

Intrinsic absorption in 3C 279 at GeV-TeV energies and consequences for estimates of the EBL

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ABSTRACT

We revisit the limits of the level of the extragalactic background light (EBL) recently reported by the MAGIC collaboration based on the observed γ -ray spectrum of the quasar 3C279, considering the impact of absorption of high-energy γ -ray photons inside the broad line region (BLR) of the quasar. We use the photoionization code CLOUDY to calculate the expected optical-UV radiation field inside the BLR and the optical depth to γ -rays for a relatively extended set of the parameters. We found that the absorption of γ -ray photons, though important for the estimate of the true radiative output of the source, does not produce an important hardening of the spectrum of 3C279 in the energy band accessible by MAGIC, supporting the method used to infer the upper limits to the level of the EBL.

Key words: quasars: individual: 3C279 – gamma rays: observations – gamma rays: theory – diffuse radiation

1 INTRODUCTION

The detection of 3C279 ($z=0.536$) in the very high energy (VHE, $E > 50$ GeV) band by the MAGIC telescope (Albert et al. 2008) extends to the quasars the group of the known extragalactic VHE sources, before limited to BL Lac objects (excluding the nearby radiogalaxy M87)¹.

For some aspects, the detection of 3C279 comes as a surprise. General theoretical arguments support the view that quasars cannot be important VHE emitters, in particular because of the expected absorption, through the pair production process $\gamma + \gamma \rightarrow e^+ + e^-$, inside the source itself (among the most recent calculations, e.g., Donea & Protheroe 2003, Liu & Bai 2006, Reimer 2007). Moreover, quasars are generally located at a relatively high redshift, implying a huge absorption by the extragalactic background light (EBL, e.g. Kneiske et al. 2004, Primack et al. 2005, Stecker et al. 2006, Franceschini et al. 2008). Last, but not least, widely adopted standard leptonic models for production of γ -rays in 3C279 (Hartman et al. 2001, Ballo et al. 2002; see also Tavecchio & Ghisellini 2008, hereafter TG08) do not predict an important emission above few tens of GeV, because of the rapid decrease of the scattering cross section (for hadronic scenarios see, e.g. Mannheim 1993). The observation of VHE photons from 3C279 by MAGIC (Albert et al. 2008) demonstrates that also quasars can, to some extent, produce high-energy γ -rays and suggests that the opacity (both intrinsic and cosmic) is less important than what previously assumed.

The detection of a source of VHE photons at relatively high

redshift offers a unique tool to probe the still poorly known EBL. Albert et al. (2008) used general arguments based on a limiting spectral slope for the emitted spectrum to infer the amount of extragalactic absorption. However, as recently pointed out by Aharonian et al. (2008) (see also Bednarek 1997), intrinsic absorption of γ -ray photons inside the source could result in rather hard observed spectra. Such spectra affected by absorption could lead to severely underestimate the level of the EBL when the arguments based on the hardness of the spectrum are used. For this reason, the use of the measured spectrum to constrain the EBL in Albert et al. (2008) triggered some discussion on the role and strength of the internal absorption in this source (Liu et al. 2008, Sitarek & Bednarek 2008).

We emphasize that the absorbed spectrum will be harder than the intrinsic one only in the case of an optical depth $\tau(E)$ decreasing with energy, E . Thus, as long as the optical depth increases (or, at least, only slightly decreases) with energy, the resulting spectrum will be softer (or slightly harder) than the intrinsic one and the standard spectral methods to constrain the EBL could be safely used. It is thus clear that the shape of $\tau(E)$, strictly related to the spectrum of the target photons, is the key element to assess the effects of absorption on these methods.

Previous attempts to calculate intrinsic absorption in the BLR (Liu & Bai 2006, Reimer 2007, Liu et al. 2008) assumed rather idealized templates for the BLR spectrum, considering the most prominent emission lines but neglecting the important contribution of the optical-UV continuum. In a recent paper, Sitarek & Bednarek (2008) consider the absorption modeling in detail the geometry of the radiation fields inside the BLR, including also the contribution of direct and scattered radiation of the accretion disc, but, again,

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¹ see <http://www.mppmu.mpg.de/~rwagner/sources>

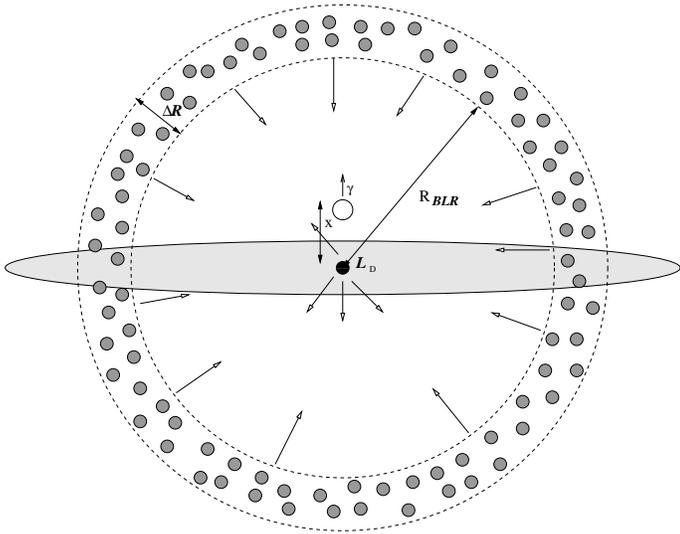


Figure 1. Sketch of the geometry assumed in the model (not to scale). The (uniform) BLR is assumed to be a spherical shell with thickness ΔR and inner radius R_{BLR} , illuminated by the central continuum with luminosity L_D . The source of γ -ray photons is at distance x from the central black hole. See text for details.

they model the BLR radiation with the simplified template of Liu & Bai (2006).

In this work (Sect. 1) we explore the effects of absorption using more realistic spectra of the BLR calculated with the photoionization code CLOUDY (Ferland et al. 1998), previously used to study in detail the inverse Compton emission from powerful blazars (TG08). In particular, we show that the optical-UV continuum plays an important role in determining the absorption, resulting in an almost constant optical depth in the broad energy range 30 GeV–30 TeV. In Sect. 2 we use the spectra corrected for absorption to revisit the constraints on the EBL based on the spectrum of 3C279 derived in Albert et al. (2008). In Sect. 3 we discuss the results.

2 INTRINSIC ABSORPTION

2.1 The model

We calculate the diffuse radiation field inside the BLR of 3C279 for different values of the BLR radius, temperature of the accretion disk, slope of the illuminating UV radiation. We refer to TG08 for a full description of the model. We assume the geometry shown in Fig. 1. The accretion flow illuminates the BLR clouds (characterized by the total hydrogen density n and the hydrogen column density N_H) isotropically filling the BLR, assumed to be a thin spherical shell with inner radius R_{BLR} . In the calculation we assume that the clouds cover a fraction $C = \Omega/4\pi = 0.1$ of the solid angle viewed from the central illuminating source. The emission from the illuminated face of the clouds is calculated with version 05.07 of CLOUDY, described by Ferland et al. (1998)². For simplicity, we discuss only the case of solar abundance and in all calculations we fix $n = 10^{10} \text{ cm}^{-3}$ and $N_H = 10^{23} \text{ cm}^{-2}$. Results do not substantially change for different densities and column densities (see

TG08). We adopt the spectrum of the illuminating continuum modeled as a combination of a UV bump (with slope α_{UV}) with a flat X-ray power-law, $L_D(\nu) \propto \nu^{-1}$, commonly assumed in these calculations (AGN model in CLOUDY, e.g. Korista & Goad 2001 and references therein). When not explicitly noted, the disk is assumed to have the “standard” temperature $T_D = 1.5 \times 10^5 \text{ K}$.

We assume that the disk in 3C279 emits a total luminosity $L_D = 2 \times 10^{45} \text{ erg/s}$ (Pian et al. 1999). More uncertain is the radius of the BLR. The empirical relations connecting the luminosity of the disk and R_{BLR} (Bentz et al. 2006, Kaspi et al. 2007) provide $R_{BLR} \simeq 1 - 3 \times 10^{17} \text{ cm}$. Given these uncertainties, below we show the results for four different values of R_{BLR} , 1, 1.6, 3.2 and $6.3 \times 10^{17} \text{ cm}$.

The optical depth for the photon-photon absorption, $\tau(E)$, is calculated as (e.g., Liu & Bai 2006):

$$\tau(E) = \int_x^{R_{BLR}} \int \int n(\nu, \Omega, l) \sigma_{\gamma\gamma}(E, \nu, \Omega) (1 - \mu) d\Omega d\nu dl(1)$$

where E is the energy of the γ -rays, l is the distance of the photons from the BH, $n(\nu, \Omega, l)$ is the number density of the radiation for solid angle at each location of the photon path, $\sigma_{\gamma\gamma}(E, \nu, \Omega)$ is the cross section and $d\Omega = 2\pi d\mu$. Note that, given the characteristics of the cross section, for a fixed geometry $\tau(E) \propto \nu n(\nu)$ with $\nu \propto 1/E$, that is the optical depth reflects the spectrum of the soft photon field (smeared by the cross section).

To calculate $\tau(E)$ from Eq.(1) one has to specify the location of the source, x . All calculations discussed below have been performed with $x = 2 \times 10^{16} \text{ cm}$. Larger values of x (a source closer to the BLR) result in a lower level of the absorption, but do not essentially affect the *shape* of $\tau(E)$. For smaller values of x one should also consider the absorption induced by photons directly coming from the accretion disk (Ghisellini & Madau 1996, Sitarek & Bednarek 2008). However, absorption from the disk is characterized, for the considered range of energies, by an optical depth monotonically increasing with energy (Sitarek & Bednarek 2008). As already discussed, in this conditions the resulting spectrum is *softer* than the emitted spectrum and thus it does not affect the constraints on the EBL.

Note that, for simplicity, we neglect the effects related to the radiative transfer *inside* the emission region (negligible as long as the size of the source is much less than $R_{BLR} - x$). Another possible effect that we do not take into account is that in the case of a moving source (as in the standard “internal shock” scenario, Spada et al. 2001), photons emitted at different times will also be characterized by different x in Eq.1 and thus will suffer a different level of intrinsic absorption. The study of these effects, in part already considered by Sitarek & Bednarek (2008), is important in view of the interpretation of the time-resolved spectra soon available thanks to the *Fermi Gamma-ray Space Telescope*.

2.2 Results

As an example, Fig.2 reports some BLR spectra derived with the model, assuming $T_D = 1.5 \times 10^5 \text{ K}$, $\alpha_{UV} = 0.5$, R_{BLR} , 1, 1.6, 3.2 and $6.3 \times 10^{17} \text{ cm}$, plotted as the number photon density, $n(\nu)\nu$. The two vertical lines indicate the spectral range interesting for absorption of γ -rays in the energy range covered by the MAGIC spectrum (upper x -axis, in the quasar rest frame). Clearly, besides the emission lines, the continuum (deriving from recombinations, scattering, both Thomson and Reyleigh, and free-free emission) provides an important contribution especially at low

² See also <http://www.nublado.org>

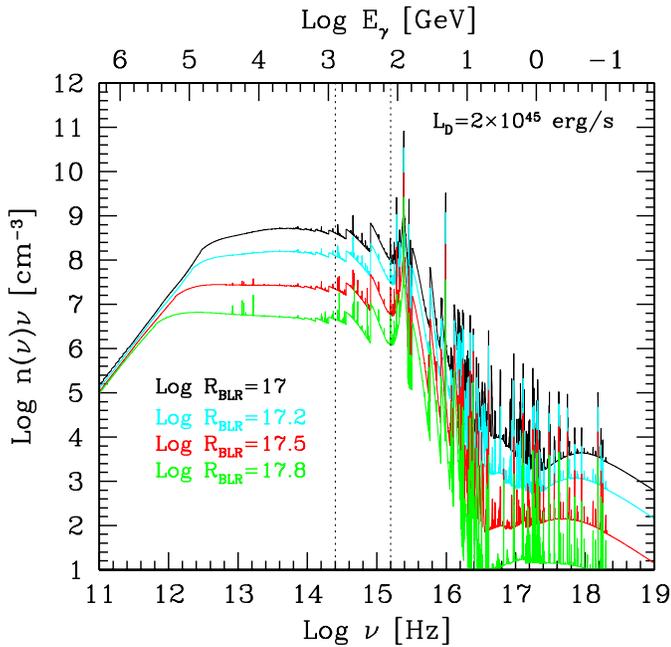


Figure 2. Number density of BLR photons for $L_D = 2 \times 10^{45}$ erg/s, $T_D = 1.5 \times 10^5$ K, $\alpha_{UV} = 0.5$ and BLR radii of 1, 1.6, 3.2 and 6.3×10^{17} cm. Note the important component in the optical-UV band. The upper x -axis reports the energy of γ -rays mainly absorbed by soft photons of the corresponding frequency. The two dotted vertical lines show the frequency range (in the quasar rest frame) interesting for absorption of γ -rays in the interval of energies covered by the MAGIC spectrum reported by Albert et al. (2008).

frequencies, below the Ly α line. The $n(\nu)\nu$ curves are almost flat below the UV band, implying an almost constant, or slightly increasing, optical depth in a rather broad interval of energies.

Fig.3 illustrates some examples of the optical depth, $\tau(E)$ (upper panel) and the corresponding absorbed spectra, assuming an intrinsic photon spectrum $F(E) \propto E^{-1.5}$ (lower panel). Different line styles and colours refer to different parameters. Short dashed, long dashed, dotted and solid lines are for R_{BLR} , 1, 1.6, 3.2 and 6.3×10^{17} cm, respectively. Black lines refer to the “standard” (S) scenario, with $\alpha_{UV} = 0.5$ (Elvis et al. 1994) and $T_D = 1.5 \times 10^5$ K. Red lines (“extreme” case, E) are calculated for a somewhat extreme value of the UV slope, $\alpha_{UV} = -1/3$ (slope expected from a standard thin disk), while green lines report the results for a “low temperature” case (L), $T_D = 5 \times 10^4$ K (and $\alpha_{UV} = 0.5$).

A common feature of these curves is the sudden increase of $\tau(E)$ starting around $E \simeq 20 - 30$ GeV, energy at the threshold for photons of the Ly α line. After reaching the maximum around 100 GeV, $\tau(E)$ displays a decreasing branch, just centered on the energy range covered by the MAGIC spectrum (vertical lines). Without the contribution of the continuum at frequencies below the Ly α line, the optical depth would fast decrease, determining a very hard observed spectrum above 100 GeV (rest frame), as in the model of Aharonian et al. (2008). However, the important contribution of the continuum produces a bump extending above the TeV band, hampering an important hardening of the out-coming γ -ray spectrum (Fig.3, lower panel).

Some general characteristics of the optical depth in the “line-

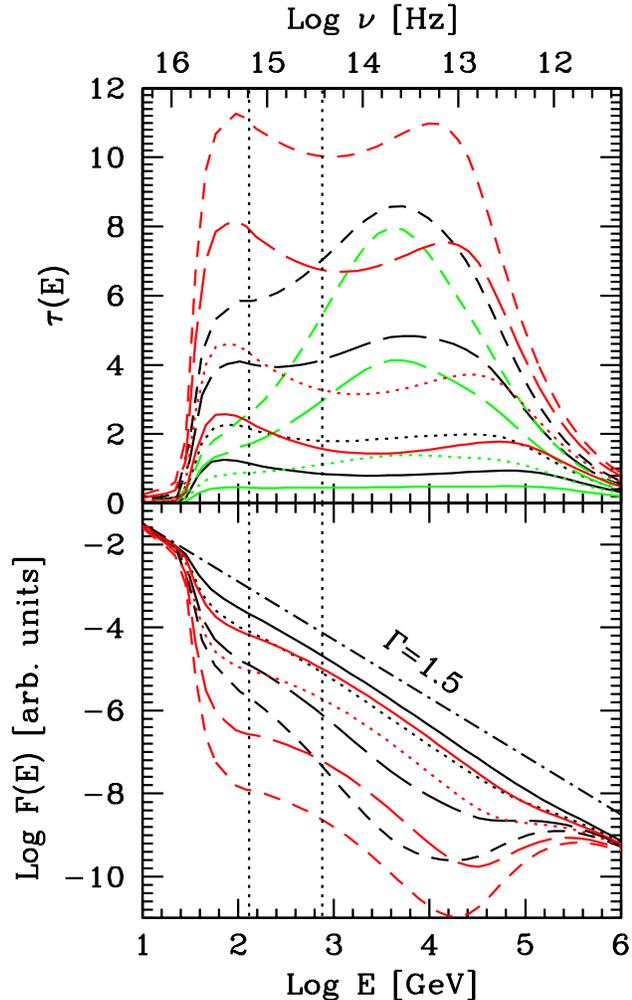


Figure 3. Upper panel: optical depth for absorption of γ -rays for different parameters. Short dashed, long dashed, dotted and solid lines: $R_{BLR} = 1, 1.6, 3.2$ and 6.3×10^{17} cm, respectively. Black lines (case S): $\alpha_{UV} = 0.5$ and $T_D = 1.5 \times 10^5$ K. Red lines (case E): $\alpha_{UV} = -1/3$. Green lines (case L): $T_D = 5 \times 10^4$ K. The two vertical lines indicate the energy range of the observed spectrum of 3C279 (quasar rest frame). The upper x -axis shows the frequency of the target photons mainly interacting with γ -rays of the energy indicated in the lower x -axis. Lower panel: modification of the intrinsic photon spectrum (assumed to be a power-law with slope $\Gamma = 1.5$, black dashed-dotted line) by absorption. For simplicity we do not report the curves of the L case, always leading to a softening of the spectrum in the MAGIC band. Lines styles and colours as above.

dominated” (below 100 GeV) and the “continuum dominated” (above 100 GeV) regions are clearly evident in these curves. The “line-dominated” bump is strongly depressed in the L case. This is due to the small fraction of photons above the Ly α energy, with the subsequent depression of the luminosity of the Ly α line. In this case the optical depth is always increasing with energy in the interesting energy range. Another trend is visible by comparing the curves corresponding to the S and the E case: in the latter the “line-dominated” component is systematically more prominent than in the S case. The reason is that, for the same luminosity, the hard illuminating continuum in the E case has a larger fraction of photons above the Ly α energy than the S case. A third trend visible in Fig.3,

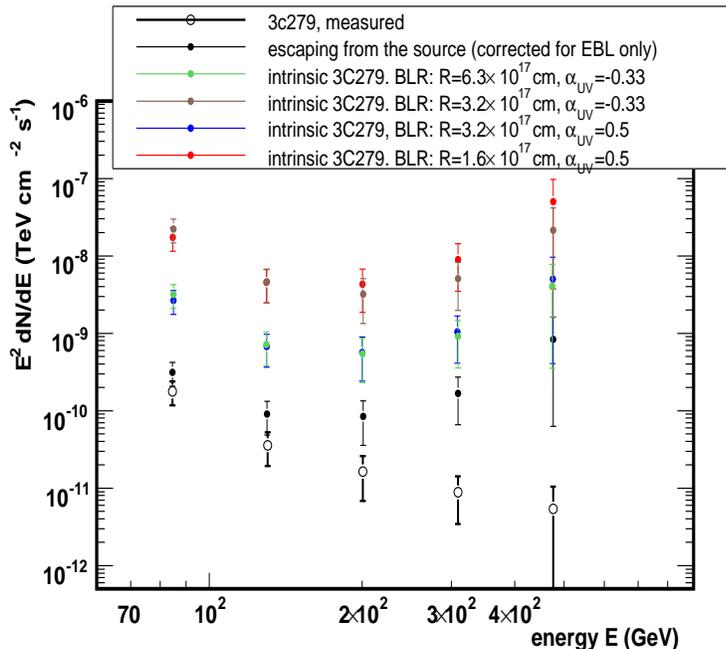


Figure 4. Energy spectrum of 3C279. The measured spectrum (open circles), EBL-corrected (filled black circles) and four different scenarios for the internal absorption (in addition to the external absorption) are shown.

especially for the L and the S curves, is the increasing role of the “continuum dominated” region when R_{BLR} decreases. The reason of this effect is the increasing number of free electrons available for scattering due to the increasing ionization for small radii. For the E case the importance of this effects is reduced, because of the paucity of the small optical-IR flux of the illuminator.

As we have already stressed, the hardening of the spectrum is realized for decreasing values of the optical depth with energy. The key parameter determining the slope of the optical depth (and thus the slope of the modified γ -ray spectrum) at energies above ~ 100 GeV is the ratio between the optical depth in the “line-dominated” bump and in the “continuum dominated” region. This is a robust consequence of the realistic models of the BLR radiation considered here. Therefore the hardest spectra will be observed in the cases of the largest value of the ratio line/continuum. As discussed above these conditions are realized for large temperatures of the disk and hard UV slopes. Case E can then be considered a conservative upper limit for the calculations.

Besides the spectral modifications, an important aspect to consider is also the level of the absorption. In general, smaller radii imply larger absorption, since $\tau \propto 1/R$. In the case of the smaller radius considered here, $R_{BLR} = 10^{17}$ cm, fluxes are depressed by more than 2 orders of magnitude for the S and the E cases, pushing the power requirements of the source to above 10^{50} erg/s. The absorption in the MAGIC band is instead limited in the case of the L case. For the largest radius, $R_{BLR} = 6.3 \times 10^{17}$ cm, the requirements are still large for the E case ($\tau \sim 2$), while for the other two cases the absorption is modest.

3 LIMITS TO THE EBL

In the following we discuss the effect of absorption on the constraints for the EBL. We use the EBL model from Kneiske et al.

(2004), modified in Albert et al. (2008) to represent an upper limit of the EBL level, which is in the same time a lower limit on the transparency of the universe to VHE γ -rays. Using this particular EBL model we examine different scenarios of the internal absorption discussed above and revisit a possibility to emit corresponding VHE spectra. From the discussion above it is clear that the modification of the spectrum in the E case should be considered a conservative upper limit to the real case. The L case is not considered since it always leads to softer spectra. Moreover we conservatively consider only the cases for which the ratio of the absorbed and the emitted flux in the MAGIC band is larger than 10^{-2} (corresponding to $\tau < 4.5$).

For the discussed scenarios of the internal absorption, we reconstructed the intrinsic spectrum of 3C279. First, we corrected the measured energy spectrum (Albert et al. 2008) for a given EBL model, corresponding to the maximum allowed level derived in that paper. In such a way we reconstruct the energy spectrum which escapes the vicinity of 3C279 towards the observer. In the next step, we corrected this spectrum for the intrinsic absorption to obtain the original (produced) energy spectrum. Results are shown in Fig.4. As discussed above, it can be seen that different scenarios for the internal absorption mainly affect the flux level of the emission but not the shape of the spectrum. Adopting the test prescription from Mazin & Raue (2007), we tested the resulting intrinsic spectra for the criterion of the hardness ($\Gamma > 1.5$) and found that in all tested cases the intrinsic spectra can be excluded. Consequently, identical or even harder EBL limits can be derived as compared to the ones obtained in Albert et al. (2008). Note that for the tests not only the fit value of the slope from a simple power law (PL) was examined but also slope values from a fit by a broken power law (BPL). The

latter one was tested in case the BPL fit gave a significantly smaller χ^2 value³ than the PL.

4 DISCUSSION

The detection of VHE γ -rays from 3C279 and EBL constraints derived in Albert et al. (2008) triggered some discussion on the role and strength of the internal absorption in this object (Liu et al. 2008, Sitarek & Bednarek 2008). In this paper, we have calculated various models for the BLR diffuse radiation and applied them for the case of 3C279. We used the code CLOUDY to calculate the models in order to have a more realistic energy spectrum of the photons inside of the BLR region. The main difference between our modeling and the work of Liu et al. (2008), Sitarek & Bednarek (2008) is the assumed BLR spectrum. In the mentioned works, the BLR spectrum consists of narrow lines. Though the radiation field of the BLR is known very poorly, we consider this an unrealistic assumption, and posit that the spectrum also includes a strong continuum component, extending on the optical-UV band (TG08). Our results confirm that radiation from the BLR modifies the primary emission of 3C279. However, we find that the internal absorption inside the BLR does not have a dramatic impact on the main conclusion concerning EBL; it does imply, however, that the intrinsic TeV emission from 3C279 could be substantially more powerful than published.

We note that the 3C279 spectrum, corrected for the EBL and internal absorption, was submitted to fits more complicated than just a simple power law for the total energy range observed. We found that for the tested BLR models, despite a possible overall softening of the 3C279 spectrum, at least part of the spectrum was significantly above an implied maximum hardness of $\Gamma = 1.5$. Our results, therefore, confirm the EBL constraints derived in Albert et al. (2008).

Note also that conclusions from Sitarek & Bednarek (2008) that an EBL model of Stecker et al. (2006) does not imply an unrealistic intrinsic spectra of 3C279 (when taking into account internal absorption in the BLR) are not accurate. The conclusions are drawn only for the “baseline” EBL model of Stecker et al. (2006). The EBL limits in this paper and in Albert et al. (2008) instead concern the “fast evolution” model of Stecker et al. (2006), implying a significantly higher EBL level in the redshift range between $z = 0$ and $z = 1$.

We finally note that the discussion on the role of absorption implicitly assumes that the highly variable high-energy γ -ray emission detected from 3C279 is produced internally to the BLR (probably through the comptonization of the BLR photons). However, given the small size of the BLR in 3C279 as estimated from the empirical relations connecting it to the disk luminosity, it is conceivable that the emission is produced outside the BLR, thus avoiding the problems connected to absorption. In this case, the mechanism responsible for the production of the observed emission cannot be the external Compton: alternatives include synchrotron self-Compton emission (Lindfors et al. 2006) or comptonization of the IR radiation from the putative dusty torus surrounding the central regions (e.g. Sikora et al. 2002, 2008; Sokolov & Marscher 2005).

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³ criterion was defined using the likelihood ratio test, for details see Mazin & Raue (2007)