ABSORPTION OF 10 GeV–1 TeV GAMMA RAYS BY RADIATION FROM THE BROAD-LINE REGION IN 3C 279

H. T. Liu,1 J. M. Bai,1 and L. Ma2

Received 2008 June 4; accepted 2008 July 18

ABSTRACT

We study the photon-photon pair production optical depth for 10 GeV–1 TeV gamma rays from 3C 279 due to the diffuse radiation of the broad-line region (BLR). Assuming a power-law spectrum $a_1 E^{-a_1}$ for the photon intensity of very high energy gamma rays, $a_1 \geq 405$ and $a_2 \geq 6.4$ are inferred from the integrated photon fluxes measured by MAGIC and H.E.S.S. Based on this power-law spectrum, the preabsorbed spectra are calculated by correcting for photon-photon absorption on the diffuse photons of the BLR (internal absorption) and the extragalactic background light (external absorption). The position of the gamma-ray-emitting region, $R_e$, determines the relative contributions of these two diffuse radiation components to the total absorption for 10 GeV–1 TeV gamma rays. The internal absorption could make the spectral shape of the gamma rays more complex than if they were corrected only for external absorption and could lead to the formation of arbitrarily softening and hardening gamma-ray spectra. It should be requisite for the internal absorption to be considered in studying 10 GeV–1 TeV gamma rays from powerful blazars. The energy of the annihilated gamma-ray photons due to the internal absorption is likely to be mainly reradiated around GeV energies. Our results indicate that $R_e$ may lie between the inner and outer radii of the BLR for 3C 279. This implies for powerful blazars that $R_e$ might be neither inside the BLR cavity nor outside the BLR, but within the BLR shell. Observations by GLAST, MAGIC, H.E.S.S., and VERITAS in the near future could provide more constraints on the position of the gamma-ray-emitting region relative to the BLR.

Subject headings: gamma rays: theory — quasars: individual (3C 279)

1. INTRODUCTION

The classical flat-spectrum radio quasar (FSRQ) 3C 279 is one of the brightest extragalactic objects in the gamma-ray sky. It was detected by the EGRET instrument aboard the Compton Gamma Ray Observatory, and its spectrum does not show any signature of gamma-ray absorption by pair production up to $\sim$10 GeV (Fichtel et al. 1994; von Montigny et al. 1995). With the detection of high-energy gamma rays from 66 blazars, comprising 51 FSRQs and 15 BL Lacertae objects, in the GeV energy range by EGRET (Catanese et al. 1997; Fichtel et al. 1994; Lin et al. 1997; Mukherjee et al. 1997; Thompson et al. 1995, 1996; Villata et al. 1997; Hartman et al. 1999; Nolan et al. 2003), an exceptional opportunity is presented for understanding the central engine operating in blazars. Some blazars have also been firmly detected by atmospheric Cerenkov telescopes at energies above 1 TeV, such as Mrk 421 (Punch et al. 1992) and Mrk 501 (Quinn et al. 1996). The High Energy Stereoscopic System (H.E.S.S.) is an imaging atmospheric Cerenkov detector with an energy threshold above 100 GeV (Funk et al. 2004; Hinton 2004; Hofmann 2003). The Very Energetic Radiation Imaging Telescope Array System (VERITAS) provides unprecedented sensitivity to photon energies between 50 GeV and 50 TeV (see, e.g., Holder et al. 2006). The Major Atmospheric Gamma Imaging Cerenkov Telescope (MAGIC) is currently the largest single-dish imaging air Cerenkov telescope in operation and has the lowest energy threshold, $\sim$30 GeV, among the new Cerenkov telescopes (see, e.g., Baixeras et al. 2004). At present, 23 active galactic nuclei (AGNs) have been detected in very high energy (VHE) gamma rays, including 21 BL Lac objects, one radio source (877), and the first FSRQ, 3C 279, which has the highest redshift ($z = 0.536$) among these VHE AGNs.3 MAGIC detected VHE gamma rays from 3C 279 (Teshima et al. 2007). H.E.S.S. observations placed an upper limit on the integrated photon flux (Aharonian et al. 2008). The Large Area Telescope instrument on the Gamma-Ray Large Area Space Telescope (GLAST), a next-generation high-energy gamma-ray observatory with sufficient angular resolution to allow identification of a large fraction of the optical counterparts, will observe gamma rays with energies from 20 MeV to greater than 300 GeV and have the unique capability to detect thousands of gamma-ray blazars to redshifts of at least $z = 4$ (see, e.g., Chen et al. 2004). GLAST was launched on 2008 June 11; combined with new TeV instruments such as MAGIC, H.E.S.S., and VERITAS, it will tremendously improve blazar spectral studies, filling in the band from 20 MeV to 10 TeV with high-significance data for hundreds of AGNs (see Gehrels & Michelson 1999). Future measurements of the shape of the blazar gamma-ray spectrum and its variability should tremendously improve our understanding of these sources.

The gamma rays from blazars are generally believed to be attributable to emission from a relativistic jet oriented at a small angle to the line of sight (Blandford & Rees 1978). These gamma-ray components are contributed by inverse Compton emissions, including synchrotron self-Compton (SSC) scattering of synchrotron seed photons and external Compton (EC) scattering of seed photons from sources outside the jet (see, e.g., Böttcher 2000). The diffuse radiation field of the broad-line region (BLR) could have a strong impact on the expected EC spectra of the most powerful blazars, FSRQs (Liu & Bai 2006; Reimer 2007; Tavecchio & Ghisellini 2008). Not only do the external soft photon fields provide target photons for the EC processes to produce these gamma-ray components, they also absorb gamma rays from the EC processes, because gamma rays between 10 GeV and 1 TeV

---

1 National Astronomical Observatories / Yunnan Astronomical Observatory, Chinese Academy of Sciences, Kunming, 650011 Yunnan, China; liuhongtao1111@hotmail.com; bajinming@ynao.ac.cn. Send offprint requests to H. T. Liu.

2 Department of Physics, Yunnan Normal University, Kunming, 650092 Yunnan, China.

3 See http://www.mppmu.mpg.de/~rwagner/sources.
interact with infrared–ultraviolet photons and are attenuated by photon-photon pair production. Many efforts to study the absorption of gamma rays have focused on photon-photon annihilation by the diffuse extragalactic background radiation in the IR, optical, and UV bands (e.g., Stecker et al. 1992, 2006; Stecker & de Jager 1998; Oh 2001; Renault et al. 2001; Chen et al. 2004; Dwek & Krennrich 2005; Schroedter 2005). This external absorption of gamma rays by the diffuse extragalactic background light (EBL) has also been proposed as a probe of the EBL itself (Renault et al. 2001; Chen et al. 2004; Dwek & Krennrich 2005; Schroedter 2005). Indeed, the absorption of gamma rays inside FSRQs could result in serious problems for the possibility of using the external absorption of gamma rays to probe the IR-optical-UV extragalactic background, because it could mask the intrinsic gamma-ray spectra (Donea & Protheroe 2003; Liu & Bai 2006; Reimer 2007). The intrinsic spectra of gamma rays are complicated by the complex spectrum of the diffuse radiation field of the BLR in FSRQs (Tavecchio & Ghisellini 2008). The mean of the intrinsic spectral index is around 2.3 for 17 BL Lac objects detected in the VHE regime (Wagner 2008).

The position of the gamma-ray–emitting region is still an open and controversial issue in blazar research. It has been suggested that gamma rays are produced inside the BLR and that the radius of the gamma-ray–emitting region, \( r_{\gamma} \), ranges roughly from 0.03 to 0.3 pc (Ghisellini & Madau 1996). It was argued by Georgopapoulou et al. (2001) that the radiative plasma in the relativistic jets of powerful blazars lies within the cavity formed by the BLR. However, other researchers argue that the gamma-ray–emitting regions are outside the BLR (Lindfors et al. 2005; Sokolov & Marscher 2005). In our previous work (Liu & Bai 2006, hereafter Paper I), the position of the gamma-ray–emitting region was a key parameter to determine whether high-energy gamma rays could escape the diffuse radiation field of the BLR for FSRQs. It is unknown whether these gamma rays could be detected by GLAST, MAGIC, H.E.S.S., and VERITAS even if blazars intrinsically produce 10 GeV–1 TeV gamma rays, because the value of \( r_{\gamma} \) is unknown. Gamma rays around 200 GeV will be strongly attenuated for 3C 279 if the emitting region is within the BLR cavity (see Paper I). However, MAGIC observations from 2006 February 23 show a clear gamma-ray signal in the VHE regime (Teshima et al. 2007). This indicates that the emitting region of these VHE gamma rays should be outside the BLR cavity; otherwise, the intrinsic flux would have to be extremely high. In Paper I, we addressed an important topic in gamma-ray astrophysics, namely, the absorption of high-energy gamma rays inside FSRQs by photons of the BLR. In this paper, we attempt to address the particular topic of absorption in the gamma-ray quasar 3C 279 using the available observational data, and its potential effect on the gamma-ray spectrum. In order to constrain the position of the gamma-ray–emitting region in 3C 279, we study the internal absorption of gamma rays by the diffuse radiation from the BLR and its potential effect on the spectra of gamma rays from 10 GeV to 1 TeV.

The structure of the paper is as follows: Section 2 analyzes the intensity of the VHE gamma rays. Section 3 presents theoretical calculations and consists of two subsections; § 3.1 presents calculations of the temperature profile, and § 3.2 the photon-photon optical depth for 3C 279. Section 4 addresses external absorption on the IR-optical-UV extragalactic background. Section 5 is devoted to the spectral shape of the VHE gamma rays. Section 6 presents the pair spectrum due to photon-photon annihilations and their radiation. Section 7 is for discussion and conclusions. Throughout, we use a flat cosmology with a deceleration factor \( q_0 = 0.5 \) and a Hubble constant \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. INTENSITY OF THE VHE GAMMA RAYS

The classical FSRQ 3C 279 is one of the brightest extragalactic objects in the gamma-ray sky, and it is also the first VHE gamma-ray FSRQ. For 3C 279, there were 10 nights of MAGIC observations from 2006 January 31 to 2006 March 31. While on most of the nights gamma-ray fluxes compatible with zero were observed, a marginal signal was seen during the 2006 February 22 observations. On the night of 2006 February 23, the observations showed a clear gamma-ray signal with an integrated photon flux \( F(E_\gamma > 200 \text{ GeV}) = (3.5 \pm 0.8) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \) (Teshima et al. 2007). This detection was not accompanied by an optical flare or by particularly high flux levels or outbursts in X-rays (Teshima et al. 2007). Within the space of 1 day, 3C 279 brightened from a marginal signal to a clear signal detected by MAGIC. This suggests that the VHE gamma-ray emission may have variations on the order of days. The GeV gamma-ray emission detected by EGRET also varied on timescales as short as 1 day (Hartman et al. 2001b). This timescale is roughly consistent with that observed by MAGIC. This agreement indicates that the GeV and VHE gamma rays may have some definite relationship. However, no VHE spectrum of 3C 279 has been published yet.

For 3C 279, observations from 2006 February 22–23 show an optical \( R \) magnitude around 14.5 (see Fig. 1 of Böttcher et al. 2007) and a flux density around 5–5.2 mJy in the \( R \) band (see Fig. 1 of Teshima et al. 2007). The average \( R \)-band magnitude from 2000 February 8 to March 1 is around 14.5 (see Fig. 2 of Kartaltepe & Balonek 2007). The simultaneous multiwavelength observations from 2000 February 8 to March 1 show a flux density from 4.2 to 8.9 mJy in the \( R \) band (Hartman et al. 2001a). These \( R \)-band magnitudes and flux densities observed from 2000 February 8 to March 1 are consistent with those observed on 2006 February 22–23. This agreement indicates that the gamma-ray emission in these two periods likely originated from very similar states. Thus, the gamma-ray emission from 2006 February 22–23 is likely due to an intermediate state. The gamma-ray emission on most of the nights, when fluxes compatible with zero were observed, likely corresponds to a low state.

Although an integrated photon flux is given by Teshima et al. (2007), no VHE spectrum of 3C 279 has been published. Fortunately, H.E.S.S. observations in 2007 January measured an upper limit on the integrated photon flux, \( F(E_\gamma > 300 \text{ GeV}) < 3.98 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \) (Aharonian et al. 2008). Observations show that the VHE spectra of the known VHE sources can be described by a power law (see Wagner 2008). Thus, a power-law spectrum \( dI/dE_\gamma = a_2 E_\gamma^{-\alpha_2} \) is assumed for the photon intensity of the VHE gamma rays. This spectrum can be constrained by the two measured integrated photon fluxes. Taking into account the MAGIC and H.E.S.S. measurements, adopting \( F(E_\gamma > 200 \text{ GeV}) = 3.5 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \) and assuming \( F(E_\gamma > 300 \text{ GeV}) = 3.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \), the photon intensity of the VHE gamma rays is inferred to be

\[
\frac{dl}{dE_\gamma} = 505 E_\gamma^{-6.4} \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1}.
\]

Although \( \alpha_2 \geq 6.4 \) is implied by the H.E.S.S. observations, we adopt \( \alpha_2 = 6.4 \) in the following calculations and discuss the potential effect of \( \alpha_2 \geq 6.4 \) on our results in the last section. The spectral slope of 6.4 is higher than that of any other known VHE source (see Wagner 2008). The maximum spectral slope of 4.21 had previously been measured in the VHE regime for PG 1553+113 (Albert et al. 2007). The value of 6.4 is also larger than the slope of 2.3 for the VHE spectrum extrapolated from the GeV spectrum.
observed from 2000 February 8 to March 1 (Hartman et al. 2001a). The average EGRET blazar spectrum was found to have a slope of 2.27 (Venters & Pavlidou 2007). The mean of the intrinsic spectral indices is $\Gamma \approx 2.3$ for 17 blazars detected in the VHE regime (see Wagner 2008). The reason that this spectral slope of 6.4 is larger than any other known gamma-ray photon index, both measured and intrinsic spectral indices, is likely the internal and external absorption of gamma rays by the diffuse radiation fields of the BLR and the EBL. Stecker et al. (1992) investigated the photon-photon absorption of the VHE gamma-ray spectrum, extrapolated from the differential spectrum of gamma rays measured by EGRET during 1991 June, on the extragalactic background infrared radiation field. The corrected photon flux is not inconsistent with the upper limit from the Whipple Observatory (Stecker et al. 1992). This indicates that the VHE and GeV gamma rays likely have some relationship. In the following section, we first calculate the internal absorption within 3C 279 due to the diffuse radiation fields produced by the BLR.

3. THEORETICAL CALCULATIONS

As described in §§ 2.1, 2.2, and 2.3 of Paper I, its equations (1)–(21) can be used to estimate the absorption optical depth due to the diffuse radiation of the BLR, adopting a spherical shell of clouds (see Fig. 1 of Paper I) and the relative intensity of broad emission lines presented in Figure 2 of Paper I, and assuming a blackbody temperature in the inner regions of the accretion disk. The assumption of a single-temperature blackbody probably differs significantly from the real case. The surface effective temperatures of accretion disks are a function of radius $r_d$, that is, $T_{\text{eff}} = T_{\text{eff}}(r_d)$ (see, e.g., Ebisawa et al. 1991; Hanawa 1989; Li et al. 2005; Pereyra et al. 2006; Shakura & Sunyaev 1973; Zimmerman et al. 2005). The continua from thin accretion disks can be well described by a multitemperature blackbody. Considering the temperature profile of the accretion disk, the factor $n_{bb}(\nu, T)$ in equations (20) and (21) of Paper I should be replaced by

$$n_{bb}(\nu, T) = \int_{X_o}^{X_e} n_{bb}(\nu, T_{\text{eff}}(X_d))dX_d,$$

where $X_o = r_o/r_d$ and $X_e = r_e/r_d$ are the inner and outer radii of the accretion disk, respectively, and $X_d = r_d/r_d$. The gravitational radius of a black hole with mass $M_{BH}$ is $r_g = G M_{BH}/c^2$, where $G$ is the gravitational constant and $c$ is the speed of light.

In the calculations of the photon-photon attenuation optical depth, the soft photon frequency is considered in the range from $\nu^2 = 10^{12.0}$ Hz to $\nu^2 = 10^{16.5}$ Hz for the diffuse continuum from the BLR. The temperature profile is computed for a standard thin accretion disk.

3.1. Temperature Profile

The local effective temperature of an accretion disk is a function of radius $r_d$ (see, e.g., Ebisawa et al. 1991; Hanawa 1989; Li et al. 2005; Pereyra et al. 2006; Shakura & Sunyaev 1973; Zimmerman et al. 2005). The standard accretion disk is modeled for a radiatively efficient, geometrically thin disk. The variability of active galactic nuclei mostly favors standard accretion disk models of AGNs (Liu et al. 2008). Although the equations required to calculate the temperature profile are the same as equations (5)–(12) of Liu et al. (2008), they are presented here as equations (A1)–(A7) to make this paper more readable (see Appendix). For high-luminosity blazars showing a clear UV bump, the ionizing luminosity $L_{\text{ion}} = L_{\text{UV}} = \eta M c^2$ according to the definition of the efficiency $\eta$ at which various types of black holes convert mass-energy into outgoing radiation (Thorne 1974). From the observed BLR luminosity $L_{\text{BLR}}$ and the relation $L_{\text{BLR}} = f_{\text{cov}} L_{\text{UV}}$ (D’Elia et al. 2003), we can estimate the mass accretion rate of the central black hole with the formula

$$\dot{M} = \frac{L_{\text{UV}}}{\eta_{\text{max}} c^2} = \frac{L_{\text{BLR}}}{\eta_{\text{max}} f_{\text{cov}} c^2}.$$  (3)

The temperature profiles can then be estimated from equations (A1)–(A7) and equation (3).

The dimensionless spin parameter of a black hole can take any value in the range $-1 \leq a_* \leq 1$, where negative values correspond to a black hole that rotates retrograde relative to its accretion disk. For simplicity we consider only prograde spins up to the Thorne spin equilibrium limit, that is, $0 \leq a_* \leq 0.998$ (Thorne 1974). Recent work on magnetohydrodynamic accretion disks suggests a rather lower equilibrium spin (e.g., Gammie et al. 2004; Krolik et al. 2005). Spin equilibrium is reached at $a_* \approx 0.93$ through accretion of gas onto the central black hole, and mergers of black holes with comparable masses can result in a final spin of $a_* \approx 0.8$–0.9 (Gammie et al. 2004). Equilibrium spins as low as $a_* \approx 0.9$ are within the realm of possibility (Krolik et al. 2005). Aschenbach et al. (2004) obtained a value of $a_* = 0.9939 \pm 0.0026$ for the Galactic center black hole. Brenneman & Reynolds (2006) obtained a formal constraint of $a_* = 0.989_{-0.002}^{+0.000}$ at 90% confidence for the Seyfert galaxy MCG 06-30-15. Considering the probable ranges of $a_*$ suggested above, we take three values, 0.5, 0.8, and 0.998, in the Kerr metric to calculate the temperature profile. Combining equations (A1)–(A7), equation (3), and the parameters $M_{BH}$, $L_{\text{BLR}}$, $f_{\text{cov}}$, and $a_*$, the surface effective temperature profiles are calculated. The results are presented in Figure 1.

3.2. Photon-Photon Optical Depth

As stated in § 5 of Paper I, the absorption of gamma rays by emission lines is unrelated to the BLR covering factor $f_{\text{cov}}$, and the gamma-ray absorption by the diffuse blackbody radiation is in proportion to the ratio $\tau_{\text{BLR}}/f_{\text{cov}}$ where $\tau_{\text{BLR}}$ is the Thomson optical depth of the BLR. Various values for the BLR covering factor have been suggested. Early estimates indicated a covering factor $f_{\text{cov}} \sim 5\%$–10\%, while recent observations indicate $f_{\text{cov}} \sim 30\%$ (see, e.g., Maiolino et al. 2001). D’Elia et al. (2003) found
only two blazars in the literature, 3C 273 and PKS 2149−306, for which both the UV continuum emission from the accretion disk and broad emission lines have been measured. They obtained $f_{\text{cov}} \sim 7\%$ for the first source and $f_{\text{cov}} \sim 10\%$ for the second. Donea & Protheroe (2003) suggested $f_{\text{cov}} \sim 3\%$ for the spherical distribution of the BLR clouds in quasars. The issue of the Thomson optical depth of the BLR has rarely been studied and has gotten nowhere for blazars. Blandford & Levison (1995) adopted $\tau_{\text{BLR}} = 0.01$. Thus, the ratio $\tau_{\text{BLR}}/f_{\text{cov}}$ is likely to be typically of order $\tau_{\text{BLR}}/f_{\text{cov}} \sim 1$ for the spherical distribution of the BLR clouds in blazars. In calculating $\tau_{\gamma\gamma}$, we adopt $\tau_{\text{BLR}}/f_{\text{cov}} = 1$ and $f_{\text{cov}} = 0.03$.

The focus of this study, 3C 279, has a BLR luminosity $L_{\text{BLR}} = 10^{44.41} \text{ ergs s}^{-1}$ (Cao & Jiang 1999) and a black hole mass of $M_{\text{BH}} = 10^{8.4} M_\odot$ (Woo & Urry 2002). It was detected by EGRET in the 0.1−10 GeV energy domain, and its spectrum can be fitted by a power law without any signature of gamma-ray absorption by pair production (Fichtel et al. 1994; von Montigny et al. 1995). First, we investigate the dependence of the effective temperature $T_{\text{eff}}$ on the central black hole spin $a_*$ for 3C 279. The inner radii of the model accretion disks (in the Kerr potential) are fixed at the marginally stable orbit $r_{m}(a_*) = \lambda_{m}(a_*)r_g$. The outer radii are fixed at $r_{\text{out}} = 200r_g$. The temperature profiles of the standard accretion disks are presented in Figure 1. It is obvious that the temperatures for the three different values of $a_*$ are nearly the same at the outer radius. Variations of $a_*$ can significantly change the temperature profile (see Fig. 1). It is evident that different temperature profiles produce different multitemperature blackbody continua, which then could result in different absorption for gamma rays.

We calculated $\tau_{\gamma\gamma}$ for 3C 279 by adopting a BLR inner radius $r_{\text{BLR, in}} = 0.1 \text{ pc}$ and an outer radius $r_{\text{BLR, out}} = 0.4 \text{ pc}$, following Hartman et al. (2001a). It has been suggested that the gamma-ray–emitting region could be within the BLR cavity (Ghisellini & Madau 1996; Georganopoulos et al. 2001). First, we assume $R_\gamma = r_{\text{BLR, in}}$ to calculate the absorption optical depth. The result is presented in Figure 2a, where it can be seen that the diffuse radiation field of the BLR is not transparent to gamma rays of energies from 10 GeV to 1 TeV in the observer’s frame if these gamma rays originate inside the BLR cavity. This result is inconsistent with observations that show no signature of gamma-ray absorption by pair production around 10 GeV (e.g., Fichtel et al. 1994; von Montigny et al. 1995; Ghisellini & Madau 1996; Wehrle et al. 1998). Thus, for ~10 GeV gamma rays, the observations do not support suggestions of the gamma-ray–emitting region residing within the BLR cavity. It is likely that this region is within the BLR, that is, $r_{\text{BLR, in}} < R_\gamma < r_{\text{BLR, out}}$. The absorption optical depth was recalculated assuming $R_\gamma = (r_{\text{BLR, out}} + r_{\text{BLR, in}})/2$ (see Fig. 3a). It is obvious that the VHE gamma rays are still significantly absorbed by the diffuse radiation of the BLR (only ~5% escape probability). The 10 GeV gamma rays are still slightly absorbed. A slightly larger covering factor $f_{\text{cov}}$ could make this slight absorption around 10 GeV vanish. Thus, the gamma-ray–emitting region is likely within the BLR. Gamma-ray–emitting regions outside the BLR have been argued for by some researchers (Lindfors et al. 2005; Sokolov & Marscher 2005). Therefore, $R_\gamma = r_{\text{BLR, out}}$ was assumed to calculate the absorption optical depth. The calculated results are presented in Figure 4. There is no absorption for 10 GeV gamma rays. This is consistent with the EGRET observations. For VHE gamma rays,
more than \( \sim 60\% \) of the primary gamma rays can escape the diffuse radiation field of the BLR (see Fig. 4).

4. EXTERNAL ABSORPTION ON THE IR-OPTICAL-UV EXTRAGALACTIC BACKGROUND

Many efforts have focused on investigating the EBL at IR-optical-UV wavelengths and the photon-photon annihilation absorption of gamma rays by the EBL in these bands (e.g., Stecker et al. 1992; Stecker & de Jager 1998; Oh 2001; Renault et al. 2001; Chen et al. 2004; Dwek & Krennrich 2005; Schroedter 2005). External absorption of gamma rays by the diffuse EBL has also been proposed as a way to probe the EBL itself (Renault et al. 2001; Chen et al. 2004; Dwek & Krennrich 2005; Schroedter 2005). Stecker et al. (1992) first pointed out the importance of
the EBL in determining the opacity of the universe to high-energy gamma rays at higher redshifts. Dwek & Krennrich (2005) detailed the observational limits and detections of the EBL, and the relevant EBL spectral templates. Their investigation showed that the absorption of gamma rays at $\leq 1$ TeV is entirely contributed by the EBL at 0.1–10 $\mu$m (see Fig. 3 of Dwek & Krennrich 2005). Dwek & Krennrich only calculated the optical depth for low-redshift sources. Stecker et al. (2006) have given the optical depth for sources at redshifts $z < 6$. Stecker et al. (1992) investigated the infrared EBL absorption on high-energy gamma rays for 3C 279 and found an absorption optical depth of $3.7 \leq \tau \leq 9.7$ for 1 TeV gamma rays. An analytic form to approximate the function $\tau_{\gamma\gamma}(E_{\gamma}, z)$ of the external EBL absorption was given as

$$\log \tau_{\gamma\gamma} = Ax^4 + Bx^3 + Cx^2 + Dx + E \quad (4)$$

(Stecker et al. 2006), where $x \equiv \log E_{\gamma}$ (eV). Coefficients $A$ through $E$ are given in Table 1 of Stecker et al. (2006) for various redshifts. This parametric approximation holds for $10^{-2} \leq \tau_{\gamma\gamma} \leq 10^2$ and $E_{\gamma} \leq 2$ TeV. We adopt the coefficients for redshift $z = 0.5$ for the baseline model fit to calculate the EBL absorption optical depth.

In order to compare the internal and external absorption, the calculated results for the external absorption are also presented in Figures 2a, 3a, and 4a (solid lines). If $R_{\gamma}$ is around the inner radius $r_{\text{BLR, in}}$, internal absorption dominates over the external absorption, and the latter mainly presents itself in the VHE interval and is much less than unity from around 10 to a few tens of GeV. The internal absorption peaks around 200 GeV, and the external absorption increases with gamma-ray energy (see Fig. 2a). If $R_{\gamma}$ is around the median of $r_{\text{BLR, in}}$ and $r_{\text{BLR, out}}$, the total absorption is dominated by internal absorption in the 10–100 GeV interval and the external absorption dominates from 300 GeV to 1 TeV. The relative contributions of the internal and external absorption to the total are comparable around 200 GeV (see Fig. 3a). If $R_{\gamma}$ is around the outer radius $r_{\text{BLR, out}}$, the internal absorption is comparable to the external from 10 to 20 GeV, and the former is dominated by the latter from 30 GeV to 1 TeV (see Fig. 4a). The position of the gamma-ray–emitting region determines the relative contributions of the internal and external absorption to the total photon-photon annihilation optical depth for 10 GeV–1 TeV gamma rays.

5. SPECTRAL SHAPE OF THE VHE GAMMA RAYS

Measured and intrinsic VHE gamma-ray spectra can be well described by a power law, and the intrinsic gamma-ray spectra of 17 BL Lac objects have been inferred by only correcting the EBL absorption in the measured spectra (Wagner 2008). If the gamma-ray–emitting regions are far from the BLR in FSRQs, it is reasonable to infer the intrinsic spectra by only correcting for the EBL absorption. Otherwise, this approach is likely to be insufficient for FSRQs to infer the intrinsic spectra from the measured VHE spectra, because the internal absorption is not negligible when compared with the external absorption (see Figs. 2a and 3a). The position of the gamma-ray–emitting region determines the relative contributions of the internal and external absorption. The dependence of the internal absorption on gamma-ray energy relies on the position of the emitting region (Figs. 2a, 3a, and 4a). The external absorption monotonically increases with gamma-ray energy, and thus its effect on the shape of the spectrum is more straightforward than that of the internal absorption. It is obvious that the external absorption softens the observed gamma-ray spectrum relative to the emitted one.

In order to study the dependence of the internal absorption on the radius of the gamma-ray–emitting region, $R_{\gamma}$, we considered gamma-ray energies $E_{\gamma}$ of 50, 100, 300, 500, and 1000 GeV to calculate the photon-photon absorption optical depth. The results are presented in Figure 5. It is obvious that the absorption optical depth $\tau_{\gamma\gamma}$ rapidly decreases with increasing $R_{\gamma}$, because the energy density of the diffuse radiation of the BLR rapidly decreases beyond $r_{\text{BLR, in}}$. For a fixed $E_{\gamma}$, $\tau_{\gamma\gamma}$ monotonically decreases as $R_{\gamma}$ increases. For a fixed $R_{\gamma}$, the dependence of $\tau_{\gamma\gamma}$ on $E_{\gamma}$ relies on $R_{\gamma}$. The internal optical absorption depth $\tau_{\gamma\gamma}$ of VHE gamma rays does not vary monotonically with $E_{\gamma}$, peaking around a few hundred GeV if $R_{\gamma} \leq 0.35$ pc. This is confirmed by the calculated results presented in Figures 2a and 3a. The optical depth $\tau_{\gamma\gamma}$ for any $E_{\gamma}$ monotonically varies with $E_{\gamma}$, if $R_{\gamma} \geq 0.35$ pc (see Figs. 4a and 5). The optical depth $\tau_{\gamma\gamma}$ of high-energy gamma rays monotonically increases with $E_{\gamma}$ for any $R_{\gamma}$ (Figs. 2a, 3a, 4a, and 5).

After correcting the gamma-ray spectra for the internal and external absorption, we show the preabsorbed spectra for three values of $R_{\gamma}$ in Figures 2b, 3b, and 4b (double-dot–dashed lines). For $R_{\gamma}$ around $r_{\text{BLR, in}}$, the preabsorbed VHE gamma-ray spectra peak around 200 GeV. The internal absorption hardens the VHE spectrum around 300 GeV–1 TeV and softens the spectrum below 200 GeV (Fig. 2b). If $R_{\gamma}$ is around the median of the inner and outer radii of the BLR, the internal absorption softens the gamma-ray spectrum below $\sim 400$ GeV and hardens the spectrum from $\sim 400$ GeV to 1 TeV (Fig. 3b). If $R_{\gamma}$ lies beyond the outer radius of the BLR, the internal absorption softens the gamma-ray spectrum (see Fig. 4b) and has the same effect as the external absorption, which softens the spectrum of the gamma rays that escape from the diffuse radiation field of the BLR. After passing through the internal and external diffuse radiation fields, the detected gamma-ray spectra are softer than the preabsorbed ones below $\sim 400$ GeV and harder than the preabsorbed ones from $\sim 400$ GeV to 1 TeV when $R_{\gamma}$ is around $r_{\text{BLR, in}}$ (Fig. 2b). For $R_{\gamma}$ beyond the median of the inner and outer radii of the BLR, the detected spectra are softer than the preabsorbed ones (Figs. 3b and 4b). If the intrinsic spectral indices have a typical value of 2.3 for VHE gamma-ray sources, the first VHE FSRQ, 3C 279, may have an intrinsic spectral index around 2.3 in the VHE regime. These preabsorbed VHE gamma rays from 200 GeV to 1 TeV can be well fitted by a power-law spectrum, with a chance probability $p < 10^{-20}$. For $R_{\gamma} = 0.1$ pc, photon indices of 5.7 $\pm$ 0.2 ($a_{\gamma} = 0.5$) and 4.9 $\pm$ 0.2 ($a_{\gamma} = 0.998$) are given by the fit. These are larger than the typical value of 2.3 for the known VHE
6. PAIR SPECTRUM DUE TO PHOTON-PHOTON ANNihilATIONS AND THEIR RADIATION

In this section, our efforts are focused on studying where the energy of annihilated gamma-ray photons is likely to be re-radiated. Böttcher & Schlickeiser (1997) derived an exact analytic solution of the pair production spectrum from photon-photon annihilation and showed that this exact solution is in very good agreement with the approximation of Aharonian et al. (1983), the most accurate of the various approximations known before. The interaction of power-law gamma-ray spectra with thermal soft photon fields is generally described within an error of a few percent at all electron/position energies if the soft photon temperature $kT/m_e c^2 \lesssim 0.1$, even if the gamma-ray spectrum extends down to $\epsilon_1 \sim 1$. Thus, we adopted the approximation of Aharonian et al. (see eq. [32] of Böttcher & Schlickeiser 1997) to estimate the pair injection rate $dn(\gamma)/dt$ due to photon-photon absorption by the diffuse radiation field of the BLR in 3C 279. A power-law spectrum proportional to $E^{-2.3}_\gamma$ is assumed for the preabsorbed gamma-ray spectrum to calculate the injection rate. For simplicity in the calculation of $dn(\gamma)/dt$, we adopt radially independent soft photon densities with such a relative intensity that can produce the comparable quantity $\int [dn(\gamma)/dt]d\gamma$, converted from the energies of annihilated gamma-ray photons, for the diffuse multi-temperature blackbody and broad emission lines. After the soft photon densities and the pair production rate $dn(\gamma)/dt$ are given, the steady state equilibrium pair distribution can be estimated. Figure 6a shows the differential pair injection rate $dn(\gamma)/dt$ for the interaction of a power-law gamma-ray spectrum $\propto E^{-2.3}_\gamma$ with the diffuse BLR radiation of 3C 279. The $\gamma$-values of annihilation electrons and positrons from the broad emission lines and gamma rays have a lower limit of $\gamma \gtrsim 10^3$. The $\gamma$-values from annihilation between the multitemperature blackbody and gamma rays have a lower limit of $\gamma \gtrsim 10^6$.

If considering the radiative cooling, synchrotron cooling, and cooling due to external Compton scattering, the steady state equilibrium pair distribution is $n(\gamma) = \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} [dn(n)/d\gamma]/\gamma$, where $\gamma = \gamma_{\text{syn}}(\gamma) + \gamma_{\text{EC}}(\gamma)$ and $\gamma = E_{\text{el}}/m_e c^2$ is the electron/positron energy. The synchrotron cooling rate is given by $\dot{\gamma}_{\text{syn}}(\gamma) = (4/3)\sigma_T E_{\text{el}}^2/m_e c^2 B^2/8\pi \gamma^2$, where $B$ is the magnetic field intensity. The EC scattering cooling rate is $\dot{\gamma}_{\text{EC}}(\gamma) = \int d\epsilon_1 \epsilon_1 \int F_{\text{KN}}(\epsilon_1, \epsilon_2, \gamma) n(\epsilon_2) \epsilon_2 d\epsilon_2$, where we use the Compton kernel $F_{\text{KN}}$ for isotropic soft photons, considering the full Klein-Nishina cross section (Jones 1968; Blumenthal & Gould 1970). The Compton kernel is

$$F_{\text{KN}} = \frac{3}{4} \frac{c \sigma_T}{\epsilon_2 \gamma^2} \left[ 2q \ln q + 1 + q - 2q^2 + \frac{(\gamma_c q)^2(1-q)}{2(1+\gamma_c q)} \right],$$

where $\gamma_{c_1} = 4\epsilon_1 \gamma_1$, $q = \epsilon_1 / [4\epsilon_2 \gamma_1 (\gamma_1 - \epsilon_1)]$, and $1/4\gamma_{c_1}^2 < q < 1$ (Jones 1968; Blumenthal & Gould 1970). Here $\epsilon_1$ and $\epsilon_2$ are the energies of gamma rays and soft photons in units of $m_e c^2$, respectively. The synchrotron emission coefficient is

$$f_{\text{syn}}(\nu) = \frac{\sqrt{5} c B}{4\pi m_e c^2} \int d\gamma n(\gamma) R_{\text{CS}}(x),$$

where $R_{\text{CS}}(x)$ is the Compton reactance.

---

**Fig. 6** — Pair production spectrum due to photon-photon annihilation. (a) The differential pair production rate produced by gamma rays (assumed $\propto E^{-2.3}$) and a multi-temperature blackbody (dotted lines), that produced by gamma rays and broad emission lines (dash-dotted line), and the total equilibrium pair distribution for the two (dashed curves). (b) Synchrotron (left) and EC (right) spectra emitted by the equilibrium pair distribution. The curves were calculated adopting $f_{\text{syn}} = 0.03$, $L_{\text{BLR}} = 10^{44.41}$ ergs s$^{-1}$, and $M_{\text{BH}} = 10^{6.4} M_\odot$. From the top down, the dotted and dashed curves correspond to $a_c = 0.998$, $a_c = 0.8$, and $a_c = 0.5$. Sources and are also larger than the intrinsic photon index of $\approx 3.6$ for PG 1553+113, the maximum among the known VHE spectra (Wagner 2008). Photon indices of $1.97 \pm 0.009$ ($a_c = 0.5$) and $1.94 \pm 0.003$ ($a_c = 0.998$) result for $R_c = 0.25$ pc. These values are smaller than the typical value of 2.3 in the VHE region but larger than the intrinsic photon index of $\approx 1.3$ for 1ES 1101−232, the minimum among the known VHE spectra (Wagner 2008). An index of $1.7 \pm 0.03$ results for $R_c = 0.4$ pc. This is smaller than the typical value of 2.3 but larger than the minimum of 1.3. If $a_2$ is allowed to rise, these fitted photon indices for the preabsorbed VHE spectra could increase. Thus, it is unlikely for 3C 279 that the gamma-ray emitting region lies within the BLR cavity.
curves were calculated adopting \(a_0 = 0.998\), and black curves are for \(a_0 = 0.5\). Dotted curves show the gamma-ray spectra corrected for internal absorption, and double-dot-dashed curves are those corrected for both internal and external absorption.

where the mean emission coefficient for a single electron or positron averaged over an isotropic distribution of pitch angles \(R_{CS}(x)\) (Crusius & Schlickeiser 1986; Ghisellini et al. 1988) is

\[
R_{CS}(x) = 2x^2K_{4/3}(x)K_{1/3}(x) - \frac{6x^3}{5}[K_{4/3}^2(x) - K_{1/3}^2(x)]
\]

(7)

with \(x = \nu/\gamma^2\nu_B\) and \(\nu_B = eB/2\pi m_e c\), and \(K_n\) the McDonald function of order \(n\) (see also Sauge & Henri 2004). The EC emission coefficient \(j_{EC}(\nu)\) is

\[
j_{EC}(\nu) = \frac{h}{4\pi} \epsilon_1 \int \frac{dI}{dE\gamma} \epsilon_2(\nu, \epsilon_2, \gamma) n(\epsilon_2) n(\gamma) d\gamma d\epsilon_2,
\]

(8)

where \(n(\epsilon_2)\) is the differential soft photon density. For 3C 279, we adopt the magnetic field intensity \(B = 1.5 \text{ G}\) from Hartman et al. (2001a). The calculated spectra are presented in Figure 6b. For FSRQs, the ratio of the EC luminosity to the synchrotron luminosity is \(L_{EC}/L_{syn} \sim 10\) on average (Ghisellini et al. 1998; Georganopoulos et al. 2001). The relative radiation intensities of the diffuse blackbody component and broad emission lines of the BLR and the magnetic field intensity adopted in the calculations could produce a ratio of \(L_{EC}/L_{syn} = \nu J_{EC}/\nu J_{syn} \sim 10\) for the pair spectrum due to photon-photon absorptions. It can be seen in Figure 6b that the synchrotron emission peaks around keV energies, and the EC emission peaks around GeV energies. Thus, the intense creation of pairs would produce strong radiation in low-energy X-rays and also around GeV energies. These produced GeV gamma rays, where the pileup of photons below the absorption threshold occurs, could result in a significant flattening of the observed spectrum relative to the emitted spectrum.

7. DISCUSSION AND CONCLUSIONS

H.E.S.S. observations from 2007 January measured an upper limit on the integrated photon flux of 3C 279 of \(F(E_{\gamma} > 300 \text{ GeV}) < 3.98 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}\) (Aharonian et al. 2008). In our calculations, we assumed \(F(E_{\gamma} > 300 \text{ GeV}) = 3.9 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}\), allowed by the H.E.S.S. observations. Combining this with the integrated photon flux \(F(E_{\gamma} > 200 \text{ GeV}) = 3.5 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}\) measured by MAGIC (Teshima et al. 2007), a power-law spectrum \(dI/dE\gamma = a_1 E_{\gamma}^{-a_2}\) is inferred with \(a_1 = 505\) and \(a_2 = 6.4\). If \(F(E_{\gamma} > 300 \text{ GeV}) = 3.6 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}\) is adopted for the H.E.S.S. observations, \(a_1 = 1510\) and \(a_2 = 6.6\). If \(F(E_{\gamma} > 300 \text{ GeV}) = 3.98 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}\) is adopted, \(a_1 = 405\) and \(a_2 = 6.36\). Thus, \(a_1 \geq 405\) and \(a_2 \geq 6.4\) are likely to be limited by the MAGIC and H.E.S.S. observations for a VHE gamma-ray spectrum of \(dI/dE\gamma = 505E_{\gamma}^{-6.4}\) but correcting for internal and external absorption (see Figs. 2b, 3b, and 4b), the photon indices of these VHE gamma rays are around 5 for \(R_{\gamma} = 0.1\ \text{ pc}\), 2.0 for \(R_{\gamma} = 0.25\ \text{ pc}\), and 1.7 for \(R_{\gamma} = 0.4\ \text{ pc}\). These inferred indices for \(R_{\gamma}\) of 0.25 and 0.4 pc are within the range of the known intrinsic photon indices. If \(a_2 = 6.6\), indices of 1.9 \pm 0.3 are found for \(R_{\gamma} = 0.4\ \text{ pc}\), 2.2 \pm 0.01 \((a_1 = 0.5)\) and 2.1 \pm 0.003 \((a_1 = 0.998)\) for \(R_{\gamma} = 0.25\ \text{ pc}\), and 6.0 \pm 0.2 \((a_1 = 0.5)\) and 5.1 \pm 0.2 \((a_1 = 0.998)\) for \(R_{\gamma} = 0.1\ \text{ pc}\). As \(R_{\gamma}\) varies from 0.1 to 0.4 pc, the photon indices of the preabsorbed VHE gamma-ray spectra are likely to be within the intrinsic photon index range from 1.3 to 3.6 (Wagner 2008). If a smaller \(F(E_{\gamma} > 300 \text{ GeV}) = 2.0 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}\) is adopted, a larger \(a_2 = 8.0\) is obtained. For \(a_2 = 8.0\), indices of 3.3 \pm 0.03 are inferred for \(R_{\gamma} = 0.4\ \text{ pc}\), 3.6 \pm 0.01 \((a_1 = 0.5)\) and 3.5 \pm 0.003 \((a_1 = 0.998)\) for \(R_{\gamma} = 0.25\ \text{ pc}\), and 7.3 \pm 0.2 \((a_1 = 0.5)\) and 6.5 \pm 0.2 \((a_1 = 0.998)\) for \(R_{\gamma} = 0.1\ \text{ pc}\). Thus, larger photon indices of the preabsorbed spectra are obtained for a fixed \(R_{\gamma}\), as larger values of \(a_2\) are adopted. If \(R_{\gamma} = r_{BLR, in}\), the photon indices of these preabsorbed gamma-ray spectra are always larger than the typical value \(\Gamma_{in} = 2.3\) and the maximum \(\Gamma_{in} = 3.6\) of the known intrinsic photon indices. Thus, it is unlikely for 3C 279 that \(R_{\gamma}\) lies within the BLR cavity; that is, it is likely that \(R_{\gamma} > r_{BLR, in}\). If \(F(E_{\gamma} > 300 \text{ GeV})\) is adopted closer to the upper limit.
from the H.E.S.S. observations, $a_2$ is not too large. Too large a value of $a_2$, such as $a_2 \simeq 10$, corresponding to $F(E, > 300 \text{ GeV}) \simeq 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, seems to be impossible for VHE gamma-ray spectra because spectra with $a_2 \simeq 10$ are much steeper (softer) than the steepest (softest) spectrum measured, that for PG 1553+113 (Albert et al. 2007). When the gamma-ray-emitting region is already beyond the BLR, the EC mechanisms, where external photons originate from the BLR, are insufficient to produce the observed gamma rays. For 3C 279, the soft photon energy density around $r_{\text{BLR, out}}$ is lower by a factor of 6 to 7 than that around $r_{\text{BLR, in}}$ for the BLR diffuse radiation produced by the spherical shell of clouds (see Fig. 1 of Paper I). Thus $R_{\gamma} > r_{\text{BLR, out}}$ is unlikely; that is, it is unlikely that $R_{\gamma} \lesssim r_{\text{BLR, out}}$.

The external absorption softens the observed spectra relative to the emitted ones in the interval from 10 GeV to 1 TeV. Whether the internal absorption softens or hardens the observed spectra depends on the radius of the gamma-ray-emitting region $R_{\gamma}$ and the energy $E_{\gamma}$. Photon index variations of the gamma-ray spectra relative to $a_2 = 6.4$ were calculated for the internal absorption and for the combined internal and external absorption (Fig. 7). For $R_{\gamma} = r_{\text{BLR, in}}$, the local photon indices decrease with $E_{\gamma}$ from 10 to 110 GeV and increase with $E_{\gamma}$ from 110 GeV to 1 TeV (Fig. 7a). The local photon indices corrected for the internal absorption recover around 270 GeV [$\Delta \Gamma_{\text{(in)}} = 0$]. The internal absorption makes the gamma-ray spectra softer and softer from 10 to 110 GeV and from 270 down to 110 GeV and makes the spectra harder and harder from 270 GeV to 1 TeV. After being corrected for internal and external absorption, the local photon indices of the gamma rays recover around 500 GeV [$\Delta \Gamma_{\text{(in+ext)}} = 0$]. The external absorption cannot change the trend of the local photon indices of the gamma-ray spectra corrected for the internal absorption. For $R_{\gamma} = (r_{\text{BLR, in}} + r_{\text{BLR, out}})/2$, the local photon indices corrected for the internal absorption behave as in the case of $R_{\gamma} = r_{\text{BLR, in}}$ (see Fig. 7b). These indices recover around 400 GeV [$\Delta \Gamma_{\text{(in)}} = 0$]. The internal absorption makes the gamma-ray spectra softer and softer from 10 to 110 GeV and from 400 down to 110 GeV, and it makes the gamma-ray spectra harder and harder from 400 GeV to 1 TeV. After being corrected for the internal and external absorption, the local photon indices of the preabsorbed gamma-ray spectra basically decrease with $E_{\gamma}$. The external absorption cannot change the trend of the local photon indices of the gamma-ray spectra corrected for the internal absorption below 100 GeV, but it changes that above 100 GeV. The gamma-ray spectra become softer and softer relative to the preabsorbed ones from 10 GeV to 1 TeV [$\Delta \Gamma_{\text{(in+ext)}} < 0$]. For $R_{\gamma} = r_{\text{BLR, out}}$, the local photon indices have a similar trend to that in the case $R_{\gamma} = (r_{\text{BLR, in}} + r_{\text{BLR, out}})/2$ (see Fig. 7c). The internal absorption makes the gamma-ray spectra softer from 10 to ~420 GeV and from 1 TeV down to ~420 GeV. After being corrected for the internal and external absorption, the local photon indices monotonically decrease with $E_{\gamma}$, and the gamma-ray spectra become softer and softer relative to the preabsorbed ones from 10 GeV to 1 TeV [$\Delta \Gamma_{\text{(in+ext)}} < 0$]. The external absorption changes the trend of the local photon indices of the gamma-ray spectra corrected for internal absorption. The calculated results presented in Figure 7 are basically independent of the particular value of $a_2$. For example, the trends of the local photon indices for $a_2 = 5.4$ are basically identical to those in the case of $a_2 = 6.4$. In summary, internal absorption can make the spectral shape more complex than if one considers only the external absorption and could lead to the formation of arbitrarily softening and hardening gamma-ray spectra (see Figs. 2–4 and 7). Thus, it should be requisite for internal absorption to be considered in studying 10 GeV–1 TeV gamma rays from FSRQs.

Assuming $\Gamma_{\text{jet}} = 15$ for 3C 279, most of the gamma rays are contained within a radiation cone with a half-opening angle of $\Delta \theta \sim 1/\Gamma_{\text{jet}} \sim 3.8^\circ$, because of the relativistic beaming effect. If the central IR-optical-UV photons coming directly from the accretion disk travel through the radiation cone, they can engage in photon-photon pair creation processes with gamma rays within the cone. Assuming a gamma-ray-emitting region at $R_{\gamma} \sim 0.1$ pc and radii of the UV radiation regions of $r_{\gamma} < 30 r_{\gamma} \sim 0.0004$ pc (see Fig. 1), the angle between the jet direction and the direction of travel of the UV photons at $R_{\gamma}$ is roughly arctan ($r_{\gamma}/R_{\gamma}$) $\leq 0.2^\circ$. Then the photons within the radiation cone have collision angles of $\theta \approx 4.0^\circ$. For UV photons at a frequency $\nu \sim 10^{15}$ Hz, with energies of $E_{\gamma} \sim 2.56 \times 10^{-4}$, and gamma rays with $E_{\gamma} \sim 2.0 \times 10^6$, corresponding to energies around 1 TeV, the left-hand side of the threshold condition presented in equation (3) of Paper I has an upper limit of $\leq 0.6$, which is less than unity, and thus the two kinds of photons cannot be absorbed by the photon-photon pair creation processes. Therefore, the central UV radiation makes a negligible contribution to the absorption of gamma rays relative to the diffuse radiation from the BLR. For optical photons, the radii of the optical radiation regions are $r_{\gamma} < 200 r_{\gamma} \sim 0.003$ pc, so the angle between the jet direction and the direction of travel of optical photons at $R_{\gamma}$ is roughly arctan ($r_{\gamma}/R_{\gamma}$) $\leq 1.7^\circ$. Thus, the photons within the radiation cone have collision angles of $\theta \approx 5.5^\circ$. For optical photons at a frequency $\nu \sim 10^{15}$ Hz, with energies of $E_{\gamma} \sim 8.1 \times 10^{-6}$, and the gamma rays of $E_{\gamma} \sim 2.0 \times 10^6$, the left-hand side of the threshold condition has an upper limit of $\leq 0.04$, which is less than unity, and thus the two kinds of photons cannot be absorbed by the photon-photon pair creation processes. Therefore, the central optical radiation also makes a negligible contribution to the absorption of gamma rays relative to the diffuse radiation from the BLR. For IR photons, the central radiation also contributes negligibly to the absorption for gamma rays. Thus, the central IR-optical-UV radiation makes a negligible contribution to the absorption for gamma rays relative to the diffuse radiation from the BLR.

Absorption of gamma rays by photon-photon annihilation and where the energy carried by the annihilated gamma rays is reradiated are important to gamma-ray research. The intense creation of pairs would produce strong radiation in the form of low-energy X-rays or at GeV energies (Protheroe & Staniey 1993; Sauge & Henri 2004; Zdziarski & Coppi 1991). The electron-positron pair cascade could cause soft X-ray excesses (Zdziarski & Coppi 1991). The produced electron-positron pairs could make a difference around 1 GeV, where the pileup of photons below the absorption threshold results in a significant flattening in the observed spectrum relative to the emitted spectrum (Protheroe & Staniey 1993). In § 6, we studied the pair spectrum due to photon-photon absorption and the synchrotron and EC spectra emitted by a steady state equilibrium pair distribution. The synchrotron radiation peaks around keV X-rays, and the EC radiation peaks around GeV gamma rays (see Fig. 6b). Thus, pairs due to annihilation absorption of gamma rays by the diffuse radiation field of the BLR are likely to make a difference around 1 GeV for 3C 279.

In this paper, in order to limit the gamma-ray-emitting radius $R_{\gamma}$, we used a BLR model to study the photon-photon absorption by the diffuse radiation of the BLR in 3C 279 for 10 GeV–1 TeV gamma rays in the observed spectrum. We calculated the internal absorption of these gamma rays for $R_{\gamma}$, $r_{\text{BLR, in}}$, $r_{\text{BLR, out}}$, and $(r_{\text{BLR, in}} + r_{\text{BLR, out}})/2$ (see Figs. 2a, 3a, and 4a). For a fixed $R_{\gamma}$, the dependence of the photon-photon absorption optical depth $\tau_{\gamma\gamma}$ on the gamma-ray energy $E_{\gamma}$ relies on $R_{\gamma}$. The dependence of $\tau_{\gamma\gamma}$ on $R_{\gamma}$ was also studied for a fixed $E_{\gamma}$ (see Fig. 5). For a fixed
\(E_{\gamma}, \tau_{\gamma\gamma}\) decreases with increasing \(R_s\). The external absorption on the IR-optical-UV EBL was also estimated for 10 GeV–1 TeV gamma rays, and it monotonically increases as \(E_{\gamma}\) increases. A comparison of the internal with the external absorption shows that \(R_s\) determines the relative contributions of the internal and external absorption to the total photon-photon annihilation absorption of 10 GeV–1 TeV gamma rays (Figs. 2a, 3a, and 4a). Based on MAGIC and H.E.S.S. observations, a power-law spectrum (eq. [1]) was adopted for the photon intensity of VHE gamma rays. The preabsorbed gamma-ray spectra were inferred from this power law after correcting for the internal and external absorption. The internal absorption could make the spectral shape of the gamma rays more complex than if they were corrected only for external absorption and could lead to the formation of arbitrarily softening and hardening gamma-ray spectra (see Figs. 2a, 3a, 4a, and 7). Thus, it should be requisite for internal absorption to be considered in the study of 10 GeV–1 TeV gamma rays from FSRQs. The value of \(R_s\) significantly influences the variations of spectral shape due to internal absorption. Our calculations imply that the energies of gamma rays annihilated as a result of the internal absorption are mainly reradiated around the GeV regime (Fig. 6b). Considering possible variations of the photon index \(a_2\), the photon indices of the preabsorbed VHE gamma-ray spectra were compared with known intrinsic photon indices. For \(R_s = r_{\text{BLR, in}}\) and \(a_2 \geq 6.4\), the photon indices of the preabsorbed gamma-ray spectra are always larger than the typical value \(\Gamma_{\text{in}} = 2.3\) and the maximum \(\Gamma_{\text{in}} = 3.6\) of the known intrinsic photon indices, and \(\tau_{\gamma\gamma}\) is larger than unity. Thus, it is likely that \(R_s > r_{\text{BLR, in}}\) for 3C 279. For \(R_s = r_{\text{BLR, out}}\) and \(6.4 \leq a_2 \leq 8.3\), the photon indices of the preabsorbed spectra are not larger than the typical value \(\Gamma_{\text{in}} = 2.3\) and \(\Gamma_{\text{in}} = 3.6\). For a fixed \(a_2\), the photon indices of the preabsorbed spectra decrease as \(R_s\) increases. Too large a value of \(a_2\) seems to be impossible for VHE gamma-ray spectra. In addition, the EC processes may be insufficient to produce the observed gamma rays, as the gamma-ray–emitting region is already beyond the BLR. Thus, it is likely that \(R_s \leq r_{\text{BLR, out}}\) for 3C 279. Our results suggest that \(R_s\), for powerful blazars might lie neither inside the BLR cavity nor outside the BLR, but within the BLR shell. This is not consistent with the suggestions of Ghisellini & Madau (1996) and Georganopoulos et al. (2001), nor is it consistent with the suggestions of Lindfors et al. (2005) and Sokolov & Marscher (2005).

Our results are model dependent, especially in terms of the assumed power-law spectrum for the VHE gamma rays. Were Teshima et al. to publish the spectral indices of the gamma-ray spectra measured by MAGIC (Teshima et al. 2007), the power-law spectrum assumed in this paper could be tested. Tavecchio & Ghisellini (2008) used the photoionization code Cloudy (Ferland et al. 1998) to calculate detailed spectra from the BLR for powerful blazars and then used these to calculate the EC spectra. Approximate BLR spectra were used in this paper and Paper I, and another set of approximate spectra were used by Reimer (2007). Differences between the detailed and approximate spectra should exist. It should be useful in future research to study the effects of this difference on the results of previous work using approximate spectra (e.g., Paper I; Reimer 2007). Observations by GLAST, MAGIC, H.E.S.S., and VERITAS in the near future could provide more observational constraints on the gamma-ray–emitting regions and the BLRs for the powerful blazars. Publication of intrinsic photon indices predicted by theoretical research and photon indices measured by observations in the VHE regime could yield stronger constraints on \(R_s\).

We are grateful to the anonymous referee for constructive comments and suggestions leading to significant improvement of this paper. H. T. L. thanks the National Natural Science Foundation of China (NSFC) for financial support (grants 10573030 and 10778726). L. M. is supported by the NSFC under grant 10778702. J. M. B. is grateful for the support of the Bairen Jihua project of the Chinese Academy of Sciences.

### APPENDIX

If the central black hole is a Kerr one, the local effective temperature of the standard disk is given in the Kerr metric as

\[
T_{\text{eff}}(X_d) = \left[ \frac{3G M_{\text{BH}} M}{8 \pi \sigma_{\text{SB}} r_{\text{d}}^2 X_d^2 R_{\text{g}}(X_d)} \right]^{1/4} \tag{A1}
\]

(Krolik 1999, pp. 151–154), where \(\sigma_{\text{SB}}\) is the Stefan-Boltzmann constant, \(M_{\text{BH}}\) is the black hole mass, \(\dot{M}\) is the mass accretion rate of the central black hole, and the function \(R_{\text{g}}(X_d)\) is

\[
R_{\text{g}}(X_d) = C(X_d)/B(X_d), \tag{A2}
\]

with the functions \(B(X_d)\) and \(C(X_d)\) given by

\[
B(X_d) = 1 - \frac{3}{X_d} + \frac{2a_s}{X_d^{3/2}}, \tag{A3}
\]

\[
C(X_d) = 1 - \frac{y_{\text{ms}}}{y} - \frac{3a_s}{2y} \ln \left( \frac{y}{y_{\text{ms}}} \right) - \frac{3(y_1 - a_s)^2}{y y_1(y_1 - y_2)(y_1 - y_3)} \ln \left( \frac{y - y_1}{y_{\text{ms}} - y_1} \right) - \frac{3(y_2 - a_s)^2}{y_2(y_2 - y_1)(y_2 - y_3)} \ln \left( \frac{y - y_2}{y_{\text{ms}} - y_2} \right) - \frac{3(y_3 - a_s)^2}{y_3(y_3 - y_1)(y_3 - y_2)} \ln \left( \frac{y - y_3}{y_{\text{ms}} - y_3} \right) \tag{A4}
\]

(Krolik 1999, 151–154). Here \(y = (X_d)^{1/2}\), \(a_s = c J / G M_{\text{BH}}^2\) is the dimensionless spin parameter of the central black hole with spin angular momentum \(J\), \(y_{\text{ms}} = X_{\text{ms}}^{1/2}\) is the value of \(y\) at the marginally stable orbit, and the \(y_i\) are the three roots of the equation \(y^3 - 3y + 2a_s = 0\) (see, e.g., Reynolds & Nowak 2003).
Assuming prograde rotation, the radius of the marginally stable orbit in the equatorial plane of a Kerr black hole is

\[ X_{ms} = 3 + Z_2 - \left(3 - Z_1\right)\left(3 + Z_1 + 2Z_2\right)^{1/2} \]  

(Bardeen et al. 1972), where

\[ Z_1 = 1 + (1 - a^2)^{1/3}\left[(1 + a_s)^{1/3} + (1 - a_s)\right], \quad Z_2 = (3a^2 + Z_1^2)^{1/2}. \]

The marginally stable orbit in the equatorial plane corresponds to the maximum efficiency of energy release as a result of accretion, assuming a prograde orbit:

\[ \eta_{\text{max}} = 1 - \frac{X_{ms} - 2 + a_sX_{ms}^{-1/2}}{\sqrt{X_{ms}(X_{ms} - 3 + 2a_sX_{ms}^{-1/2})}} \]

(Kembhavi & Narlikar 1999, p. 107).

REFERENCES

Aharonian, F., et al. 2008, A&A, 478, 387
Aharonian, F. A., Atoyan, A. M., & Nagapetyan, A. M. 1983, Astrofizika, 19, 323 (English transl. Astrophysics, 19, 187)
Albert, J., et al. 2007, ApJ, 654, L119
Aschenbach, B., Giro, N., Porquet, D., & Prodehl, P. 2004, A&A, 417, 71
Baixeras, C., et al. 2004, Nucl. Instrum. Methods Phys. Res. A, 518, 188
Bardeen, J. M., Press, W. H., & Teukolsky, S. A. 1972, ApJ, 178, 347
Bardeen, J. M., & Rees, M. J. 1978, in Pittsburgh Conf. on BL Lac Objects, ed. A. M. Wolfe (Pittsburgh: Dept. Phys. Astron., Univ. Pittsburgh), 328
Blumenthal, G. R., & Gould, R. J. 1970, Rev. Mod. Phys., 42, 237
Böttcher, M. 2000, in AIP Conf. Proc. 515, GeV Gamma Ray Astrophysics Workshop, ed. B. L. Dingus, M. H. Salamon, & D. B. Kieda (Melville, NY: AIP), 31
Böttcher, M., & Schlickeiser, R. 1997, A&A, 325, 866
Böttcher, M., et al. 2007, ApJ, 670, 968
Brenneman, L. W., & Reynolds, C. S. 2006, ApJ, 652, 1028
Cao, X., & Jiang, D. R. 1999, MNRAS, 301, 451
Cen, A.-C., & Protheroe, R. J. 2003, Astropart. Phys., 18, 377
Chen, A., Reyes, L. C., & Ritz, S. 2004, ApJ, 608, 686
Chen, A., & Schlickeiser, R. 1986, A&A, 164, L16
Coffey, J., & Protheroe, R. J. 2003, Astropart. Phys., 18, 377
Dwek, E., & Krennrich, F. 2005, ApJ, 618, 657
Ebisawa, K., Matsu, S., & Hanawa, T. 1991, ApJ, 367, 213
Eisen, S., & Schlickeiser, R. 1996, A&A, 282, 13
Ferland, G. J., Korista, K. T., Verner, E. M. 1998, PASP, 110, 761
Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, M. 1998, PASP, 110, 761
Fischel, C. E., et al. 1999, ApJ, 549, 551
Funk, S., et al. 2004, Astropart. Phys., 22, 285
Gammie, C. F., Shapiro, S. L., & McKinney, J. C. 2004, ApJ, 602, 312
Gehrels, N., & Michel, P. 1999, Astropart. Phys., 11, 277
Georganopoulos, M., Kirk, J. G., & Mastichiadis, A. 2001, in ASP Conf. Ser. 227, Blazar Demographics and Physics, ed. P. Padovani & C. M. Urry (San Francisco: ASP), 116
Gijsel, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, MNRAS, 301, 451
Gijsel, G., & Madau, P. 1996, MNRAS, 280, 67
Hanawa, T. 1998, ApJ, 431, 948
Hartman, R. C., et al. 1999, ApJS, 123, 79
———. 2001a, ApJ, 553, 683
———. 2001b, ApJ, 558, 583
Hinton, J. 2004, A&A, 448, 331
Holman, W. 2003, Proc. 28th Int. Cosmic-Ray Conf. (Tsukuba), 2811
Holder, J., et al. 2006, Astropart. Phys., 25, 391
Jones, F. C. 1968, Phys. Rev., 167, 1159
Kartaltepe, J. S., & Balonek, T. J. 2007, APJ, 133, 2866
Kembhavi, A. K., & Narlikar, J. V. 1999, Quasars and Active Galactic Nuclei: An Introduction (Cambridge: Cambridge Univ. Press)