The Astrophysical Journal, 665:1023–1029, 2007 August 20

THE REDSHIFT DEPENDENCE OF GAMMA-RAY ABSORPTION IN THE ENVIRONMENTS OF STRONG-LINE AGNs

A. Reimer[1]

Received 2007 April 5; accepted 2007 May 9

ABSTRACT

The case of γ-ray absorption due to photon-photon pair production of jet photons in the external photon environments, such as the accretion disk and the broad-line region radiation fields, of γ-ray–loud active galactic nuclei (AGNs) that exhibit strong emission lines is considered. I demonstrate that this "local opacity," if detected, will almost unavoidably be redshift-dependent in the sub-TeV range. This introduces nonnegligible biases and complicates approaches for studying the evolution of the extragalactic background light with contemporary GeV instruments such as the *Gamma-Ray Large Area Space Telescope* (*GLAST*), where the γ-ray horizon is probed by means of statistical analysis of absorption features (e.g., the Fazio-Stecker relation) in AGN spectra at various redshifts. It particularly applies to strong-line quasars, where external photon fields are potentially involved in γ-ray production.

Subject headings: diffuse radiation — galaxies: active — galaxies: evolution — galaxies: nuclei — gamma rays: theory — radiation mechanisms: nonthermal

Online material: color figures

1. INTRODUCTION

Following the unification scheme, the central nucleus of an active galaxy consists of a black hole (BH), an accretion disk, line-emitting clouds, and a dust torus, and it emanates prominent jets when classified as radio-loud. The properties of radio-loud active galactic nuclei (AGNs) viewed at a small angle to the line of sight are in general agreement with the common blazar properties (e.g., Urry & Padovani 1995; Padovani et al. 2007). Their broadband emission covers the complete electromagnetic band, from the radio up to the γ-ray band, in some cases even reaching TeV energies, and is widely dominated by beamed nonthermal emission from a relativistic jet. The blazar class subdivides into BL Lac objects and flat-spectrum radio quasars (FSRQs). The difference dividing both subclasses is generally considered in the detection of strong emission lines in the case of FSRQs, while in BL Lac objects the equivalent width of emission lines is depressed, or the lines are entirely absent. The physical reason is thought to lie predominantly in the weak accretion disk radiation field of BL Lac objects, whereas BHs in the nuclei of FSRQs accrete with high rates, leading to luminous accretion disk photon fields. The present work deals with γ-ray–loud AGNs observed during an epoch of a bright accretion disk and accompanied with the appearance of strong emission lines. For simplicity, I refer to them as "quasars" in the following, although some radio-loud AGNs classified conventionally as BL Lac objects may occasionally fall into this category as well (e.g., Falomo et al. 1994; Sbarufatti et al. 2006), and vice versa.

Gamma-ray production mechanisms, both leptonic and hadronic, in AGN jets often involve either the external radiation fields associated with the immediate AGN environment or internal jet photons. For example, contributions from interactions in the accretion disk or broad-line region (BLR) radiation fields are often required in order to explain the overall γ-ray spectral energy distribution (SED) from FSRQs (e.g., Ghisellini & Madau 1996; Böttcher 2000), while the SEDs of low-luminosity BL Lac objects are often fitted with either synchrotron self-Compton models (e.g., Ghisellini et al. 1985) or their hadronic equivalent, the synchrotron-proton blazar models (e.g., Mannheim 1993; Mücke & Protheroe 2000; Aharonian 2000; Mücke et al. 2003). The former scenario places the γ-ray emission region rather close to the BLR clouds. This has immediate consequences: if external radiation fields in quasar environments play a nonnegligible role for γ-ray production, then at the same time they are also significant for the quasi-resonant process of photon-photon pair production, whose peak cross section possesses a comparable value to the Thomson cross section. It should be noted, however, that the position of the high-energy emission region is still a matter of debate, with locations proposed to be also far away from the BLR (e.g., Lindfors et al. 2005; Sokolov & Marscher 2005). If this is the case, external Compton emission (e.g., Dermer & Schlickeiser 1993) or pair cascade radiation initiated by ultra–high energy cosmic-ray interactions on external photon fields (e.g., Protheroe 1997; Atoyan & Dermer 2003) in those sources does not provide an appreciable contribution to the observed high-energy emission.

The present work concerns specifically opacity features in the >10 GeV regime created by photon absorption through e^+-e^- pair production in radiation fields in the vicinity of the BH, but external to the jets, in γ-ray–loud quasars. Past works on this subject (e.g., Protheroe & Biermann 1997; Donea & Protheroe 2003; Becker & Kafatos 1995) indicate the importance of this process for constraining AGN properties such as the location of the γ-ray region above the disk, the disk radiation fields, and the torus temperature. In contrast to these works, I will be focusing on the evolution of external radiation fields in quasar environments and the consequences for the resulting opacity features in the γ-ray band covered by current and near-future instruments. This is primarily motivated by the anticipated studies of the evolution of the extragalactic background light (EBL) through the detection of absorption features in a large sample of high-redshift sources using the Large Area Telescope (LAT) on board *GLAST.* Dedicated methods have been developed here to probe the evolution of the

[1] W. W. Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305; afr@stanford.edu.

EBL via detecting the horizon of γ-rays emitted from extragalactic sources such as AGNs and gamma-ray bursts (GRBs) while they are propagating through the EBL to the Earth (e.g., Chen et al. 2004; Kneiske et al. 2004). They involve either the determination of the ratio of absorbed to unabsorbed flux versus redshift, z, or the detection of the e-folding cutoff energy $E(\tau_{\gamma\gamma} = 1)$ versus redshift (the "Fazio-Stecker relation"; Fazio & Stecker 1970) in a large number of sources at various redshifts in order to disentangle intrinsic blazar features from absorption-caused ones during propagation in the EBL. The common underlying reasoning for this procedure is that the observation of any redshift-dependent attenuation in γ-ray AGNs can only be attributed to absorption in the EBL and that no other sources of redshift-dependent opacity exist in those sources. Here I will demonstrate that opacity due to photon absorption from photon-photon pair production caused in external radiation fields within the AGN system (in the following called "local absorption," to be distinguished from "self-absorption" in the internal jet radiation fields) will most likely result in optical depth values that increase with the source redshift and coincidentally mimic redshift-dependent EBL-caused absorption.

The outline of this paper is organized as follows. Sections 2 and 3 describe the considered external target photon fields (the accretion disk and the BLR radiation field) for photon-photon pair production and the corresponding optical depth calculation, respectively. In § 5 I will apply various models of supermassive BH growth and accretion rate evolution, which are described in § 4, to the γ-ray attenuation calculations. The results, with particular emphasis on the possibility of a redshift dependence of the local opacity, are presented in § 5. The paper closes with conclusions and a discussion in § 6.

2. CHARACTERIZATION OF EXTERNAL RADIATION FIELDS IN QUASARS

The most relevant target radiation fields in AGN environments for photon absorption in the LAT energy range, ~0.02–300 GeV,[2] are the optical/UV bands of the accretion disk photon field and the radiation field of the BLR. These will be considered in the following subsections. I assume the radiation fields to be located azimuthally symmetric with respect to the jet axis and to radiate persistently during γ-ray emission.[3]

2.1. *Quasar Accretion Disk Radiation Fields*

The accretion disk spectrum in FSRQs is assumed to follow the cool, optically thick blackbody solution of Shakura & Sunyaev (1973), with a given accretion rate $\dot{M}_{\rm acc}$ suitable for AGNs that show strong emission lines ("strong-line AGNs"). The differential photon density $n(\epsilon, \Omega)$ into a solid angle $d\Omega = 2\pi\, d\mu$, where $\mu = \cos\xi$, is

$$\frac{dn(\epsilon, \Omega)}{d\Omega} = \frac{dn}{2\pi\, d\mu} = \frac{\epsilon^2}{2\mu c^3}\left(\frac{m_e c^2}{h}\right)^3 \left\{\exp\left[\frac{\epsilon}{\theta(R)}\right] - 1\right\}^{-1}, \tag{1}$$

where $R = l(\mu^{-2} - 1)^{1/2}$, l is the distance of the emission region above the BH, ϵ is the photon energy, and

$$\theta(R) = \frac{k_{\rm B} T(R)}{m_e c^2} \simeq 1.44\left(\frac{M_{\rm BH}}{M_\odot}\right)^{-1/2}\left(\frac{\dot{M}_{\rm acc}}{M_\odot\ {\rm yr}^{-1}}\right)^{1/4} \times \left(\frac{R}{R_g}\right)^{-3/4}\left(1 - \sqrt{\frac{R_i}{R}}\right)^{1/4}, \tag{2}$$

where $R_i = 6GM_{\rm BH}/c^2$ for a Schwarzschild metric, $R_g = GM_{\rm BH}/c^2$, and $k_{\rm B}$ is the Boltzmann constant. For the opacity calculations the disk is considered to extend from 6 to $10^5 R_g$. Typical accretion rates for strong quasars approach the Eddington accretion rate $\dot{M}_{\rm Edd}$, $\dot{M}_{\rm acc} = 0.1$–$1\dot{M}_{\rm Edd}$; likewise, typical luminosities for strong quasars approach the Eddington luminosity $L_{\rm Edd}$.

2.2. *The BLR Radiation Field in Quasars*

The accretion disk is considered to be the photoionizing source of the BLR material, and emission lines are produced through recombination. The BLR geometry is approximated as a spherical shell with radius r that is filled with clouds, extending from $r_{\rm in}$ to $r_{\rm out}$. In this picture the accretion disk is located at $r = 0$. In the following the shell size is fixed to $r_{\rm in} = 0.01$ pc and $r_{\rm out} = 0.4$ pc, which are typical values for quasars (e.g., Kaspi et al. 2004). A geometrically extended shell is supported from the observations by the AGN Watch campaigns.[4] The opacity calculations require both spectral and spatial knowledge of the emissivity of the BLR radiation field. Information about the cloud sizes and their spatial distribution can be deduced in general from reverberation mapping. Although most of the details on BLR physics and geometry have been derived by the study of radio-quiet AGNs, no major differences in the broad-line flux between radio-quiet and radio-loud sources have been found so far (e.g., Corbin 1992; Wills et al. 1993). For the present calculations, both the number density $n_{\rm cl} \propto r^\alpha$ and the cross section $\sigma_{\rm cl} \propto r^\beta$ of the clouds are assumed to follow a power law, with exponents $\alpha = -1.5$ and $\beta = 0.6$, respectively, as derived by Kaspi & Netzer (1999). A fraction $d\tau_{\rm BLR} = n_{\rm cl}\sigma_{\rm cl}\, dr$ of the central source luminosity $L_{\rm disk}$ is reprocessed into line radiation such that the total BLR luminosity, which is assumed to be optically thin, is $L_{\rm BLR} = \tau_{\rm BLR} L_{\rm disk}$, and these lines are assumed to radiate isotropically. Observational support for a very narrow range of values of $\tau_{\rm BLR}$ (i.e., the ratio of emitted to ionizing continuum photons) is provided by the observation of a linear correlation between Balmer line and optical disk luminosity in AGNs over several orders of magnitude (e.g., Yee 1980; Shuder 1981). This is compatible with photoionization/recombination theory, which expects the H line brightness to be correlated with the ionizing continuum flux, as the line luminosity is driven by this ionizing disk continuum. A statistical blazar study of Celotti et al. (1997) implies $\tau_{\rm BLR} \simeq 0.01$, which is used in the following. Changing the parameters (e.g., $\tau_{\rm BLR}$, $r_{\rm in}$, $r_{\rm out}$) that are fixed here will alter the absolute values of the γ-ray attenuation; however, any redshift dependence remains unaffected.

The calculation of the γ-ray opacity follows the procedure outlined in Donea & Protheroe (2003) for the geometrically thick shell case, but uses a more refined BLR line spectrum. The "average" BLR spectrum of Francis et al. (1991), together with the Hα line strength reported by Gaskell et al. (1981), sums up to 35 lines, with Hα and Lyα being the strongest lines. For the

[2] See http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.

[3] Optical continuum variations that are generally attributed to accretion disk radiation in AGNs are typically observed on timescales of months to years (e.g., Peterson 1993). This is significantly longer than typical variability timescales in the γ-ray domain and thus allows the disk emission to be approximated as a constant photon field for the purpose of the present work.

[4] See http://www.astronomy.ohio-state.edu/~agnwatch/.

present work, the BLR spectrum is approximated as a two-component spectrum, $n(\epsilon) \propto \delta(\epsilon - \epsilon_{\mathrm{H}\alpha}) + \delta(\epsilon - \epsilon_{\mathrm{Ly}\alpha})$, with the total luminosity of all lines at >4000 Å (~32%) to be radiated at the strongest optical line (Hα) wavelength and the total line luminosity at <4000 Å (~68%) emitted at the strongest UV line, Lyα. A refined treatment of the BLR spectrum is straightforward but will not alter the results on the redshift dependence of the local opacity, nor will it add qualitatively new insights to the subject of the present work.

3. GeV PHOTON ABSORPTION IN QUASAR RADIATION FIELDS

The calculation of the optical depth,

$$d\tau_{\gamma\gamma}(E, l) = dl \int_{\epsilon_0}^{\infty} d\epsilon \int_{\mu_{\min}}^{\mu_{\max}} d\mu\,(1-\mu)\sigma_{\gamma\gamma}(s)2\pi \frac{dn(\epsilon, l, \mu)}{d\Omega}$$
$$= \frac{dl}{4E^2}\int_{\epsilon_0}^{\infty} d\epsilon\,\epsilon^{-2}\int_{s_{\min}}^{s_{\max}} s\sigma_{\gamma\gamma}(s)\,\frac{dn(\epsilon, l, \mu)}{d\mu}, \qquad (3)$$

where E is the primary γ-ray photon energy, $\mu = \cos\xi$, $s = 2E\epsilon(1-\mu)$, $\epsilon_0 = \min(\epsilon_{\mathrm{thr}}, \epsilon_{\min})$, $\epsilon_{\mathrm{thr}} = (2m_e c^2)^2/[2E(1-\mu_{\min})]$, $\epsilon_{\min} = s_{\min}/[2E(1-\mu_{\min})]$, $s_{\min} = 2E\epsilon(1-\mu_{\max})$, and $s_{\max} = 2E\epsilon(1-\mu_{\min})$, takes into account the full angle-dependent cross section (e.g., Gould & Schréder 1967; Jauch & Rohrlich 1976). The quantities $\mu_{\min}$ and $\mu_{\max}$ are determined by the geometry of the target photon field. The total cross section maximizes at $x = (1-y^{-1})^{1/2} \approx 0.7$, where $y = (1/2)E\epsilon(1-\mu)/(m_e^2c^4) > 1$ (ξ is the photon interaction angle) is the threshold condition of the pair production process. The very prominent peak of the cross section near threshold reaches roughly $\sigma_{\gamma\gamma,\max} \approx 0.26\sigma_{\mathrm{T}}$, where σ_{T} is the Thomson cross section. The narrowness of the pair production cross section forces over half the interactions to occur in a small target photon energy interval $\Delta\epsilon \approx (4/3 \pm 2/3)\epsilon^*$ centered on $\epsilon^* \approx 0.8(E/\mathrm{TeV})^{-1}$ eV for a smooth broadband spectrum (Aharonian 2004).

Figure 1 shows the resulting opacity from different distances l_0 of the γ-ray production region above the black hole to $l \to \infty$, both in the accretion disk (*light gray curves*) and in the BLR radiation field (*dark gray curves*), for typical quasar accretion rates and BH masses. The two "bumps" in the dark gray opacity curves are the result of absorption in the Hα and Lyα lines of the BLR, and they smooth out when a detailed multiline (>30 lines) spectrum is used. In typical quasar environments the strength of local absorption is strongly dependent on the location of the emission region with respect to the target photon field. If the γ-ray emission region is located not well beyond the BLR, which is mandatory for γ-ray production that involves external photon fields, local γ-ray absorption features in FSRQ spectra have to be expected at values of $E(1+z)$ that are greater than or equal to several tens of GeV.

4. BLACK HOLE EVOLUTION AND ACCRETION RATES

The key step of this work is the application of cosmological black hole and quasar evolution to the expected pair production opacity of γ-ray photons in AGNs, with direct implications for studies of the evolution of the EBL.

With the availability of large AGN data archives, enormous advances in BH demographics have been made. The cosmic evolution of the BH mass accretion rate has recently been studied by Netzer & Trakhtenbrot (2007), based on $\sim 10^4$ SDSS type 1 radio-loud and radio-quiet AGNs in a large redshift range ($z \leq 0.75$). Significantly higher accretion rates at larger redshifts were derived with an Eddington ratio of the accretion luminosity $L_{\mathrm{acc}}/L_{\mathrm{Edd}} \propto (1+z)^{\delta(M_{\mathrm{BH}}, z)}$, with $\delta(M_{\mathrm{BH}}, z) \simeq 6$–9.

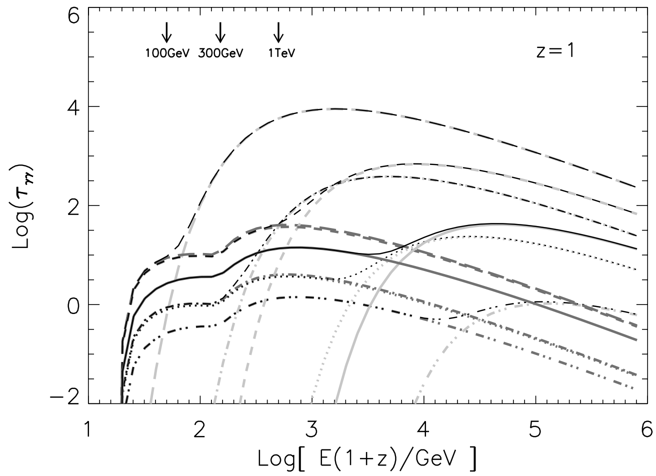

Fig. 1.—Optical depths from $l = l_0$ to ∞ for jet γ-rays interacting with accretion disk photons (*light gray curves*) and BLR photons (*dark gray curves*) with accretion rates taken from Netzer & Trakhtenbrot (2007) for type I AGNs at redshift $z = 1$. The black curves correspond to the sum of opacities in both the accretion disk and the BLR radiation field. Parameters are as follows: The black hole mass $M_{\mathrm{BH}} = 10^8\,M_\odot$ ($L_{\mathrm{disk}} = 0.2L_{\mathrm{Edd}}$, $\dot{M}_{\mathrm{acc}} = 0.5\,M_\odot\,\mathrm{yr}^{-1}$), with $l_0 = 0.1$ pc (*dash–double-dotted curves*), 0.01 pc (*dotted curves*), 0.001 pc (*dash-dotted curves*), and $M_{\mathrm{BH}} = 10^9\,M_\odot$ ($L_{\mathrm{disk}} = 0.2L_{\mathrm{Edd}}$, $\dot{M}_{\mathrm{acc}} = 5.3\,M_\odot\,\mathrm{yr}^{-1}$), with $l_0 = 0.1$ pc (*solid curves*), 0.01 pc (*dashed curves*), and 0.001 pc (*long-dashed curves*). Energies in the observer frame are indicated by arrows. [*See the electronic edition of the Journal for a color version of this figure.*]

The intriguing similarity observed of the time history of star formation (SF) and BH accretion rate density (e.g., Marconi et al. 2004), as well as established relations between BH mass and some bulge properties of the host galaxy, lead to the widely accepted picture of a joint evolution of QSOs/BHs and their host galaxies (see also Barger et al. 2001; Marconi et al. 2004).[5] Moreover, the observed BH mass function is consistent with that inferred from quasar luminosities for simple assumptions of the accretion efficiency (e.g., Soltan 1982; Cavaliere & Padovani 1988; Marconi et al. 2004). The evolution of their luminosity functions at both soft and hard X-rays shows the number density of fainter AGNs to peak at lower redshifts than that of the brighter ones (e.g., Ueda et al. 2003; Hasinger et al. 2005; Barger et al. 2005). This evidence of "downsizing" directly leads to the picture of an "antihierarchical" BH growth (i.e., high-mass BHs grow faster and low-mass BHs grow preferably at lower redshift) and has meanwhile been confirmed by multiple studies: an analysis based on the fundamental plane of accreting BHs (Merloni 2004); the phenomenological approach of Marconi et al. (2004) for determining the evolution of the BH mass function using observational constraints from the local BH mass function, the evolving X-ray luminosity functions, and energetics from the X-ray background; determinations of low-luminosity, high-redshift quasar luminosity functions by the GOODS collaboration (e.g., Cristiani et al. 2004); and the COMBO-17 survey at higher luminosities (Wolf et al. 2003), to name just a few. The combination of these observational findings with the theoretically advocated hierarchical clustering paradigm (based on cold dark matter) led to the awareness of feedback processes working during the process of BH mass growth in AGN systems (see, e.g., Granato et al. 2004; Lapi et al. 2006; Fontanot et al. 2006).

While the parameter space is still large, the advocated evolution of BH growth and thus accretion rates has severe implications for

[5] Since the evolution of the EBL is strongly influenced by the cosmic SF history, one may in turn even speculate about an indirect imprint of the BH accretion history into the evolution of the EBL.

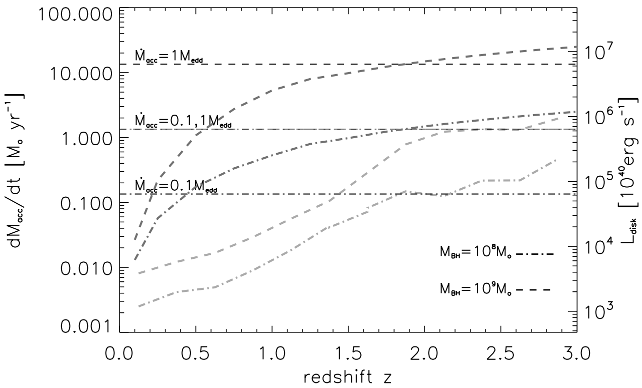

FIG. 2.—Evolution of BH mass accretion rates. Dark gray curves are from the Netzer & Trakhtenbrot (2007) analysis for $z \leq 0.75$, complemented with a mild evolution at large redshifts (Lapi et al. 2006). Light gray curves are from the Marconi et al. (2004) model. An accretion radiation efficiency of 0.1 was used to convert the average BH growth history into evolution of accretion rates. Black horizontal lines represent no evolution, with $\dot{M}_{\rm acc} = 0.1\text{–}1\dot{M}_{\rm Edd}$. Dash-dotted curves are for $M_{\rm BH} = 10^8\ M_\odot$, and dashed curves are for $M_{\rm BH} = 10^9\ M_\odot$. [*See the electronic edition of the Journal for a color version of this figure.*]

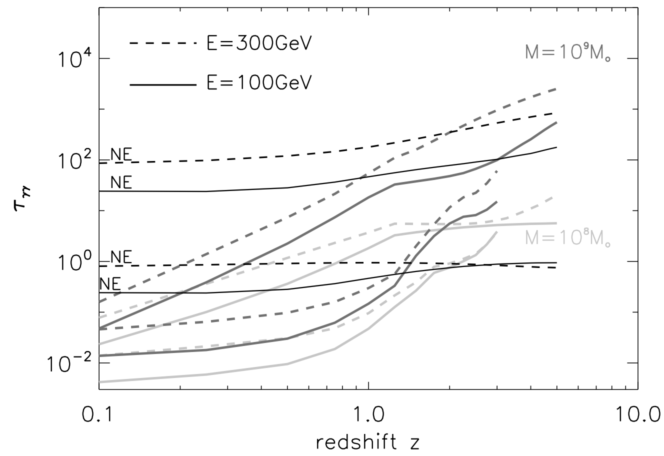

FIG. 4.—Redshift dependence of the "local opacity" of jet γ-rays interacting with accretion disk and BLR photons, with accretion rates following the Netzer & Trakhtenbrot (2007)–Lapi et al. (2006) (*upper gray curves*) and the Marconi et al. (2004) evolution model (*lower gray curves*), compared to resulting opacities for nonevolving accretion rates (shown with label "NE" *upper black curves*: $M_{\rm BH} = 10^9\ M_\odot$, $\dot{M}_{\rm acc} = \dot{M}_{\rm Edd}$, $L_{\rm disk} \approx 0.5L_{\rm Edd} \approx 6 \times 10^{46}$ ergs s^{-1}; *lower black curves*: $M_{\rm BH} = 10^8\ M_\odot$, $\dot{M}_{\rm acc} = 0.1\dot{M}_{\rm Edd}$, $L_{\rm disk} \approx 0.05L_{\rm Edd} \approx 6 \times 10^{44}$ ergs s^{-1}). A strong redshift dependence is apparent in almost all cases, including the case of nonevolving accretion rates. The rather constant $\tau_{\gamma\gamma}(z)$ curve at 300 GeV for the nonevolving low-rate, low–BH mass case is due to the photon-photon interactions occurring predominantly in the valley between the $\tau_{\gamma\gamma}(E)$ curves for the BLR and accretion disk photon field (see Fig. 3). [*See the electronic edition of the Journal for a color version of this figure.*]

the γ-ray quasar population, where local γ-ray absorption in accretion disk and BLR radiation fields is potentially important.

In the following I use three models as examples for the evolution of the cosmic BH accretion rate (Fig. 2): (a) the Netzer & Trakhtenbrot (2007) analysis, complemented by the Lapi et al. (2006) model for redshifts $z > 1$, where only modest evolution is proposed, (b) the "antihierarchical" BH growth picture of Marconi et al. (2004), and (c) a nonevolution scenario for comparison. The evolution of the accretion rate of model (b) has been derived by using the average BH growth history as published in Marconi et al. (2004) from redshift $z = 3$ (where 100% source activity has been assumed as an initial condition) to $z = 0$, together with their supported accretion radiation efficiency of 0.1. Models (a) and (b) both show strongly redshift-dependent BH accretion rates, with higher rates at larger redshifts for BH masses of $10^8\text{–}10^9\ M_\odot$, typical for quasars. For the present work, the chosen models are used plainly as means and agencies to demonstrate how any evolution of accretion rates transforms into a redshift dependence of the local optical pair production depth in strong-line quasars.

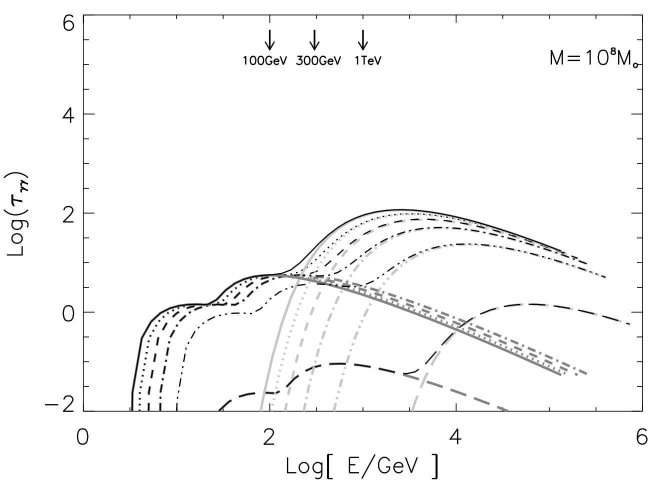

FIG. 3.—Optical depths from $l = 0.01$ pc to $l \rightarrow \infty$ for jet γ-rays interacting with accretion disk photons (*light gray curves*) and BLR photons (*dark gray curves*), with accretion rates following the Netzer & Trakhtenbrot (2007)–Lapi et al. (2006) evolution curves for a BH with mass $M_{\rm BH} = 10^8\ M_\odot$. The black curves represent the sum of both opacity in the accretion disk and the BLR radiation field and correspond to redshifts $z = 0.1$, 1, 2, 3, 4, and 5 from bottom to top, respectively. The fast evolution of accretion rates at low redshift is apparent. Note that for a large energy range, γ-ray absorption occurs mostly near the increasing part of the $\tau_{\gamma\gamma}(E)$ function, near the pair production threshold. [*See the electronic edition of the Journal for a color version of this figure.*]

5. IS THE LOCAL OPACITY REDSHIFT-DEPENDENT?

When studying the evolution of the EBL by means of a statistical analysis of signatures of γ-ray attenuation with effective opacity $\tau_{\rm eff} = \tau_{\rm EBL} + \tau_{\rm source}$ from extragalactic objects, recognizing and disentangling absorption taking place within the source system ("local opacity"; $\tau_{\rm source}$) and in the EBL during photon propagation to the Earth ("EBL-caused opacity"; $\tau_{\rm EBL}$) is a crucial task. If both opacities depend on redshift in the same direction, but the exact value of each is unknown, the redshift parameter alone will not be sufficient to extract the evolution of the EBL-caused opacity. In order to assess the probability for this to take place in quasar-like AGNs, in the following I will apply realistic evolving, as well as nonevolving, cosmic accretion rate curves (see Fig. 2) to the calculation of the expected opacity from γ-ray absorption in the accretion disk and BLR radiation fields, using the procedure outlined in § 2. Any evolution of accretion rates translates into an evolution of the target photon fields under consideration for photon-photon interactions, and thus into a redshift dependence of the local opacity. For this study, the position of the γ-ray production is fixed to $l_0 = 0.01$ pc. A location of the γ-ray emission region close to the BLR is particularly preferred by both leptonic and hadronic blazar emission models that require external photon fields such as the accretion disk and BLR radiation as an ingredient for γ-ray production through particle-photon interactions. If γ-ray production is located well beyond the BLR, photon-photon pair production on external photon fields ceases to be an important process, and so will external Compton scattering above the pair production threshold, owing to their comparable cross section values there, or photo-pion production on accretion disk and BLR photons.

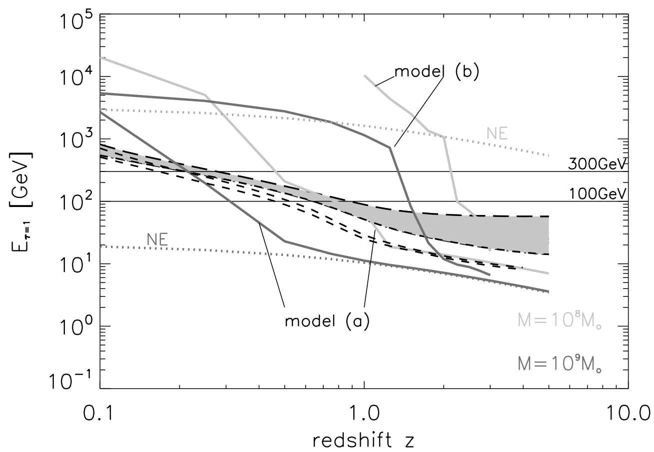

FIG. 5.—Critical energy $E(\tau_{\gamma\gamma} = 1, z)$ vs. redshift (γ-ray horizon) of jet γ-rays interacting with accretion disk and BLR photons, with accretion rates following the Netzer & Trakhtenbrot (2007)–Lapi et al. (2006) [*lower solid gray curves*; model (a)] and the Marconi et al. (2004) evolution picture [*upper solid gray curves*; model (b)], and for nonevolving accretion rates (*dotted curves*: $\dot{M}_{\rm acc} = 0.1$ [*light gray*] and 1 [*dark gray*]), compared to the Fazio-Stecker presentation of various evolutionary EBL models of Kneiske et al. (2004) (*gray shaded area*) and Stecker et al. (2006) (fast evolution model, *upper short-dashed line*; baseline model, *lower short-dashed line*). Example observer energies of 100 and 300 GeV are indicated by solid black lines. All models show a redshift dependence of $E(\tau_{\gamma\gamma} = 1)$. [*See the electronic edition of the Journal for a color version of this figure.*]

The goal of this exercise is to verify a possible *redshift dependence* of the local opacity. The absolute $\tau_{\gamma\gamma}$ values depend on the details of the target radiation fields and the location of the γ-ray production (see, e.g., Donea & Protheroe 2003) and thus come with uncertainties that reflect the dimension of the free parameter space.

Figure 3 shows the resulting opacity curves in the observer frame when using the evolutionary behavior of accretion rates from Netzer & Trakhtenbrot (2007) and Lapi et al. (2006) for the target photon fields for photon-photon interactions. The fast evolution of accretion rates at low redshifts is apparent. The corresponding curves for a $M_{\rm BH} = 10^9\ M_\odot$ black hole are inflated toward higher values of $\tau_{\gamma\gamma}(E)$ by more than an order of magnitude, and for $E \geq 100$ GeV the photon-photon collisions occur predominantly in the accretion disk radiation field. Energy redshifting is the reason why the threshold and energy of the maximum interaction probability, $E^* \approx 1.2/(1+z)(\epsilon/{\rm eV})^{-1}$ TeV, decreases with redshift. Note that for most energies <1 TeV, γ-ray absorption occurs preferentially near the increasing part of the $\tau_{\gamma\gamma}(E)$ function, near the pair production threshold. If the distance l_0 of the γ-ray production site from the disk rises beyond the BLR, γ-ray attenuation tails off as indicated in Figure 1. An increase in BLR size leads to an opacity decrease for an unchanged BLR luminosity by an amount that corresponds to the decrease in target photon density with increasing BLR volume.

A direct view on the redshift dependence of the local opacity opens up by slicing Figure 3 at the energies of interest. Figure 4 shows the resulting $\tau_{\gamma\gamma}(z)$ curves at observer energies of 100 GeV (*solid lines*) and 300 GeV (*dashed lines*) for all three evolution pictures for the accretion rate as shown in Figure 2 and for typical quasar BH masses ($M_{\rm BH} = 10^8\ M_\odot$, *light gray curves*; $M_{\rm BH} = 10^9\ M_\odot$, *dark gray curves*). The black curves represent the optical depths for the situation of a nonevolving high–accretion rate disk with a high-mass BH and of a nonevolving low–accretion rate system with a lower mass BH. A strong redshift dependence is apparent in almost all cases. Even for the case of nonevolving accretion rates, the local opacities show redshift dependence if the photon-photon pair production occurs predominantly close to the threshold, with an increasing slope of $\tau_{\gamma\gamma}(z)$ with redshift. The reason lies basically in the prominent peak of the pair production cross section, together with cosmological energy redshifting: the prominent peak in the cross section leads to most photon-photon collisions occurring in a rather narrow energy range $\Delta\epsilon^*$ near the threshold for smooth broadband target photon spectra. If those source spectra are located at cosmological distances, the energy redshifting into the observer frame leads to the presented redshift dependence of $\tau_{\gamma\gamma}$.

It is straightforward to then determine the evolution of the *e*-folding cutoff energy $E(\tau_{\gamma\gamma} = 1)(z)$ for the series of accretion rate evolution models used so far. Figure 5 shows a Fazio-Stecker–like presentation for the local absorption and compares it with the typically expected behavior for absorption of γ-rays in the evolving EBL (e.g., Primack et al. 1999; Kneiske et al. 2004; Stecker et al. 2006). Potential EBL probes are located at redshifts $z \geq 0.5$ for the *GLAST* LAT. In all cases, and this includes also nonevolving accretion rates, the *e*-folding cutoff energy decreases with redshift, similar to the Fazio-Stecker relation for EBL-caused absorption. If local absorption in the external radiation fields of AGNs leaves measurable imprints in the γ-ray spectra, these will be almost unavoidably redshift-dependent and will remain to be distinguished from the γ-ray opacity of the EBL.

6. CONCLUSIONS AND DISCUSSION

This work is devoted to the investigation of whether any redshift dependence of the opacity $\tau_{\gamma\gamma}$ of γ-rays produced in systems of strong-line blazars can be uniquely attributed to photon absorption in the EBL. The possible existence of further sources of redshift dependence of $\tau_{\gamma\gamma}$ other than those caused during propagation in the EBL will lead to ambiguities in estimating the EBL evolution. Strong-line quasars are in general considered to be high-luminosity sources in the γ-ray domain, which have a marked probability of providing sufficient photon statistics to enable one to search for absorption breaks in a spectral analysis. Their bright external photon fields (i.e., accretion disk, BLR) are used in many high-energy emission models as a necessary ingredient for γ-ray production; e.g., via inverse Compton scattering. If this, however, takes place in the Klein-Nishina regime, and therefore above the pair production threshold, γ-ray absorption due to photon-photon interactions is of comparable importance. In some hadronic blazar models, the observed γ-ray output is the result of redistributing the injected nucleon energy via pair cascades that develop in external photon fields and thus inevitably involves photon-photon pair production there. The focus of this study is therefore directed to photon-photon pair production in photon environments (here specifically the accretion disk and the BLR radiation field) of γ-ray–loud blazars where the interactions of relativistic particles in external photon fields potentially contributes significantly to the γ-ray output above ~50–100 GeV.

The search for any redshift dependence of this "local" γ-ray opacity leads to the following conclusions:

1. If the γ-ray emission region is located not well beyond the BLR, as is mandatory for γ-ray production that involves external photon fields, local γ-ray absorption features in strong-line quasar spectra have to be expected at values of $E(1+z)$ greater than several tens of GeV. Local γ-ray absorption in external AGN radiation fields ceases to be important if the γ-ray production site is sufficiently distant from the BLR. Although evolutionary studies of the EBL by means of γ-ray absorption signatures would not be affected in that case, it will lead to important implications for the high-energy blazar emission models.

2. Following recent progress in BH demographics, BH growth and corresponding accretion rates turn out to show a redshift dependence, with higher rates at larger redshifts. Correspondingly, the critical energy $E(\tau_{\gamma\gamma} = 1)$ due to local absorption in quasar disk and BLR radiation fields decreases with redshift, similar to the Fazio-Stecker relation for EBL absorption.

3. Even for the case of no evolution of quasar disk accretion rates, $E(\tau_{\gamma\gamma} = 1)$ decreases with redshift for sources of a given BH mass at $z > 1$, very similar to the Fazio-Stecker presentation of EBL absorption with the current knowledge of those systems. It results from the interplay of local absorption near the pair production threshold and cosmological energy redshifting.

4. Any observed redshift dependence of absorption features in blazars, which are prone to local γ-ray absorption, can therefore *not* serve as a unique signature for absorption occurring in the EBL radiation field. This complicates approaches for estimating the evolution of the EBL using GeV-sensitive instruments that utilize the Fazio-Stecker relation or similar methods and for γ-ray AGNs, whose external photon fields are considered important in γ-ray production. As a result, it seems that only "naked γ-ray jet sources" (i.e., AGNs without noticable optical/UV radiation fields close to the γ-ray emission region; "true type 2 AGNs") are unbiased probes for studies of the evolution of the EBL that are based on the Fazio-Stecker relation and the use of GeV instruments such as *GLAST*.

Consequently, an obvious choice for suitable candidate sources for this task would be blazars with particular weak or absent emission lines, generally classified as BL Lac objects (although exceptions exist; see § 1). Predictions for the expected number of GeV BL Lac objects range from several hundred (Dermer 2007) to a few thousand (Mücke & Pohl 2000) above the LAT sensitivity. It remains to be seen whether the near-future GeV instruments will detect a sufficient number of suitable sources at $z \geq 0.5$ to allow a sensible analysis based on naked γ-ray jet sources only.

Although the finding of this work adds fundamentally to already recognized complications (e.g., flux and spectral source variability) in analysis aiming to probe EBL evolution through the γ-ray horizon, it also offers new options for constraining AGN physics. The relevance of γ-ray absorption for cutting off the SED at the high-energy end in the different blazar types, possibly as a consequence of the location of γ-ray production, could be probed by means of a statistical study of $\tau_{\gamma\gamma}(E, z)$ as a function of source type or object parameters. If simultaneously measured emission lines and/or accretion disk signatures indicate the presence of luminous photon fields external to the jet, the position of the γ-ray production site could be constrained. Monitoring both the time history of the external target photon fields in AGNs and the jet γ-ray flux may offer independent verification of the importance of local absorption and external inverse Compton scattering there and may allow conclusions to be made regarding the γ-ray production location and some properties of the BLR material (Böttcher & Dermer 1995). At the same time, any nondetection of absorption features with sensitive GeV instruments will put limits on the external radiation fields in those AGNs.

If local opacity shapes part of the γ-ray–loud AGN population, its evolution may influence the luminosity function and the extragalactic γ-ray background contribution of AGNs above the 50–100 GeV energy range. In both cases, a redshift dependence of the local opacity of γ-ray–loud quasars will have far-reaching implications.

I am thankful for valuable feedback from the *GLAST* LAT AGN science working group, and in particular for very useful comments from C. Dermer, G. Madejski, and B. Lott. I also thank F. Stecker for providing his model curves and for interesting discussions. This work is supported by the National Aeronautics and Space Administration under contract NAS5-00147 with Stanford University.

REFERENCES

Aharonian, F. A. 2000, NewA, 5, 377
———. 2004, Very High Energy Cosmic Gamma Radiation (River Edge: World Scientific)
Atoyan, A. M., & Dermer, C. D. 2003, ApJ, 586, 79
Barger, A. J., Cowie, L. L., Bautz, M. W., Brandt, W. N., Garmire, G. P., Hornschemeier, A. E., Ivison, R. J., & Owen, F. N. 2001, AJ, 122, 2177
Barger, A. J., Cowie, L. L., Mushotzky, R. F., Yang, Y., Wang, W.-H., Steffen, A. T., & Capak, P. 2005, AJ, 129, 578
Becker, P. A., & Kafatos, M. 1995, ApJ, 453, 83
Böttcher, M. 2000, in AIP Conf. Proc. 515, GeV-TeV Gamma Ray Astrophysics Workshop, ed. B. L. Dingus, M. H. Salamon, & D. B. Kieda (New York: AIP), 31
Böttcher, M., & Dermer, C. D. 1995, A&A, 302, 37
Cavaliere, A., & Padovani, P. 1988, ApJ, 333, L33
Celotti, A., Padovani, P., & Ghisellini, G. 1997, MNRAS, 286, 415
Chen, A., Reyes, L. C., & Ritz, S. 2004, ApJ, 608, 686
Corbin, M. R. 1992, ApJ, 391, 577
Cristiani, S., et al. 2004, ApJ, 600, L119
Dermer, C. D. 2007, ApJ, 659, 958
Dermer, C. D., & Schlickeiser, R. 1993, ApJ, 416, 458
Donea, A.-C., & Protheroe, R. J. 2003, Astropart. Phys., 18, 377
Falomo, R., Scarpa, R., & Bersanelli, M. 1994, ApJS, 93, 125
Fazio, G. G., & Stecker, F. W. 1970, Nature, 226, 135
Fontanot, F., Monaco, P., Cristiani, S., & Tozzi, P. 2006, MNRAS, 373, 1173
Francis, P. J., Hewett, P. C., Foltz, C. B., Chaffee, F. H., Weymann, R. J., & Morris, S. L. 1991, ApJ, 373, 465
Gaskell, C. M., Wampler, E. J., & Shields, G. A. 1981, ApJ, 249, 443
Ghisellini, G., & Madau, P, 1996, MNRAS, 280, 67
Ghisellini, G., Maraschi, L., & Treves, A. 1985, A&A, 146, 204
Gould, R. J., & Schréder, G. P. 1967, Phys. Rev., 155, 1404
Granato, G. L., De Zotti, G., Silva, L., Bressan, A., & Danese, L. 2004, ApJ, 600, 580
Hasinger, G., Miyaji, T., & Schmidt, M. 2005, A&A, 441, 417
Jauch, J. M., & Rohrlich, F. 1976, The Theory of Photons and Electrons (2nd ed.; New York: Springer)
Kaspi, S., & Netzer, H. 1999, ApJ, 524, 71
Kaspi, S., Netzer, H., Maoz, D., Shemmer, O., Brandt, W. N., & Schneider, D. P. 2004, in Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html
Kneiske, T., Bretz, T., Mannheim, K., & Hartmann, D. H. 2004, A&A, 413, 807
Lapi, A., Shankar, F., Mao, J., Granato, G. L., Silva, L., De Zotti, G., & Danese, L. 2006, ApJ, 650, 42
Lindfors, E. J., Valtaoja, E., & Türler, M. 2005, A&A, 440, 845
Mannheim, K. 1993, A&A, 269, 67
Marconi, A., Risaliti, G., Gilli, R., Hunt, L. K., Maiolino, R., & Salvati, M. 2004, MNRAS, 351, 169
Merloni, A. 2004, MNRAS, 353, 1035
Mücke, A., & Pohl, M. 2000, MNRAS, 312, 177
Mücke, A., & Protheroe, R. J. 2000, in AIP Conf. Proc. 515, GeV-TeV Gamma Ray Astrophysics Workshop, ed. B. L. Dingus, M. H. Salamon, & D. B. Kieda (New York: AIP), 149
Mücke, A., Protheroe, R. J., Engel, R., Rachen, J. P., & Stanev, T. 2003, Astropart. Phys., 18, 593
Netzer, H., & Trakhtenbrot, B. 2007, ApJ, 654, 754
Padovani, P., Giommi, P., Landt, H., & Perlman, E. S. 2007, ApJ, 662, 182
Peterson, B. M. 1993, PASP, 105, 247
Primack, J. R., Bullock, J. S., Somerville, R. S., & MacMonn, D. 1999, Astropart. Phys., 11, 93
Protheroe, R. J. 1997, in IAU Colloq. 163, Accretion Phenomena and Related Outflows, ed. D. T. Wickramasinghe, G. V. Bicknell, & L. Ferrario (ASP Conf. Ser. 121; San Francisco: ASP), 585
Protheroe, R. J., & Biermann, P. L. 1997, Astropart. Phys., 6, 293
Sbarufatti, B., Falomo, R., Treves, A., & Kotilainen, J. 2006, A&A, 457, 35
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shuder, J. M. 1981, ApJ, 244, 12

Sokolov, A., & Marscher, A. P. 2005, ApJ, 629, 52
Soltan, A. 1982, MNRAS, 200, 115
Stecker, F. M., Malkan, A., & Scully, S. T. 2006, ApJ, 648, 774 (erratum 658, 1392 [2007])
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Wills, B. J., Brotherton, M. S., Fang, D., Steidel, C. C., & Sargent, W. L. W. 1993, ApJ, 415, 563
Wolf, C., Wisotzki, L., Borch, A., Dye, S., Kleinheinrich, M., & Meisenheimer, K. 2003, A&A, 408, 499
Yee, H. K. C. 1980, ApJ, 241, 894