

# ABSORPTION OF 10 GeV–1 TeV GAMMA RAYS FROM 3C 279

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## ABSTRACT

In this paper, we revisit gamma-ray-emitting region for 10 GeV–1 TeV gamma rays from 3C 279 through studying the photon–photon absorption optical depth due to the diffuse radiation of the broad-line region (BLR) and the extragalactic background light (EBL). Based on the power-law spectrum detected by MAGIC, the preabsorbed spectra are inferred by correcting the photon–photon absorption on the diffuse photons of the BLR (internal absorption) and the EBL (external absorption). Position of gamma-ray-emitting region  $R_\gamma$  determines the relative contributions of this two diffuse radiations to the total absorption. Our results indicate that  $R_\gamma$  may be within the BLR shell for 3C 279, likely closer to the inner radius, which is consistent with our previous results. This is neither consistent with the suggestions of Böttcher et al., that very high energy (VHE) gamma-ray emission is produced far outside the BLR, nor with the assumptions of Tavecchio and Mazin, that VHE gamma-ray-emitting region is inside the BLR cavity.  $R_\gamma$  is a key physical quantity that could set some constraints on emission mechanisms that produce the VHE gamma rays from 3C 279. Observations of *Fermi*–Large Area Telescope, MAGIC, H.E.S.S., and VERITAS in the near future could give more constraints on the position of gamma-ray-emitting region relative to the BLR.

**Key words:** gamma rays: theory – quasars: individual (3C 279)

**Online-only material:** color figures

## 1. INTRODUCTION

The classical flat spectrum radio quasar (FSRQ) 3C 279 is one of the brightest extragalactic objects in the gamma-ray sky. It lies at a redshift of  $z = 0.536$  (Marziani et al. 1996). It was detected by EGRET, 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, including 51 FSRQs and 15 BL Lacertae (BL Lac) objects, in the GeV energy range by EGRET (Fichtel et al. 1994; Thompson et al. 1995, 1996; Catanese et al. 1997; Lin et al. 1997; Mukherjee et al. 1997; 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. Venters & Pavlidou (2007) found that the most likely Gaussian intrinsic spectral index distribution for EGRET blazars has a mean of 2.27 and a standard deviation of 0.20, as well as some indication that FSRQs and BL Lac objects may have different intrinsic spectral index distributions (with BL Lac objects being harder). Bloom (2008) confirmed the radio and gamma-ray correlation of EGRET blazars, and replicated through Monte Carlo simulations the observed luminosity relationship if a synchrotron self-Compton (SSC) model is assumed. Recently, Thompson (2008) summarized results from EGRET and reported that a central feature of the EGRET results was the high degree of variability seen in many gamma-ray sources, indicative of the powerful forces at work in objects visible to gamma-ray telescopes. The first three months of sky-survey operation with the *Fermi* Gamma Ray Space Telescope (*Fermi*)–Large Area Telescope (LAT) revealed 132 bright sources (Abdo et al. 2009). Associations of 106 of these sources are indicated on high confidence with known active

galactic nuclei (AGNs): two radio galaxies, namely, Cen A and NGC 1275, and 104 blazars consisting of 57 FSRQs, 42 BL Lac objects, and five blazars with uncertain classification (Abdo et al. 2009). Four new blazars were discovered on the basis of the LAT detections, and only 33 of the 106 sources were previously detected with EGRET (Abdo et al. 2009). It was revealed for the LAT blazars that the average GeV spectra of BL Lac objects are significantly harder than the spectra of FSRQs (Abdo et al. 2009). Some BL Lac objects 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). At present, 27 AGNs have been detected in very high energy (VHE) gamma rays, including 23 BL Lac objects, two radio sources (M 87 and Cen A), an unidentified MAGIC source (MAGIC J0223+430, possibly associated with the radio galaxy 3C 66B), and the first FSRQ, 3C 279, which has the highest redshift among these VHE AGNs.<sup>4</sup> Anderhub et al. (2009) reported upper limits to the VHE flux of the FSRQ 3C 454.3 ( $z = 0.859$ ) derived by the Cherenkov telescope MAGIC during the high states of 2007 July/August and 2007 November/December. The positive detection of 3C 279 in VHE gamma rays by the MAGIC telescope (Albert et al. 2008) comes unexpectedly. It was suggested that FSRQs are unlikely to be important VHE gamma-ray emitter, but BL Lac objects are important emitter (e.g., Fossati et al. 1998; Ghisellini et al. 1998; Böttcher & Dermer 2002). Observations showed that these suggestions are right before 3C 279 was detected by MAGIC. The most recent calculations showed that the internal absorption could significantly annihilate VHE gamma rays from FSRQs (Donea & Protheroe 2003; Liu & Bai 2006; Reimer 2007; Aharonian et al. 2008a; Liu et al. 2008; Sitarek & Bednarek 2008; Tavecchio & Mazin 2009).

The gamma rays from blazars are generally believed to be attributable to emission from a relativistic jet oriented at a

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small angle to the line of sight (Blandford & Rees 1978). The diffuse radiation field of broad-line region (BLR) could have a strong impact on the expected external Compton (EC) spectra of the most powerful blazars, FSRQs (e.g., Sikora et al. 1994; Wang 2000; Liu & Bai 2006; Reimer 2007; Aharonian et al. 2008a; Liu et al. 2008; Sitarek & Bednarek 2008; Tavecchio & Ghisellini 2008; Tavecchio & Mazin 2009). Not only do the external soft photon fields from the BLR provide target photons for the EC processes to produce these gamma-ray components, they also absorb gamma rays from the EC processes 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; Stecker & de Jager 1998; Oh 2001; Renault et al. 2001; Chen et al. 2004; Dwek & Krennrich 2005; Schroedter 2005; Stecker et al. 2006; Stecker & Scully 2009; Tavecchio & Mazin 2009). This external absorption of gamma rays by the diffuse extragalactic background light (EBL) has also been proposed to probe the EBL itself (Renault et al. 2001; Chen et al. 2004; Dwek & Krennrich 2005; Schroedter 2005; Stecker & Scully 2009; Tavecchio & Mazin 2009). 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; Liu et al. 2008). 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; Tavecchio & Mazin 2009).

The position of the gamma-ray-emitting region is still an open and controversial issue in the researches on blazars (Ghisellini & Madau 1996; Georganopoulos et al. 2001; Lindfors et al. 2005; Sokolov & Marscher 2005). In our previous work (Liu & Bai 2006, hereafter Paper I; Liu et al. 2008, hereafter Paper II), the position of the gamma-ray-emitting region was a key parameter to determine whether gamma rays could escape the diffuse radiation field of the BLR for FSRQs. VHE gamma rays will be strongly attenuated for 3C 279 if the emitting region is within the BLR cavity (see Papers I and II). However, MAGIC detected VHE gamma-ray spectrum from 3C 279 (Albert et al. 2008). H.E.S.S. observations placed an upper limit on the integrated photon flux for 3C 279 (Aharonian et al. 2008b). 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 Paper II, we addressed the particular topic of absorption in the gamma-ray quasar 3C 279 using the available observational data, the integrated photon flux measured by MAGIC (Teshima et al. 2008) and the upper limit placed by H.E.S.S. (Aharonian et al. 2008a), and its potential effect on the gamma-ray spectrum. Photon index of  $\gtrsim 6.4$  was limited and used to constrain the position of gamma-ray-emitting region in 3C 279 (see Paper II). In this paper, we attempt to address the same topic as in Paper II by using the VHE gamma-ray spectrum detected by MAGIC.

The structure of this paper is as follows. Section 2 presents intensity of VHE gamma rays. Section 3 presents theoretical calculation of photon–photon optical depth for 3C 279. Section 4 presents spectral shape of VHE gamma rays. Section 5 is for discussions and conclusions. Throughout this paper, 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 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. 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. 2008). H.E.S.S. observations in 2007 January measured an upper limit of integrated photon flux  $F(E_\gamma > 300 \text{ GeV}) < 3.98 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$  (Aharonian et al. 2008a). VHE gamma-ray emission from 2006 February 22 to 23 is likely due to an intermediate state, and on the rest of the nights it likely correspond to a low state (Paper II). GeV gamma-ray emission from 2000 February 8 to March 1 and VHE gamma-ray emission from 2006 February 22 to 23 likely originated from very similar states (see Paper II).

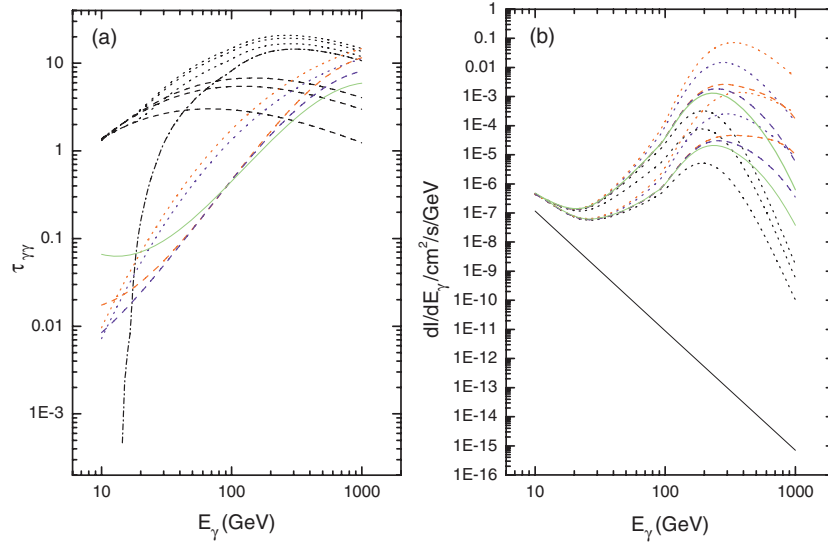
Recently, VHE spectrum of 3C 279 has been published from the MAGIC Collaboration (Albert et al. 2008), and the photon intensity of the VHE gamma rays is

$$\frac{dI}{dE_\gamma} = (5.2 \pm 1.7) \times 10^{-13} \times \left( \frac{E_\gamma}{200 \text{ GeV}} \right)^{-(4.11 \pm 0.68)} \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1}. \quad (1)$$

In Paper II, spectral index of  $\gtrsim 6.4$  is limited by the integrated photon fluxes measured by MAGIC and H.E.S.S., because no VHE spectrum of 3C 279 has been published before Paper II. Within error, the spectral slope of 4.11 is consistent with the maximum spectral slope of 4.21 measured in the VHE regime for PG 1553+113 (Albert et al. 2007). The value of 4.11 is larger than the slope of 2.3 for the VHE spectrum extrapolated from the GeV spectrum observed on 2000 February 8 to March 1 (Hartman et al. 2001). 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  $\bar{\Gamma} \approx 2.3$  for 17 blazars detected in the VHE regime (see Wagner 2008). 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.

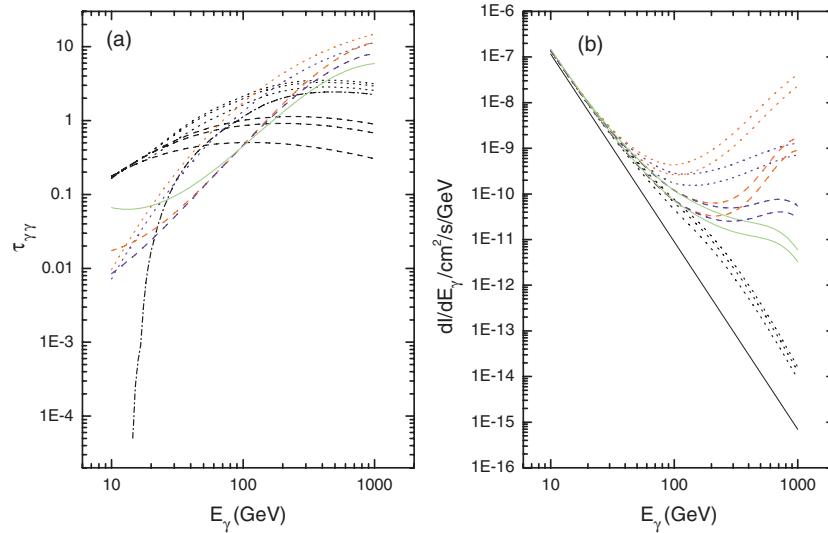
## 3. PHOTON–PHOTON OPTICAL DEPTH

The internal absorption of gamma rays due to the diffuse photons of the BLR is adopted from Paper II for 3C 279 (see Figures 2–4). 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, and investigated the infrared EBL absorption on high-energy gamma rays for 3C 279 and found an absorption optical depth of  $3.7 \lesssim \tau \lesssim 9.7$  for 1 TeV gamma rays. 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  $\lesssim 1 \text{ TeV}$  is entirely contributed by the EBL at  $0.1\text{--}10 \mu\text{m}$  (see Figure 3 of Dwek & Krennrich 2005). They only calculated the optical depth for low-redshift sources. Stecker et al. (2006) have given the optical depth for sources at redshifts  $z < 6$ . An analytic form to approximate the



**Figure 1.** (a) Photon–photon absorption optical depth for 3C 279. Dashed lines, absorption by multitemperature blackbody; dash-dotted line, absorption by broad emission lines; dotted lines, the total internal absorption by the two. In calculating  $\tau_{\gamma\gamma}$ , we assumed  $R_\gamma = r_{\text{BLR},\text{in}}, \tau_{\text{BLR}}/f_{\text{cov}} = 1$ , and  $f_{\text{cov}} = 0.03$ , and adopted  $r_{\text{BLR},\text{in}} = 0.1$ ,  $r_{\text{BLR},\text{out}} = 0.4$ ,  $L_{\text{BLR}} = 10^{44.41}$  erg s $^{-1}$ , and  $M_{\text{BH}} = 10^{8.4} M_\odot$ . From the top down, the dotted and dashed lines are for  $a_* = 0.5$ ,  $a_* = 0.8$ , and  $a_* = 0.998$ . (b) Gamma-ray spectrum of 3C 279: the spectrum given by Equation (1) (solid line) and the spectra corrected for the internal absorption (black dotted lines). From the top down, the black dotted lines are for  $a_* = 0.998$ ,  $a_* = 0.8$ , and  $a_* = 0.5$ . Color lines in (a) are the external absorption due to the EBL, estimated according to Equation (2): red and blue dotted lines are the fast evolution and baseline models, respectively, red and blue dashed lines the best-fit and low-IR Kneiske et al. (2004) models, respectively, green line the Primack et al. (2005) model. Color lines in (b) correspond to the black dotted lines in (b) for the cases of  $a_* = 0.5$  and  $a_* = 0.998$ , but corrected for the EBL absorption described by the relevant color lines in (a).

(A color version of this figure is available in the online journal.)



**Figure 2.** Same as Figure 1, but for  $R_\gamma = (r_{\text{BLR},\text{in}} + r_{\text{BLR},\text{out}})/2 = 0.25$ .

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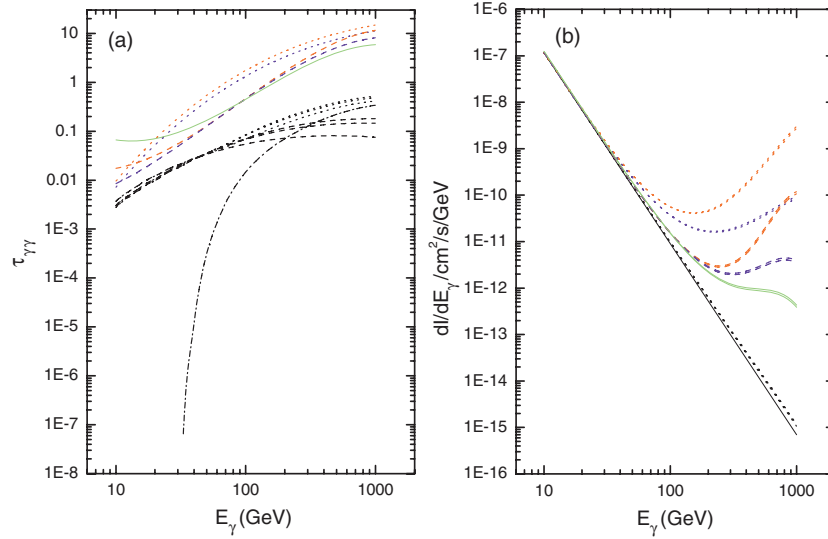
function  $\tau_{\gamma\gamma}(E_\gamma, z)$  of the external EBL absorption is given in Stecker et al. (2006). Five models are considered in Stecker & Scully (2009) to calculate the EBL absorption for 3C 279, and the five EBL absorptions were approximated as

$$\log \tau_{\gamma\gamma} = a_1 x^3 + a_2 x^2 + a_3 x + a_4, \quad (2)$$

where  $x \equiv \log E_\gamma$  (GeV). Coefficients  $a_1$  through  $a_4$  are given in Table 1 of Stecker & Scully (2009). We adopt these coefficients for five EBL models to calculate the EBL absorption optical depth.

In order to compare the internal and external absorption, the two absorptions are presented in Figures 1(a), 2(a), and 3(a).

The external absorption monotonically increases with gamma-ray energy. If  $R_\gamma$  is around the inner radius  $r_{\text{BLR},\text{in}}$ , the 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. If  $R_\gamma$  is around the median of  $r_{\text{BLR},\text{in}}$  and  $r_{\text{BLR},\text{out}}$ , the total absorption is dominated by internal absorption in the 10–100 GeV interval and the external absorption dominates from around 400 GeV to 1 TeV (see Figure 2(a)). The relative contributions of the internal and external absorption to the total are comparable from around 100 to 400 GeV (see Figure 2(a)). If  $R_\gamma$  is around the outer radius  $r_{\text{BLR},\text{out}}$ , the internal absorption is comparable to the external around 10 GeV, and the former is dominated by



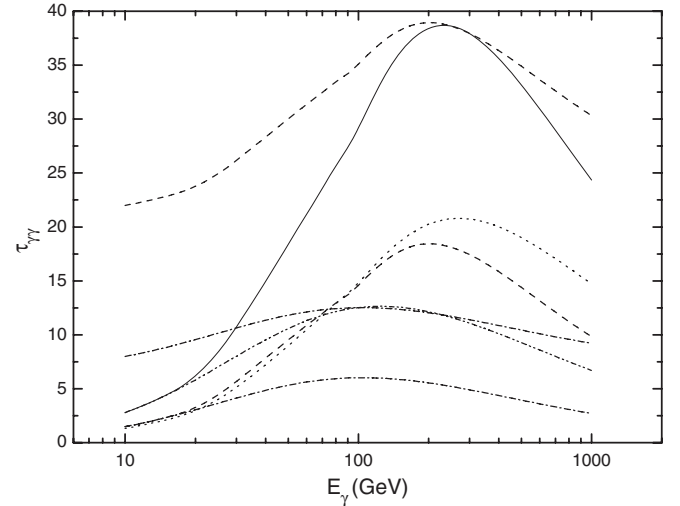
**Figure 3.** Same as Figure 1, but for  $R_\gamma = r_{\text{BLR,out}}$ .  
(A color version of this figure is available in the online journal.)

the latter from around 30 GeV to 1 TeV (see Figure 3(a)). The position of 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.

#### 4. SPECTRAL SHAPE OF 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 for the EBL absorption in the measured spectra (Wagner 2008). If the gamma-ray-emitting region is 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 Figures 1(a) and 2(a)). The position of 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 (see Figures 1(a), 2(a), and 3(a)). The external absorption monotonically increases with gamma-ray energy, and thus its effect on the shape of 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. 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 1(b), 2(b), and 3(b) (color lines). For  $R_\gamma$  is around  $r_{\text{BLR,in}}$ , the preabsorbed VHE gamma-ray spectra peak from around 200 to 400 GeV (Figure 1(b)). If  $R_\gamma \gtrsim (r_{\text{BLR,in}} + r_{\text{BLR,out}})/2$ , the preabsorbed VHE gamma-ray spectra are concave except these green lines in Figures 2(b) and 3(b). After passing through the internal and external diffuse radiation fields, the detected gamma-ray spectra are softer than the preabsorbed ones, when  $R_\gamma$  range from around 0.25 to 0.4 (see Figures 2(b) and 3(b)).

These preabsorbed VHE gamma rays from 500 GeV to 1 TeV can be well fitted by a power-law spectrum. For  $R_\gamma = 0.1$ , photon indices of  $2.14 \pm 0.05$  to  $4.95 \pm 0.06$  are given by the



**Figure 4.** Photon–photon absorption optical depth for 3C 279 as  $a_* = 0.5$ ,  $r_{\text{BLR,in}} = 0.1$ ,  $r_{\text{BLR,out}} = 0.4$ , and  $R_\gamma = 2 \times 10^{16}$  cm. Solid line is the total absorption optical depth as  $R_1 = R_\gamma$  and  $R_2 \gg r_{\text{BLR,in}}$ . The lower dashed line is the total one as  $R_1 = R_\gamma$  and  $R_2 = r_{\text{BLR,in}}$ . Dash-double-dotted line is the absorption optical depth due to the diffuse continuum as  $R_1 = R_\gamma$  and  $R_2 \gg r_{\text{BLR,in}}$ . The lower dash-dotted line is the absorption optical depth due to the diffuse continuum as  $R_1 = R_\gamma$  and  $R_2 = r_{\text{BLR,in}}$ . The upper dashed line is the upward shifted one of the lower dashed line. The upper dash-dotted line is the upward shifted one of the lower dash-dotted line. Dotted line is the upper dotted line in plot (a) in Figure 1.

fit for color dotted lines; values of  $1.87 \pm 0.15$  to  $5.92 \pm 0.14$  are given for color dashed lines; and values of  $6.36 \pm 0.15$  to  $7.54 \pm 0.15$  are given for green lines (Figure 1(b)). The values of  $6.36 \pm 0.15$  to  $7.54 \pm 0.15$  for green lines are larger than the typical value of 2.3 for the known VHE sources and are also larger than the intrinsic photon index of  $\simeq 3.6$  for PG 1553+113, the maximum among the known VHE spectra (Wagner 2008). Values of  $2.14 \pm 0.05$  to  $4.95 \pm 0.06$  for color dotted lines and values of  $1.87 \pm 0.15$  to  $5.92 \pm 0.14$  for color dashed lines are not inconsistent with the range of intrinsic photon index from 1.3 to 3.6 for the known VHE sources (Wagner 2008). For  $R_\gamma = 0.25$  and  $R_\gamma = 0.4$ , the preabsorbed VHE gamma-ray spectra are concave except those described by the green lines



(Figures 2(b) and 3(b)). Values of  $1.69 \pm 0.12$  to  $1.81 \pm 0.12$  are given for green lines in Figure 2(b) and values of  $1.08 \pm 0.10$  are given for green lines in Figure 3(b). These are smaller than the typical value of 2.3 for the known VHE sources.

Five models considered in Stecker & Scully (2009) to calculate the EBL absorption for 3C 279 are the fast evolution and baseline models of Stecker et al. (2006), the best-fit and low-IR models of Kneiske et al. (2004), and the model of Primack et al. (2005). For  $R_\gamma \gtrsim 0.25$ , the preabsorbed VHE gamma-ray spectra are concave as the Stecker et al. models and the Kneiske et al. models are used, but convex for the Primack et al. model. After VHE gamma-ray spectra measured by MAGIC are corrected for the EBL, the preabsorbed spectra of 3C 279 have a concave shape (Albert et al. 2008; Tavecchio & Mazin 2009).

## 5. DISCUSSIONS AND CONCLUSIONS

In Papers I and II, the template of the diffuse BLR radiation includes the continuum in the IR–optical–UV band. This diffuse continuum is presented by the diluted blackbody radiation in Paper I, and is presented by the diluted multitemperature blackbody radiation in Paper II. The details of the diluted blackbody are illustrated by Equation (20) in Paper I and the first paragraph of Section 3 in Paper II. Though, these approximations to the continuum from the BLR gas differ from the realistic continuum emitted by the BLR gas, these approximate continua have an important role in shaping the optical depth to gamma rays at energies  $> 100$  GeV (see Figures 2(a)–4(a) in Paper II, and Figures 1(a)–3(a) in this paper). In Paper II and this paper, the approximate energy spectrum of the continuous part of the BLR emission is given by the normalized multitemperature blackbody spectrum integrated all over the standard accretion disk, similar to the case E in Tavecchio & Mazin (2009). The optical depth to gamma rays from 10 GeV to 1 TeV is similar to that of the case E (see red lines in Figure 3 of Tavecchio & Mazin 2009). The diluted multitemperature blackbody spectrum has a long low-energy tail in IR–optical band, and this feature is similar to that from simulation run by Tavecchio & Ghisellini (2008) and Tavecchio & Mazin (2009). Böttcher et al. (2008b) confirmed the findings of Paper II: the dependence of the photon–photon absorption depth on the dimensionless photon energy and the location of the gamma-ray production site. These similarities and confirmations indicate that our approximation to the continuum from the BLR gas is reasonable. Position of gamma-ray-emitting region  $R_\gamma$  can significantly affect the shape of the optical depth to gamma rays from 10 GeV to 1 TeV, including the emission line and continuum absorption optical depth and the total one (see Figures 2(a)–4(a) in Paper II and Figures 1(a)–3(a) in this paper). The peak of  $\tau_{\gamma\gamma}(E_\gamma)$  tends to move toward higher energy as  $R_\gamma$  increases. The integral over  $R$  has an upper limit of  $R_2 = r_{\text{BLR}}$  in Equation (1) in Tavecchio & Mazin (2009), where  $r_{\text{BLR}}$  is equivalent to  $r_{\text{BLR,in}}$  in our papers. However, this upper limit of  $R_2$  adopted in Papers I and II and this paper is much more than  $r_{\text{BLR}}$ . This difference of this upper limit results in a steeper photon–photon absorption optical depth than that in Tavecchio & Mazin (2009; see Figure 4). The absorption due to the soft photons outside  $r_{\text{BLR}}$  is comparable to or larger than that from these soft photons inside  $r_{\text{BLR}}$  (see Figure 4), and cannot be ignored in calculations of the total absorption. Furthermore, the two absorptions have different profiles in the VHE regime due to the two different integral ranges of  $R$ . These effects are presented in Figure 4. For comparison to illustrate these effects, the lower dashed and dash-dotted lines, corresponding to the

total absorption optical depth and the absorption optical depth due to the diffuse continuum from the BLR, are shifted upward to the solid and dash-double-dotted lines, respectively. These curves in Figure 4 are estimated as  $a_* = 0.5$ ,  $r_{\text{BLR,in}} = 0.1$ ,  $r_{\text{BLR,out}} = 0.4$ , and  $R_\gamma = 2 \times 10^{16}$  cm which is the same as in Tavecchio & Mazin (2009). There exists an important (almost flat) optical–IR component in the model of Tavecchio & Mazin (2009), and this component dominates  $\tau_{\gamma\gamma}$  at energies above 100 GeV. This component could result in a bump around 10 TeV in  $\tau_{\gamma\gamma}$ . In the case E of Tavecchio & Mazin (2009), there is another bump around 100 GeV in  $\tau_{\gamma\gamma}$  (see red lines in the upper panel, Figure 3). There are also valleys between the two bumps in the case E. Due to the steepening effect of  $\tau_{\gamma\gamma}$  as the upper limit  $R_2$  of the integral over  $R$  increases, these valleys become steeper as  $R_2$  increases. Thus, the case E of Tavecchio & Mazin (2009) could produce much more pronounced variations in the opacity from 100 GeV to 1 TeV if  $R_2 \gg r_{\text{BLR}}$ . We think that the profiles of these curves presented in Figure 1 should be reliable. Thus, it is likely to see the presence of the important bump in the intrinsic spectrum around 300 GeV in some of the cases (e.g., Figure 1(b) in this paper and Figure 2(b) in Paper II). One more realistic approach to get the energy spectrum emitted by the BLR gas is as follows: on the basis of the observational energy spectrum in IR–optical–UV band with the high resolution and the high ratio of signal to noise, the BLR energy spectrum can be derived by subtracting narrow emission lines, and the continua emitted by jet and host galaxy from the observed spectrum of blazars. The BLR spectra obtained by this way should be relatively closer to the realistic ones than those assumed or simulated previously.

Five EBL models are used in this paper to estimate the EBL absorption to gamma rays. The model of Primack et al. (2005) exhibits a steep mid-IR valley that is directly in conflict with solid lower limits obtained from galaxy counts from observations at mid-IR wavelengths (Altieri et al. 1999; Elbaz et al. 2002), because this model does not take the warm dust, polycyclic aromatic hydrocarbon, and silicate emission components of mid-IR galaxy spectra into account, but was based on strictly theoretical galaxy spectra (e.g., Stecker & Scully 2009). This conflict is clearly shown in Figure 2 of the supplemental online material of Albert et al. (2008). Even so, we still consider the model of Primack et al. as one possible EBL model to estimate the EBL absorption. However, this model only gives a lower limit to the EBL absorption. The fast evolution model is favored by the *Spitzer* observations (e.g., Stecker et al. 2007). It provides a better description of the deep *Spitzer* number counts at 70 and 160  $\mu\text{m}$  than the baseline model. However, *Galaxy Evolution Explorer* (GALEX) observations indicate that the evolution of UV radiation for  $z < 1$  may be more consistent with the baseline model, and the 24  $\mu\text{m}$  *Spitzer* source counts are closer to the baseline model than the fast evolution model (e.g., Stecker et al. 2007). Albert et al. (2008) suggested that the detection of 3C 279 in VHE regime would appear to disfavor the EBL models of Stecker et al. (2006). Recently, Stecker & Scully (2009) concluded that the five EBL models used in this paper equally produce reasonable fits to the observational data of 3C 279. Aharonian et al. (2006) argued that intrinsic spectra must have spectral index of  $\Gamma \geq 1.5$  for blazars. Combining this assumption with H.E.S.S. observations of 1ES 1101-232, they placed an upper limit on the EBL at 1.5  $\mu\text{m}$ . This limit is consistent with the baseline model, but not with the fast evolution model that is favored by the *Spitzer* observations. Stecker et al. (2007) reexamined the assumption of spectral

index of  $\Gamma \geq 1.5$  made by Aharonian et al. (2006). They found that relativistic shock acceleration can produce particle population with a significant range of spectral indices, including those with  $\Gamma_e \leq 2$  corresponding to inverse Compton gamma-ray spectra with  $\Gamma \leq 1.5$ . Franceschini et al. (2008) found that the de-absorbed TeV spectra of BL Lac objects are all softer than  $\Gamma = 1.5$ , as assumed in Aharonian et al. (2006). Later, Krennrich et al. (2008) showed that the differential spectral index of intrinsic spectrum is  $\Gamma = 1.28 \pm 0.20$  or harder for the three TeV blazars 1ES 0229+200, 1ES 1218+30.4, and 1ES 1101-232. Franceschini et al. (2008), based on an impressive amount of observational data, showed that the level of the EBL should be close to what is estimated through galaxy counts. As pointed out in Krennrich et al. (2008), their result is based on observational constraints, but Franceschini et al.'s (2008) is based on theoretical modeling. Thus, it is allowable  $\Gamma < 1.5$ . These low values of  $\Gamma < 1.5$  indicate that the upper limit on the near IR EBL obtained by Aharonian et al. (2006) is allowed to increase to higher level. Such a result is consistent with the fast evolution model. Thus, the five models used in this paper, the baseline and fast evolution models of Stecker et al. (2006), the best-fit and low-IR models of Kneiske et al. (2004), and the model of Primack et al. (2005), are partly favored or not fully supported by observations. Then, the five EBL models are likely to be reliable. In consequence, the preabsorbed spectra (described by the color lines in Figures 1(b), 2(b), and 3(b)) should be also reliable. According to comparisons of intrinsic photon indices discussed in Section 4, photon indices of 6.4–7.5 for the green lines in Figure 1(b) are larger than the maximum among the known VHE spectra, and photon indices of 1.1 for the green lines in Figure 3(b) are smaller than the minimum among the known VHE spectra. Thus,  $R_\gamma$  should be between the inner and outer radii of the BLR. For the gamma-ray-emitting region outside the median of inner and outer radii of the BLR, the preabsorbed gamma-ray spectra have concave shape in the range from several ten GeVs to TeV (Figures 2(b) and 3(b)).

The intrinsic spectra of Mrk 421 and Mrk 501 were derived for all the realizations of the EBL templates, and some EBL realizations led to an unphysical behavior in the blazar intrinsic VHE spectrum, characterized by an exponential rise after a decline or flat behavior with energy (Dwek & Krennrich 2005). These intrinsic VHE gamma-ray spectra with physical behavior mostly show power law or convex shapes. Measured and intrinsic VHE gamma-ray spectra can be well described by a power law for 17 BL Lac objects (Wagner 2008). Many researches on the spectrum energy distribution (SED) of VHE gamma-ray have not shown concave shape, but convex shape for blazars (e.g., Böttcher et al. 2008a, 2008b; Dermer et al. 2009; Mannheim & Biermann 1992; Saugé & Henri 2004; Tavecchio & Ghisellini 2008). Thus, it is reliable that the intrinsic VHE spectra of blazars should generally have convex shapes. For  $R_\gamma$  beyond the median of inner and outer radii of the BLR, the SEDs,  $E_\gamma^2 dI/dE_\gamma$ , of the preabsorbed spectra denoted by the red and blue dotted lines and the red dashed lines in Figures 2(b) and 3(b) have concave shapes in the range from several ten GeVs to TeV. This indicates that  $R_\gamma$  is likely to be inside the median of inner and outer radii of the BLR for 3C 279. For  $R_\gamma = r_{\text{BLR, in}}$ , the internal absorption optical depth is larger than unity for 10 GeV gamma rays, and this is not consistent with observations of EGRET (see Papers I and II). This indicates  $R_\gamma \gtrsim r_{\text{BLR, in}}$ . According to comparisons of intrinsic photon indices discussed in Section 4,  $R_\gamma \sim r_{\text{BLR, in}}$  is allowed. Thus, the gamma-ray-emitting region is likely between the inner radius and the median

of inner and outer radii of the BLR, and is probably closer to the inner radius.

Böttcher et al. (2008b) studied the simultaneous optical, X-ray, and VHE gamma-ray data from the day of the VHE detection for 3C 279, and discussed the implications of the SED for jet models of blazars. A hadronic model is proposed to explain the SED of 3C 279 by Mannheim & Biermann (1992). Böttcher et al. (2008b) showed that the observed SED of 3C 279 can be reasonably well reproduced by a hadronic model. However, a rather extreme jet power is required by various versions of the hadronic model. They also employed the homogeneous leptonic jet models, including the EC and SSC models, to explain the simultaneous SED of 3C 279. The EC models can reproduce the simultaneous optical and VHE gamma-ray spectrum of 3C 279, but require either a unusually low magnetic field or an unrealistically high Doppler factor, as well as unable to reproduce the observed X-ray data. The SSC models can reproduce the simultaneous X-ray–VHE gamma-ray SED of 3C 279, but fail to reproduce the optical data. The SSC models require the gamma-ray-emitting region far outside the BLR. Bai & Lee (2001) predicted existence of large-scale synchrotron X-ray jets in radio-loud AGNs, especially, the X-ray jet is bright on 10 kpc scales in most red blazars and red blazar-like radio galaxies. According to their predictions, the large-scale synchrotron X-ray jets can produce VHE gamma rays by the SSC processes. In this case, the VHE gamma rays from 3C 279 are produced by the same ways as in the high peaked-frequency BL Lac objects (HBL). However, the cooling rate in the inner jets of HBLs is lower than that of FSRQs due to the thinner external soft photons in HBLs. Thus, electron population in jets of HBLs can earlier gain more energies enough to emit VHE gamma rays in a closer region to the central engines than that of FSRQs. If the VHE gamma rays from 3C 279 are emitted by the large-scale synchrotron X-ray jet on kpc scales, the VHE gamma-ray-emitting region is likely to be imaged by *Fermi*/LAT, and then the SSC processes could be tested and the gamma-ray-emitting position could be constrained by observations of *Fermi*/LAT. The gamma-ray-emitting position is a key physical quantity that constrains radiation mechanisms that produce the VHE gamma rays from 3C 279.

In this paper, we revisit the position of gamma-ray-emitting region for 10 GeV–1 TeV gamma rays from 3C 279 through studying the photon–photon absorption optical depth due to the diffuse radiation of the BLR and the EBL. Based on the power-law spectrum detected by MAGIC, the preabsorbed spectra are inferred by correcting the internal absorption by the BLR and the external absorption by the EBL. For the gamma-ray-emitting region outside the median of inner and outer radii of the BLR, the preabsorbed gamma-ray spectra have concave shape in the range from several ten GeVs to TeV (Figures 2(b) and 3(b)). However, many researches on intrinsic VHE gamma-ray spectra showed power law or convex shapes in the VHE regime for blazars (e.g., Böttcher et al. 2008a, 2008b; Dermer et al. 2009; Mannheim & Biermann 1992; Saugé & Henri 2004; Tavecchio & Ghisellini 2008; Wagner 2008). Thus, it is likely  $R_\gamma \lesssim (r_{\text{BLR, in}} + r_{\text{BLR, out}})/2$  for 3C 279. Based on studies of the photon–photon optical depth and the intrinsic spectral indices,  $R_\gamma \gtrsim r_{\text{BLR, in}}$ . Thus, the gamma-ray-emitting region in 3C 279 is likely between the inner radius and the median of inner and outer radii of the BLR, probably closer to the inner radius. This is consistent with our previous results (Paper II). However, this is neither consistent with the suggestions of Böttcher et al. (2008b), that VHE gamma-ray emission is produced far outside the BLR for

3C 279, nor with the assumptions of Tavecchio & Mazin (2009), that VHE gamma-ray-emitting region is inside the BLR cavity for 3C 279. This also is neither consistent with suggestions that  $R_\gamma$  lies within the BLR cavity for powerful blazars (Ghisellini & Madau 1996; Georganopoulos et al. 2001), nor consistent with suggestions that  $R_\gamma$  are outside the BLRs for powerful blazars (Lindfors et al. 2005; Sokolov & Marscher 2005).  $R_\gamma$  determines the relative contributions of the BLR and the EBL to the total absorption, and is a key physical quantity that constrains emission mechanisms that produce the VHE gamma rays from 3C 279. Observations of *Fermi*/LAT, MAGIC, H.E.S.S., and VERITAS in the near future could give more constraints on  $R_\gamma$ . Publications of intrinsic spectra predicted by theoretical researches and these measured by observations in the VHE regime could give stronger constraints on the position of gamma-ray-emitting region relative to the BLR.

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