeV. Even sources at more modest redshift, $z_{\rm em} \sim 1$, would be strongly attenuated above 40 GeV. Below 20 GeV collisions preferentially take place with near-ultraviolet radiation, while absorption by photons at ~ 1 μm dominates the opacity above 100 GeV. As depicted in Figure 1*b*, although the universe is much more transparent in the NE scenario, γ-ray sources at $z = 1.8$ will still be effectively undetectable above 50 GeV.

Therefore, according to the SE scenario, an EBL which is ~ 6 times higher than the value contributed by ordinary galaxies will produce a rollover in the γ-ray spectrum of quasar 1633+382 at energies $\gtrsim 10$ GeV. The highest energy photon detected from 1633+382 so far has an energy of 11 ± 1.6 GeV (Mattox et al. 1993; Mattox 1994), so no firm conclusion is possible at the present time. Unfortunately, because of the typically low photon statistics at $\gtrsim 10$ GeV (the EGRET effective area decreases gradually from 1500 cm^2 at 0.5–1 GeV to ~ 700 cm^2 at 10 GeV for targets near the center of the field of view), it appears unlikely that further EGRET observations of this blazar might be used to set useful constraints on the EBL energy density.

We can also derive, from Figure 1*b*, what is the minimum level of the background energy density which is needed to make the universe to $z_{\rm em} \sim 2$ optically thick to high-energy γ-ray photons. In the strong evolution case, we have $\tau(E_0 \sim 40\ {\rm GeV}) < 0.5$ for $U_B(0) < 2.5 \times 10^{-4}$ eV cm^{-3}, and $\tau(E_0 \sim 200\ {\rm GeV}) < 0.5$ for $U_{\rm IR}(0) < 2 \times 10^{-5}$ eV cm^{-3}, where $U_{\rm IR}(0)$ is the observed EBL density above 0.9 μm. (These values decrease by a factor of 10 in the no-evolution case.) A cosmic background with density comparable to the integrated blue light of known galaxies, $U_B(0) \sim 8 \times 10^{-4}$ eV cm^{-3}, would produce $\tau(E_0 \sim 20\ {\rm GeV}) \sim 0.5$. If more than 1% of the observed near-IR integrated contribution from known galaxies (see eq. [13]) were produced at early epochs, a cutoff at ~ 200 GeV should be easily detected in the γ-ray spectra of $z_{\rm em} \sim 2$ quasar by the next generation of ground-based Cherenkov detectors.

4.2. *EBL Models B*

In these models a fraction $\sim 50\%$ of the integrated galaxy light in the B-band (eq. [12]) originates in an early generation of massive stars radiating mainly in the near-ultraviolet. We compute the spectra for star-forming galaxies using the isochrone

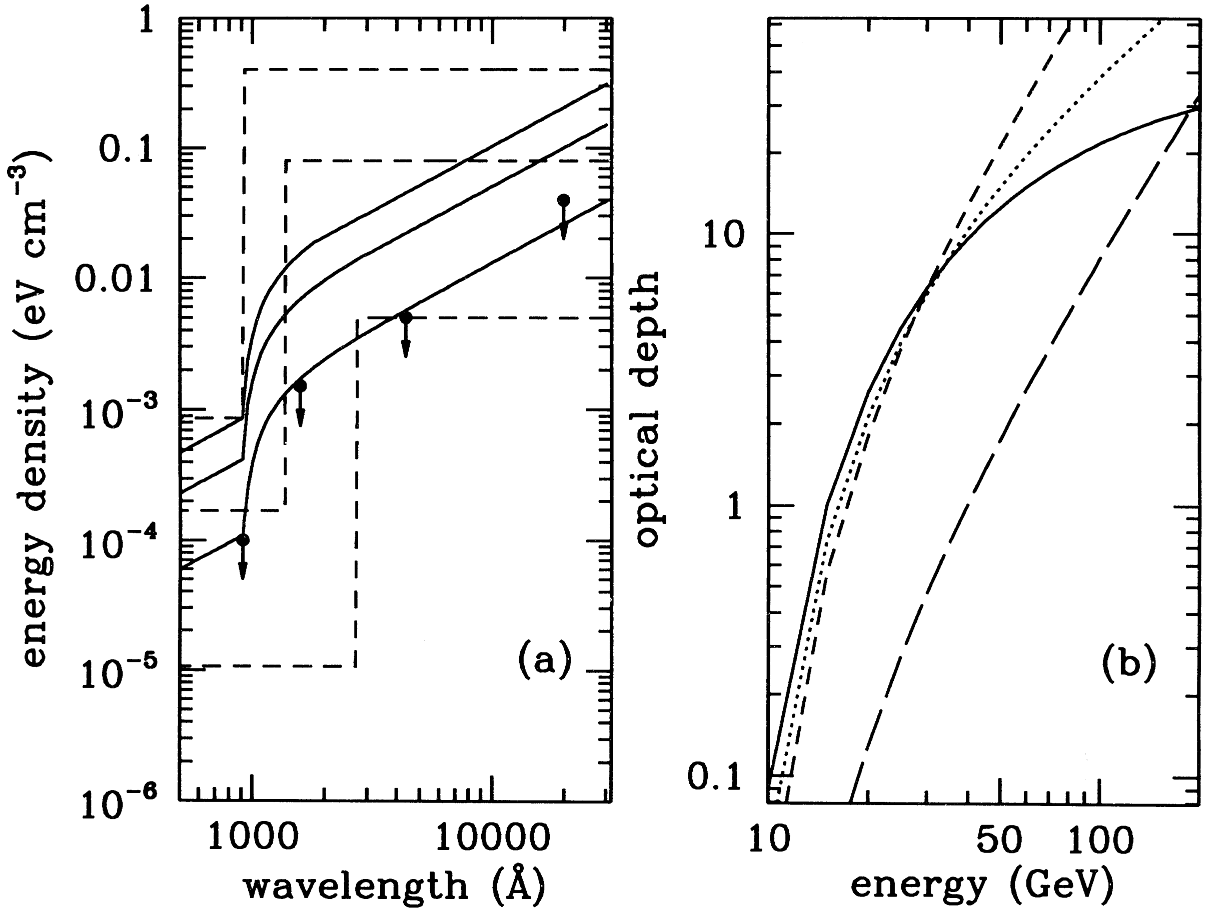

FIG. 1.—(*a*) The extragalactic background energy density vs. wavelength at redshifts $z = 0$, 1, and 2, according to models A (see text for details). *Solid lines*: constant comoving emissivity model, with power-law index $\alpha = 2$. *Dashed lines*: strong evolution model, with $\alpha = 0$. The upper limits derived at the Lyman edge from Hα observations of intergalactic hydrogen clouds (Vogel et al. 1995), at 1600 Å from direct background measurements (Bowyer 1991), in the *B* band from all-sky photometry (Toller 1983), and in the *K* band from the Whipple observations of Mrk 421 (Dwek & Slavin 1994) are indicated by arrows. (*b*) The $\gamma\gamma \rightarrow e^+e^-$ optical depth along the line of sight to redshift $z_{\rm em} = 1.8$ as a function of the observed γ-ray photon energy E_0, for a Friedmann cosmology with $H_0 = 50$ km s^{-1} Mpc^{-1} and $2q_0 z \ll 1$. The curves depict the opacity estimated in a strong evolution scenario with $\alpha = 0$ (*solid line*), 1 (*dotted line*), and 2 (*short-dashed line*), and in a constant comoving emissivity scenario with $\alpha = 2$ (*long-dashed line*).

synthesis spectral evolutionary code of Bruzual & Charlot (1993). The spectra extend from 5 Å to 3 μm and pertain exclusively to the stellar component. The models have solar metallicities and rely on Kurucz (1979) model atmospheres at ultraviolet wavelengths for stars in all stages with effective temperatures $40{,}000 < T_{\rm eff} < 50{,}000$ K. We consider two extreme histories of star formation in the model galaxies: an instantaneous coeval burst, appropriate, e.g., for star clusters that form on short timescales, and a constant star formation rate (SFR). Intermediate models characterized by exponentially declining SFR with timescale $t_{\rm burst}$ have the colors of a constant SFR model for $t < t_{\rm burst}$, after which they resemble a single burst population (Bruzual & Charlot 1993). We adopt a Salpeter initial mass function (IMF) with lower and upper cutoffs of 0.1 and 125 $M_\odot$, and ignore the effects of H I and dust in the local interstellar medium on the transfer of ultraviolet photons.

Figure 2*a* depicts our constant SFR model stellar background at redshifts $z = 0$, 1, and 2, and, for comparison, the background spectrum at $z = 2$ for the starburst model. In both cases the radiation field is normalized to produce a metagalactic flux at the Lyman edge of $J_{\rm L} = 10^{-21}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at $z = 2$. We assume, for simplicity, an ensemble-averaged galaxy spectrum at age 3×10^8 yr for the constant SFR case, and age 10^7 yr for the instantaneous burst case. The background emissivity is taken to be a δ-function at $z_{\rm on} = 2.8$ (constant SFR) and $z_{\rm on} = 2.3$ (starburst). In this sense, both models correspond to the case of strong evolution of the galaxy luminosity function. The delta function approximation for the galaxy emissivity is consistent with a constant SFR spectrum at age $t_{\rm age}$ provided $t_{\rm age} \ll t_{\rm H}$, where $t_{\rm H}$ is the Hubble time at $z_{\rm on}$.

We model the transfer of ionizing radiation through the intergalactic medium following Madau (1992). Both the numerous, optically thin Lyα forest clouds and the rare, optically thick Lyman-limit systems contribute significantly to the effective photoelectric optical depth of the universe (Madau 1991). LyC absorption along the line of sight produces a mean attenuation of the metagalactic flux between the present epoch and $z_{\rm on} = 2.8$ equal to $\langle e^{-\tau} \rangle = 0.37$, 0.03, and 0.06 at observed wavelengths 3200, 2000, and 1000 Å. The sharp drop in the $z = 0$ EBL spectrum at ∼850 Å is due to photoelectric absorption from intergalactic, singly ionized helium.

Note that the EBL models in Figure 2*a* provide only between 5% and 10% of the observed background energy density from galaxies in the *K*-band (eq. [13]). With the adopted population synthesis spectra, no simple constant comoving emissivity scenario

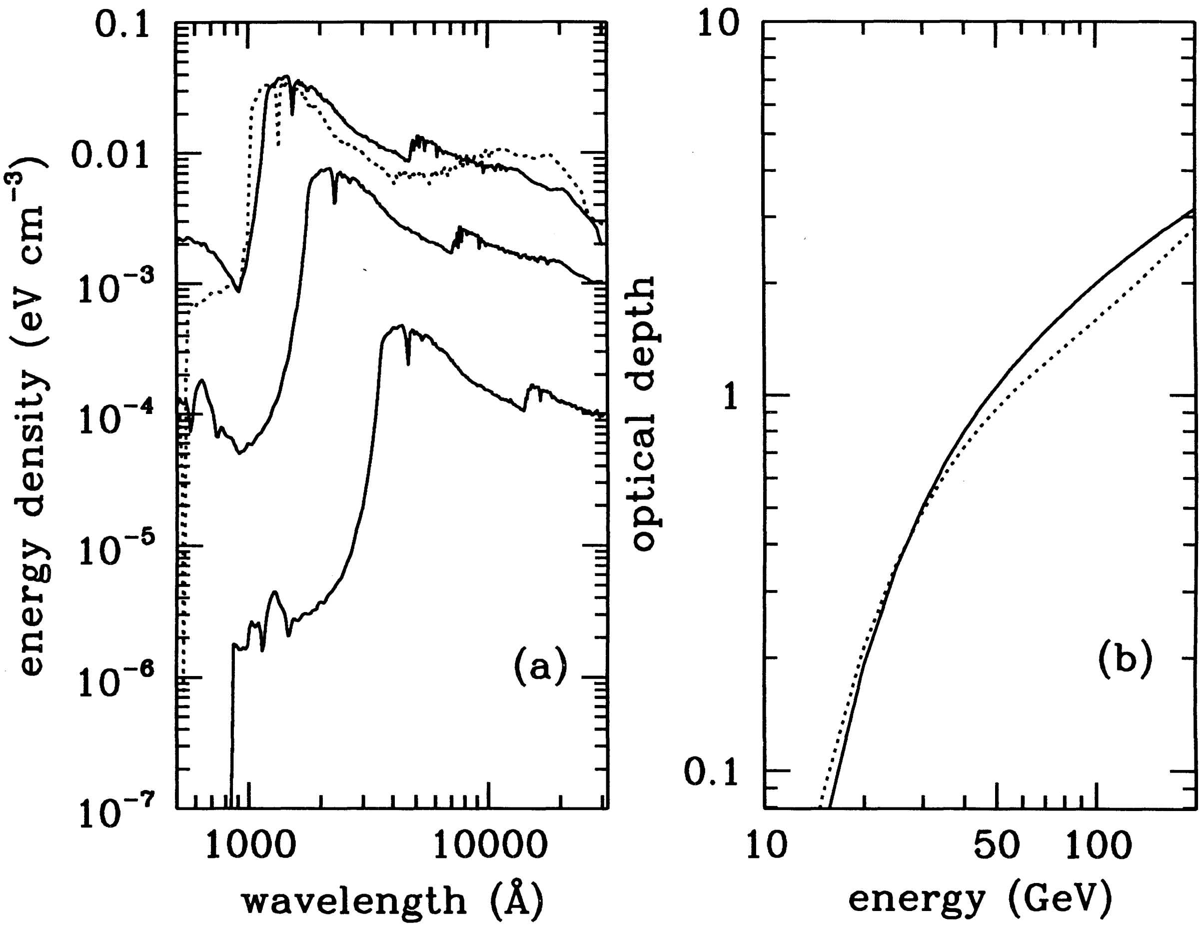

FIG. 2.—(*a*) The extragalactic background energy density vs. wavelength according to models B. *Solid lines*: strong evolution model, constant star-formation rate, observer redshift $z = 0$, 1, and 2, turn-on redshift $z_{\rm on} = 2.8$. *Dotted line*: strong evolution model, starburst, observer redshift $z = 2$, turn-on redshift $z_{\rm on} = 2.3$ (see text for details). The transfer of ionizing radiation through the intergalactic medium has been modeled following Madau (1992). (*b*) The pair production optical depth along the line of sight to redshift $z_{\rm em} = 2$. *Solid line*: constant star-formation rate spectrum. *Dotted line*: starburst spectrum.

was found to satisfy the upper limits to the observed ultraviolet flux and, at the same time, generate the LyC photon flux required at $z \sim 2$ by the proximity effect.

The ensuing cosmological pair-production opacity is plotted in Figure 2*b*. Again, we find that the universe to $z_{\rm em} = 2$ is optically thick to γ-ray photons with energies $E_0 \gtrsim 50$ GeV.

5. CONCLUSIONS

In this paper we have presented a detailed investigation of the $\gamma\gamma \rightarrow e^+e^-$ cosmological optical depth along the line of sight. We have focused our attention to the 10–200 GeV domain, where the attenuation is sensitive to the number density of near-UV, optical, and near-IR background photons, and shown that, for a variety of models of the extragalactic background intensity and evolution, the universe to intermediate redshifts might be optically thick to γ-ray photons above few tens of GeV. A number of ground-based detectors are being planned or designed at the present time to measure γ-ray fluxes in the critical energy window 10–500 GeV, the most promising of them being the Solar One Observatory (Tümer et al. 1991), the world's largest area atmospheric Cherenkov detector. Deeper observations of the EGRET $z_{\rm em} \sim 2$ sources, together with possible bright sources of GeV radiation at higher redshift, could provide, for the first time, direct constraints on the presence of starlight at early cosmological epochs, probing the era over which galaxies and the EBL actually form.

We finally note that other signatures of the effect of γ-ray attenuation by interactions with cosmic background radiation might be potentially detectable. When a γ-ray is absorbed and converted to an e^+e^- pair, the electrons cool by inverse Compton scattering on the microwave background ambient photons (see, e.g., Aharonian, Coppi, & Völk 1994). In the case of a 20 GeV primary photon, for example, the scattered secondary photons are initially of MeV energy, but as the pairs cool, a few percent of the total energy is scattered into keV X-rays, with a scattering angle of a few arcminutes. If the pairs are not deflected by an intergalactic magnetic field, these X-rays will move in a narrow cone about the direction of their parent γ-rays. Thus the γ-ray source will appear to be surrounded by a " halo " of scattered X-rays. The physics and detectability of these X-ray diffuse halos, and their use as probes of the intergalactic magnetic field, will be discussed in a companion paper (Phinney & Madau 1995).

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