

# ON WEAK REDSHIFT DEPENDENCE OF GAMMA-RAY SPECTRA OF DISTANT BLAZARS

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## ABSTRACT

Line-of-sight interactions of cosmic rays provide a natural explanation of the hard gamma-ray spectra of distant blazars, which are believed to be capable of producing both gamma rays and cosmic rays. For sources with redshifts  $z \gtrsim 0.1$ , secondary gamma rays produced in cosmic-ray interactions with background photons close to an observer can dominate over primary gamma rays originating at the source. The transition from one component to another is accompanied by a change in the spectral index depending on the source redshift. We present theoretical predictions and show that they agree with the data from *Fermi* Large Area Telescope. This agreement, combined with the spectral data from Atmospheric Cherenkov Telescopes, provides evidence of cosmic-ray acceleration by active galactic nuclei and opens new opportunities for studying photon backgrounds and intergalactic magnetic fields.

**Key words:** BL Lacertae objects; general – galaxies: active – gamma rays: general

*Online-only material:* color figures

## 1. INTRODUCTION

Active galactic nuclei (AGNs) are powerful sources of gamma rays, and they are widely believed to produce cosmic rays. It was recently proposed that the hardness of gamma-ray spectra of distant blazars can be naturally explained by the line-of-sight interactions of cosmic rays accelerated in the blazar jets (Essey & Kusenko 2010; Essey et al. 2010, 2011a, 2011b). While primary gamma rays emitted by the blazar are attenuated in their interactions with extragalactic background light (EBL; Salamon & Stecker 1998), cosmic rays with energies  $10^{16}$ – $10^{19}$  eV can cross cosmological distances and can produce secondary gamma rays in their interactions with the background photons. The predicted spectra of these secondary gamma rays are very robust and are not sensitive to the uncertainties in the level of EBL or the spectrum of protons at the source, except for the cosmic-ray luminosity. The predictions are in excellent agreement with the data (Essey & Kusenko 2010; Essey et al. 2010, 2011b; Murase et al. 2012). In the absence of cosmic-ray contribution, some unusually hard intrinsic spectra (Stecker et al. 2007; Lefa et al. 2011; Dermer & Lott 2012) or hypothetical new particles (de Angelis et al. 2007) have been invoked to explain the data.

The success of this picture lends support to the hypothesis of cosmic-ray acceleration in AGNs. Identifying the origin of ultrahigh-energy cosmic rays (UHECR) is difficult because the deflections of protons and ions in the galactic magnetic fields weaken the correlations of UHECR arrival directions with the positions of their sources (The Pierre Auger Collaboration 2007, 2008). Furthermore, a contribution of transient galactic sources of high-energy nuclei can further complicate identification of extragalactic sources (Calvez et al. 2010). In contrast, a definitive confirmation of the line-of-sight interactions (Essey & Kusenko 2010; Essey et al. 2010, 2011b; Murase et al. 2012) would make possible gamma-ray astronomical observations of cosmic rays while they are still well outside the reach of strong galactic magnetic fields. One can use the existing gamma-ray data to set lower limits on the power of cosmic-ray acceleration in blazars (Razzaque et al. 2012).

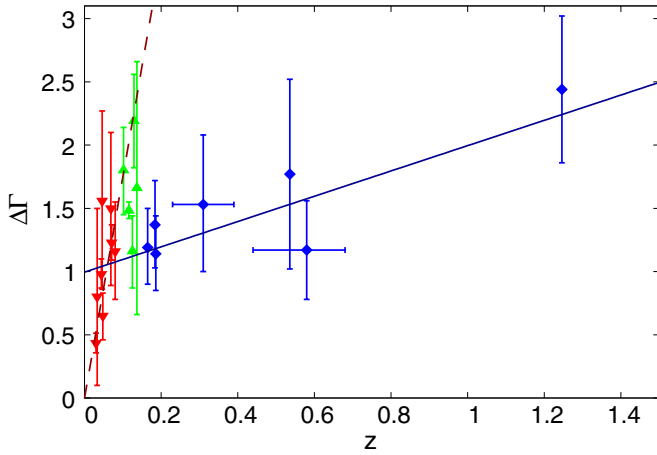
At small distances, primary gamma rays dominate the observed signals of blazars, and it is only at redshifts  $z \gtrsim 0.15$  that the cosmic-ray-induced contribution comes to dominate because the primary gamma rays are attenuated by their interactions with EBL. The existence of two independent components implies a change in the spectral index and the existence of some intermediate range of redshifts in which one or the other component can be seen, depending on the individual properties of blazars. We will identify the spectral properties of both components, and we will use the Second AGN catalog from *Fermi* Large Area Telescope (LAT; The Fermi-LAT Collaboration 2011) to test our predictions.

For primary gamma rays, Stecker & Scully (2006, 2010) have derived a simple scaling law which explained the redshift dependence of spectra of the nearby blazars. Although their original fit has some additional parameters, the spectral evolution due to absorption over distance  $d \approx z/H_0$  can be described by a simplified expression:

$$F \propto \frac{e^{-d/\lambda_\gamma}}{d^2} E^{-(\Gamma_s + D H_0 d)}. \quad (1)$$

Here  $\lambda_\gamma$  is the distance at which EBL opacity to TeV gamma rays is of the order of 1,  $\Gamma_s$  is the intrinsic spectral index of gamma rays at the source,  $H_0$  is the Hubble constant, and  $D$  is a parameter that describes spectral change due to attenuation in gamma-ray interactions with EBL (Stecker & Scully 2006, 2010). This simple law, as well as its more precise implementations (Stecker & Scully 2006, 2010), provides an excellent fit to the data at small redshifts. However, at higher redshifts, there is a significant deviation from the Stecker & Scully (2006, 2010) relation: the spectral index evolution with redshift is much slower, as shown in Figure 1.

We note that most of the low-redshift sources are high-synchrotron-peaked blazars, while the distant sources are dominated by intermediate-synchrotron-peaked (ISP) blazars and flat spectrum radio quasars (FSRQ). For ISP and FSRQ the GeV signal may be at or below the Compton peak and our analysis above does not take this spectral variation into account. However, this



**Figure 1.** Spectral change,  $\Delta\Gamma = \Gamma_{\text{TeV}} - \Gamma_{\text{GeV}}$ , for TeV detected blazars observed by *Fermi*. Data points from the *Fermi* Second catalog (The *Fermi*-LAT Collaboration 2011) were separated into three sets: nearby sources (red inverted triangles), intermediate sources (green triangles), and distant sources (blue diamonds). The lines are the best fits to Equation (10) with  $D = 17.46$  (dashed line) and  $(\Gamma_p - \Gamma_s) = 0.995$  (solid line).

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

effect would increase  $\Delta\Gamma$  because the variation implies some additional softening due to moving past the Compton peak, which is not supported by the data. TeV spectra, if they are secondary gamma rays produced along the line of sight, do not depend significantly on the gamma-ray or proton spectra of their sources (Essey & Kusenko 2010; Essey et al. 2010, 2011b; Murase et al. 2012; Razzaque et al. 2012). The dependence on the EBL model (Finke et al. 2010; Franceschini et al. 2008; Stecker et al. 2006; Gilmore et al. 2009; Orr et al. 2011) is very weak (Essey et al. 2011b). Thus, the spectral variation does not affect our conclusion that the behavior in Figure 1 is consistent with a new component taking over and dominating the signal for  $z \gtrsim 0.15$ . For the same reason, our best-fit line in Figure 1 does not depend on the choice of the EBL model.

Line-of-sight interactions of cosmic rays can account for the hard spectra of distant blazars because, in this case, the observed multi-TeV gamma rays are produced in interactions of cosmic rays with the background photons relatively close to Earth (Essey & Kusenko 2010; Essey et al. 2010, 2011b; Murase et al. 2012). For this reason, the distance to the source is much less important than in the case of primary sources. One, therefore, expects the spectra of secondary gamma rays to exhibit a slower change with redshift.

## 2. SOFTENING OF A TWO-COMPONENT SPECTRUM

We would like to generalize the Stecker & Scully (2006, 2010) scaling law to include the additional component at high redshift. The fluxes of primary gamma rays produced at the source and of secondary gamma rays produced in line-of-sight interactions of protons scale with distance  $d$  as follows (Essey et al. 2011b):

$$F_{\text{primary}, \gamma}(d) \propto \frac{1}{d^2} e^{-d/\lambda_\gamma} \quad (2)$$

$$F_{\text{secondary}, \gamma}(d) \propto \frac{\lambda_\gamma}{d^2} (1 - e^{-d/\lambda_\gamma}) \quad (3)$$

$$\sim \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases} \quad (4)$$

Obviously, for a sufficiently distant source, secondary gamma rays must dominate because they do not suffer from exponential suppression as in Equation (2). The predicted spectrum of  $\gamma$ -rays turns out to be similar for all the distant AGNs. Essey & Kusenko (2010) and Essey et al. (2010, 2011b) have calculated the spectra for redshifts of 3C279, 1ES 1101-232, 3C66A, 1ES0229+200, and several other blazars, all of which yield a remarkably good (one-parameter) fit to the data (Essey & Kusenko 2010; Essey et al. 2010, 2011b).

Based on our numerical results using a Monte Carlo propagation code described by Essey & Kusenko (2010) and Essey et al. (2010, 2011b), we find that the spectra have a weak redshift dependence and, in the TeV energy range, for  $0.2 \lesssim z \lesssim 0.6$ , it can be approximated by the following simple relation:

$$\Gamma_{\text{TeV}} \simeq \Gamma_p + \alpha z, \quad (5)$$

where  $\Gamma_p$  is a constant and  $\alpha \approx 1$ .

Let us now consider a flux of TeV gamma rays which is the sum of two components that have the above-mentioned scaling with distance:

$$F_{\text{TeV}} = F_1 \frac{1}{d^2} \exp(-d/\lambda_\gamma) E^{-(\Gamma_s + D H_0 d)} + F_2 \frac{1}{d^2} (1 - e^{-d/\lambda_\gamma}) E^{-(\Gamma_p + \alpha H_0 d)} \quad (6)$$

$$= \frac{1}{d^2} \left[ e^{-d/\lambda_\gamma} (F_1 E^{-(\Gamma_s + D H_0 d)} - F_2 E^{-(\Gamma_p + \alpha H_0 d)}) + F_2 E^{-(\Gamma_p + \alpha H_0 d)} \right]. \quad (7)$$

While the overall  $1/d^2$  factor does not affect the spectral index, the exponential suppression of the first term in squared brackets in Equation (7) guarantees a sharp change from the Stecker & Scully (2006, 2010) scaling law to a flatter scaling law which shows only a weak redshift dependence. The change occurs when the distance  $d$  is of the order of  $\lambda_\gamma$ , i.e., at a distance from the source where EBL optical depth approaches 1. Based on our numerical calculations, and in agreement with Stecker & Scully (2006), the corresponding redshift is  $z \approx H_0 d \approx 0.1$ . Taking into account that  $F_1 \gg F_2$ , one can write an approximate scaling law as

$$z^2 F_{\text{TeV}} \propto e^{-z/0.1} F_1 E^{-(\Gamma_s + D z)} + F_2 E^{-(\Gamma_p + \alpha z)}. \quad (8)$$

At lower energies, in the GeV energy range, the flux is expected to show very little attenuation for  $z \lesssim 0.5$  and to follow the simple relation

$$z^2 F_{\text{GeV}} \propto \tilde{F}_1 E^{-\Gamma_s}. \quad (9)$$

Thus, we expect that  $\Delta\Gamma = \Gamma_{\text{TeV}} - \Gamma_{\text{GeV}}$  should exhibit the following behavior:

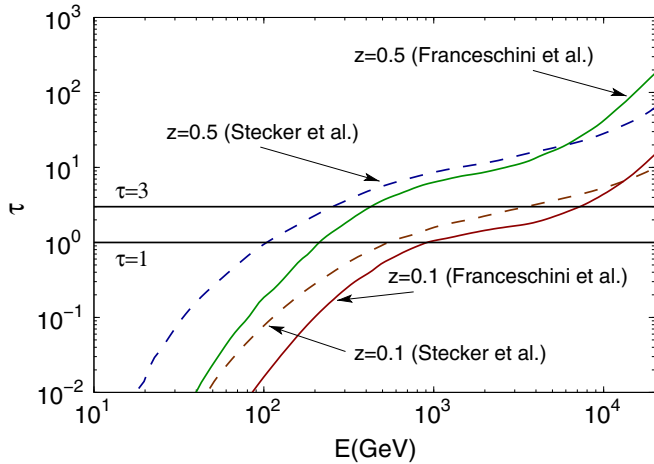
$$\Delta\Gamma \simeq \begin{cases} D z & \text{for } z \lesssim 0.1, \\ (\Gamma_p - \Gamma_s) + \alpha z, & \text{for } z \gtrsim 0.1. \end{cases} \quad (10)$$

For practical reasons, it is easier and more instructive to compare the spectral slopes given by Equation (10) with the data rather than to fit the fluxes in Equation (9).

To select distant sources that are likely to be powerful sources of cosmic rays (see Table 1), we applied two selection criteria: we selected gamma-ray emitters which (1) have been

**Table 1**  
Distant Sources and their Redshifts (with References)

Source Name	Redshift
H2356–309	0.165 (Falomo 1991)
IES 1218+304	0.184 (Bade et al. 1998)
IES 1101–232	0.186 (Remillard et al. 1989)
S5 0716+714	$0.31 \pm 0.08$ (Nilsson et al. 2008)
3C279	0.536 (Hewitt & Burbidge 1993)
3C66A	0.58 (0.44–0.68) (Lanzetta et al. 1993; Yang & Wang 2010; Aleksić et al. 2011a)
PKS 0447–439	1.246 (Landt 2012)



**Figure 2.** Optical depth  $\tau$  for the Franceschini et al. (2008) and Stecker et al. (2006) models of EBL, for two redshifts. The horizontal lines represent  $\tau = 1$  and  $\tau = 3$ , between which the transition from primary component to secondary component takes place.

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

observed at energies where the optical depth for pair production  $\tau$  greatly exceeds one, and which (2) showed no short-scale time variability at these relevant energies. We emphasize that these sources can show variability at lower energies, where the energy-dependent optical depth  $\tau(E) \lesssim 1$ . Time variability has been reported for integrated flux at  $E > 200$  GeV for 3C 66A (Abdo et al. 2011) and at  $E > 150$  GeV for 3C 279 (Aleksić et al. 2011b). However, for a falling spectrum, the flux of gamma rays with  $E > 200$  GeV ( $E > 150$  GeV) is dominated by the photons with energies  $E \approx 200$  GeV ( $E \approx 150$  GeV). There is no evidence of variability at higher energies, at which gamma rays detected from these two blazars are consistent with secondary gamma rays. For a detailed discussion of time variability in cosmic-ray-induced secondary gamma rays we refer the reader to Prosekin et al. (2012).

Although the exact point where the secondary signal dominates the primary is dependent on the ratio of cosmic-ray luminosity to gamma ray luminosity, one can estimate the transition energy by demanding that the primary signal be attenuated by at least an order of magnitude. Since the attenuation beyond this point grows exponentially, this estimate should be fairly accurate. In Figure 2, we show the optical depth ( $\tau$ ) for two models of EBL for two redshifts. The transition from primary to secondary photons is expected to occur between  $\tau = 1$  and  $\tau = 3$  lines.

In Figure 1, we show that the best fit for  $D$  and  $(\Gamma_p - \Gamma_s)$  are in good agreement with the data from the *Fermi* two-year catalog.  $D$  was fitted for sources with  $z \lesssim 0.1$ , where the primary signal is expected to dominate, and  $(\Gamma_p - \Gamma_s)$  was obtained from the

data for sources with  $z \gtrsim 0.15$ , where the secondary signal is expected to dominate. The fit at high  $z$  gives  $\chi^2 = 1.05$  with 5 degrees of freedom yielding the confidence probability of  $P = 0.96$ . The agreement with the data is evident. In particular, a recent measurement of the redshift of PKS 0447–439 (Landt 2012), which was detected by HESS at energies above TeV (Zech et al. 2011), is in agreement with the trend. We note that, for the relevant proton energies,  $E \sim 10^{17}$ – $10^{18}$  eV, the energy attenuation length of protons is much greater than the distance to a source at  $z = 1.2$  (see, e.g., Figure 9 of Bhattacharjee & Sigl 2000). Therefore, the scaling laws in Equations (2)–(4) are valid for this extremely distant source. The inferred luminosity of this source in protons is  $L_p \sim 10^{47}$  erg s $^{-1}$ , assuming a  $6^\circ$  ( $3^\circ$  radius) beam. This is comparable or below the Eddington luminosity for a billion-solar-masses black hole. Based on the analysis of Chokshi & Turner (1992), we estimate that several (between 1 and 10) supermassive black holes with masses  $> 10^9 M_\odot$  can be found in the  $z \leq 1.2$  volume with a  $6^\circ$  jet pointing at Earth. This possibility should motivate observations of other distant blazars with atmospheric Cherenkov telescopes, as they may lead to discoveries of additional TeV sources at  $z \sim 1$ .

In the intermediate region,  $0.1 \lesssim z \lesssim 0.15$ , one can detect primary signals from blazars that are brighter than average in gamma rays and accelerate fewer cosmic rays, and one can also detect secondary signals from those blazars that are more powerful cosmic-ray accelerators. Hence, in this intermediate range of redshifts, one can expect both spectral slopes to be present. This is, indeed, evident from the data plotted in Figure 1, where the blazars with  $0.1 \lesssim z \lesssim 0.15$  have a broader spread of spectral indices, and some of the blazars tend to the *primary* curve, while other blazars agree with the *secondary* scaling law.

Secondary gamma rays can contribute to point sources only if intergalactic magnetic fields (IGMFs) are in the range  $0.01$  fG  $< B < 30$  fG (Essey et al. 2011a), although these bounds can be affected by the source variability (Dermer et al. 2011; Dolag et al. 2011). The lower and the upper limits were obtained by Essey et al. (2011a) for the case of line-of-sight interactions using only the spectral data, with no reference to the source morphology. The agreement of spectral evolution with the data strengthens these inferences regarding IGMFs. In the upper part of this range, the angular resolution of *Fermi* should be good enough to resolve halos of AGN images (Aharonian et al. 1994), which can provide an independent measurement.

### 3. CONCLUSIONS

We have generalized the spectral softening relation of Stecker & Scully (2006, 2010) to include the contribution of cosmic-ray interactions along the line of sight. The predicted scaling with redshift agrees with the data, which lends further support to the hypothesis of cosmic-ray acceleration in blazars and to the inferences regarding universal backgrounds and AGN

powers made by Essey & Kusenko (2010), Essey et al. (2010, 2011a, 2011b), Murase et al. (2012), Razzaque et al. (2012), and Prosekin et al. (2012).

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