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THE MYSTERY OF SPECTRAL BREAKS: LYMAN CONTINUUM ABSORPTION BY PHOTON-PHOTON PAIR PRODUCTION IN THE *FERMI* GEV SPECTRA OF BRIGHT BLAZARS

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ABSTRACT

We reanalyze *Fermi*/LAT gamma-ray spectra of bright blazars with a higher photon statistics than in previous works and with new Pass 7 data representation. In the spectra of the brightest blazar 3C 454.3 and possibly of 4C +21.35 we detect breaks at ∼5 GeV (in the rest frame) associated with the photon-photon pair production absorption by He II Lyman continuum (LyC). We also detect confident breaks at ∼20 GeV associated with hydrogen LyC both in the individual spectra and in the stacked redshift-corrected spectrum of several bright blazars. The detected breaks in the stacked spectra univocally prove that they are associated with atomic ultraviolet emission features of the quasar broad-line region (BLR). The dominance of the absorption by hydrogen Ly complex over He II, rather small detected optical depth, and the break energy consistent with the head-on collisions with LyC photons imply that the gamma-ray emission site is located within the BLR, but most of the BLR emission comes from a flat disk-like structure producing little opacity. Alternatively, the LyC emission region size might be larger than the BLR size measured from reverberation mapping, and/or the γ-ray emitting region is extended. These solutions would resolve a long-standing issue how the multi-hundred GeV photons can escape from the emission zone without being absorbed by softer photons.

Subject headings: black hole physics – BL Lacertae objects: general – galaxies: active – galaxies: jets – gamma rays: general – quasars: emission lines

1. INTRODUCTION

The spectra of bright blazars obtained by *Fermi Gamma-ray Space Telescope* (*Fermi*) Large Area Telescope (LAT) showed clear deviations from a power-law shape (Abdo et al. 2009, 2010). There spectra could not be described by smooth functions such as exponentially cutoff power-law or a log-parabola (log-normal distribution), but were found to be better described by a broken power-law. The derived break energies lying in the 1–10 GeV energy range (Abdo et al. 2010; Poutanen & Stern 2010; Harris et al. 2012) were rather stable (Ackermann et al. 2010; Abdo et al. 2011; Stern & Poutanen 2011). Those breaks seemed puzzling: the hypothesis that the break is caused by photon-photon annihilation through $e^{\pm}$ pair production was considered and rejected by Abdo et al. (2010), who argued that "to produce a break in the 1–10 GeV, the photon field should have an energy peaking in the 0.05–0.5 keV range, which excludes the broad-line region peaking in the UV." The conclusion that such large energies of the target photons were required was based on an erroneous assumption that the break energy correspond to the maximum cross-section for pair production.

Poutanen & Stern (2010) suggested that the breaks should actually appear at the energies close to the threshold for a corresponding reaction, where the opacity has a sharp rise. The observed breaks at a few GeV correspond then well (correcting for the redshift) to the Lyman recombination continuum (LyC) and Lyα emission of ionized He. They also showed that the inner part of the BLR can provide sufficient flux of He II Lyman lines and LyC to provide enough opacity for GeV photons and to produce a spectral break. Poutanen & Stern (2010) further demonstrated that the data for a number of bright blazars are well described by a power-law spectrum modified by the absorption within the BLR. The fits with this model were acceptable and the reduction in χ^2 (compared to a simple power-law model) was very significant. Similar χ^2 could also be achieved with the broken power-law model which, however, does not have any physical basis.

A high significance of the spectral breaks partially results from a null hypothesis for the underlying spectrum, which is assumed to be a power-law. However, a typical blazar has a curved spectrum extending over many orders in energy and peaking in the MeV–GeV range. This implies that the spectrum in the *Fermi* energy band should be slightly concave and the power-law null hypothesis gives an overestimated significance of the break. As a more realistic null hypothesis one can take a lognormal distribution (log-parabola), which is the simplest way to introduce a curvature in logarithmic coordinates.

Stern & Poutanen (2011) studied in details the spectrum of the exceptionally bright flat-spectrum radio quasar (FSRQ) 3C 454.3 and indeed found that the spectrum below the absorption break significantly differs from the power-law and can be well described by a log-parabola. With this null hypothesis the statistical significance of any break is lower than with a power-law hypothesis. However, the absorption break in the time-

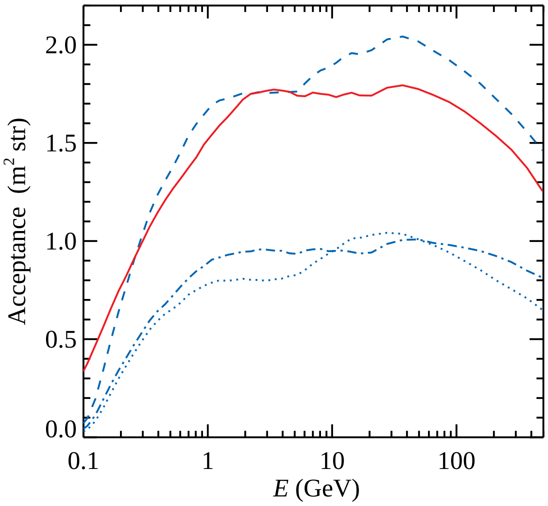

Figure 1. Acceptance (i.e. effective area integrated over the field of view) of *Fermi*/LAT. The solid red curve gives the acceptance for Pass 7 version `P7_CLEAN_V6`. The blue curves are for Pass 6 version `P6_V3_DIFFUSE`: the dashed upper curve is the total acceptance for two detectors, the dotted curve is for the front detector and the dot-dashed curve is for the back detector. The acceptance of the front detector has a hump starting at ∼3 GeV and peaking at 30 GeV, which enhances the He II absorption feature or even mimics it.

integrated spectrum of 3C 454.3 was still highly significant and its energy coincided with the predicted one from He II LyC absorption.

While the main attention of the cited papers has been payed to the GeV breaks, Poutanen & Stern (2010) and Stern & Poutanen (2011) also revealed hydrogen LyC breaks at ∼20 GeV, which were less significant and less impressive because of a lower photon statistics in that energy range. Actually, it is obvious that in most cases H Ly radiation should produce a stronger absorption feature that He II Ly emission. That is why it is important to revisit the spectral analysis of bright blazars with a higher statistics that was accumulated since previous works. Another, more important reason to revisit previous results is a slight but significant difference in the blazar spectra obtained with the new Pass 7 version of the *Fermi*/LAT data and detector response and those obtained with the older Pass 6 version. The new spectra look smoother and this is a reason to suspect that the sharp breaks at a few GeV were the artifacts of the Pass 6 response function – partially or completely.

2. DATA AND THEIR ANALYSIS

We use *Fermi*/LAT photon data for 1740 days (from 2008 August 6 till 2013 May 12) using the new Pass 7 event classification, selecting photons of clean class, and imposing the cut on the zenith angle at $\theta < 105°$. We used `P7_CLEAN_V6` response function. The diffuse background was calculated using the background model elaborated by the *Fermi* team.

It should be noted that the Pass 7 response function significantly differs from the Pass 6 one in at least two aspects:

1. it has a wider point spread function,
2. it has a different effective area function (see Fig. 1).

The second fact is of crucial importance for the analysis of the GeV energy breaks because the Pass 6 response has

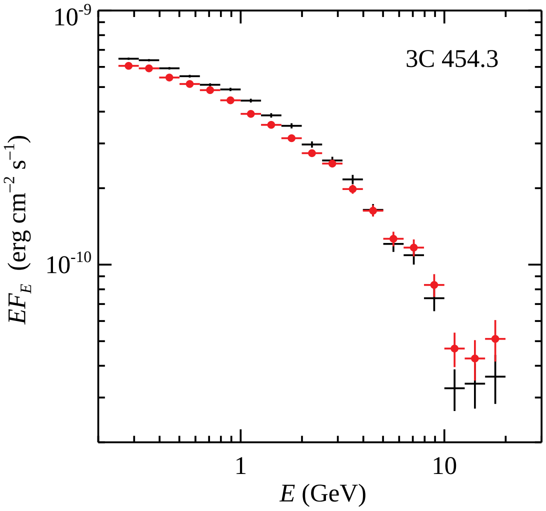

Figure 2. Central part of spectra of 3C454.3 using response functions for Pass 6 version `P6_V3_DIFFUSE` (black crosses) and Pass 7 version `P7_CLEAN_V6` (red circles and crosses).

a hump starting at 4–5 GeV, which introduces a break in the photon spectrum at energies close to the He II LyC absorption (see Fig. 2 for comparison of the spectra of 3C 454.3 obtained with Passes 6 and 7). The break is not very strong: it changes the index of the power-law by ∼0.1. If one then fits the resulting spectrum with a broken power law, one obtains a significant break. We believe that the break in the Pass 6 effective area is not real, because there is no clear reason for existence of such a feature at this energy. Moreover, it looks strange that the hump appears only in the effective area of the front detector. The Pass 7 version of the effective area does not have such a feature and looks more natural.

The energy-dependent exposure function was calculated using the spacecraft pointing history:

$$\mathrm{Exposure}(E, \Delta T) = \int_{\Delta T} S(E, \theta(t))\, dt, \qquad (1)$$

where ΔT is the time interval of interest, θ is the angle between the detector axis and the direction to the object and $S(E, \theta)$ is the detector effective area at energy E. We accumulated counts in the circle centered at the source location with the energy-dependent radius $r(E) = \min\{r_{90}, 4°\}$, where r_{90} is the radius of 90% event containment, which was calculated with Monte-Carlo integration of the point-spread function assuming the isotropic distribution of the exposure angle. Then number of counts in each energy bin was corrected to the containment factor for $r(E)$.

In order to reveal the absorption features in the blazar emission, we analyzed the spectra of individual bright FSRQs as well as the stacked spectra of various samples. We have selected a sample of 15 brightest objects from the 2nd Fermi catalog (Nolan et al. 2012) using the following criteria:

1. the total number of counts above 1 GeV after background subtraction is above 1800,
2. the signal/background ratio exceeds 2,
3. known redshift (according to the 2nd Fermi catalog),

Table 1
The brightest GeV blazars

Object	Group[a]	Redshift	Dates[b]
3C 454.3		0.859	0–1740
4C +55.17	1, 2	0.896	0–1740
PKS 0537−441	1, 2	0.892	0–1740
PKS 2326−502	1	0.518	600–1740
4C +21.35 (PKS 1222+21)	1, 2	0.433	350–1100
PKS B1424−418	1, 2	1.522	1200–1740
PKS 0426−380	1, 2	1.111	0–1740
PKS 0454−234	1, 2	1.003	0–1740
PKS 0727−11	1	1.591	0– 800
PKS 1510−08	1, 2	0.360	0–1740
3C 279	1	0.536	0–1300
PKS 1502+106	1, 2	1.893	0– 500
B2 1520+31	1	1.484	0–1400
PKS 0235+164	1	0.940	0– 400
4C +38.41	1	1.813	0–1740
	BL Lacs		
Mrk 421	3	0.030	0–1740
3C 66A	3	0.444	0–1740
S5 0716+714	3	0.310	0–1740
PKS 2155−304	3	0.117	0–1740

[a] Group memberships.
[b] The start and the end of the observation measured from MJD 54684 (2008 August 6).

4. classification as a FSRQ, or as a low-synchrotron peak BL Lac if its redshift exceeds 0.5 (which would mean that the latter is probably a misclassified FSRQ),

5. there is no strong source confusion.

The brightest blazar 3C 454.3 was excluded from the stacking analysis and studied only individually because of its exceptional brightness, which is comparable to the total signal from other selected objects. The remaining 14 FSRQs bright above 1 GeV constitute Group 1, where we hoped to reveal the absorption break at ∼5 GeV associated with He II LyC emission (Poutanen & Stern 2010).

We also selected Group 2 of eight blazars with the highest number of counts above 5 GeV (more than 200 after background subtraction). This sample was more promising to study H LyC absorption break at ∼20 GeV. All such blazars also belong to Group 1 despite the selection was independent.

To optimize the signal-to-noise ratio, we have selected for each blazar a time interval, when its flux substantially exceeded the background. Limits of these time intervals are given in Table 1. In order to prepare the stacked spectra, we first derived individual spectra using the energy bins with the width of 0.1 in decimal logarithm. The bin edges were adjusted in such a way that they are the same in the object rest frame. Each spectrum was blue-shifted by a factor $(1+z)$. We summed up the obtained spectra with their absolute normalization, so that the spectra of the brighter objects have a larger contribution. Such approach optimizes relative statistical errors. The blazar spectra were modeled with a lognormal function with the superimposed absorption by the BLR emission (see Sect. 3). We use the opacity computed for different ionization parameters ξ of the BLR as described in Poutanen & Stern (2010). We also checked a simpler monochromatic absorber model (H and He II LyC), which is less realistic but helps to estimate separate contributions of H and He emission.

We have also constructed two comparison spectra, where breaks are not expected, to make sure that the detection of the breaks is not an artifact of the detector response. The first one is the stacked redshift-corrected spectrum of four bright BL Lacs (Group 3 in Table 1). The second one is the "empty" sky spectrum. The sky was sliced into 72 000 bins of equal area (1.74×10^{-4} str) and the photons were collected from the bins where number of photons above 100 MeV is less that 300, these bins constitute about 0.226 fraction of the sky. The main contribution to this spectrum is from the high-energy protons producing pions and a smaller contribution of unresolved BL Lacs.

Statistical errors were treated as Gaussian, except in a few bins at higher energies, where the number of photons is low, we use Poisson likelihood adding $-2\ln P(n,\mu)$ to χ^2 (here n is the number of counts in the bin and μ is the prediction of the model). The number of such bins is small and the meaning of χ^2 is not significantly affected. For the minimization we use the standard code MINUIT from the CERN library.

3. GAMMA-RAY OPACITY

Gamma-ray photons emitted presumably by the relativistic jet emanating from the black hole are strongly beamed. They propagate through the radiation field made by the accretion disk, the BLR and the dusty torus are potentially can be absorbed by photon-photon pair production. The disk radiation moves nearly parallel to the photon beam and therefore does not interact efficiently. The infrared photons from the dust absorb radiation mostly in the TeV range. Thus, the most important source of opacity is the optical/UV (nearly) isotropic radiation from the BLR.

The opacity depends on the BLR spectrum, which is computed using spectral synthesis code XSTAR (version 2.2, Kallman & Bautista 2001) as described by Poutanen & Stern (2010). We repeat here the basic assumption for completeness. The ionizing spectrum of a quasar is taken as a sum of the standard multi-color accretion disk plus a power law of total luminosity 10% extending to 100 keV (Laor et al. 1997). The BLR clouds are assumed to be simple slabs of constant gas density and a clear view to the ionizing source. The hydrogen column density was fixed at $N_{\rm H} = 10^{23}$ cm^{-2} and the BLR spectra were computed for different ionization parameters $\xi = L/(r^2 n_{\rm H})$ varying from $10^{0.5}$ to $10^{2.5}$. If one assumes a dependence of the cloud density on distance from the black hole $n_{\rm H} = 10^{10} r_{18}^{-1}$, then $\xi = 10\ L_{47} r_{18}^{-1}$ and our ionization range would correspond to the distance interval between 1 and 0.01 pc to the ionizing source for a quasar luminosity $L = 10^{47}$ erg s^{-1}.[1] The scaling and the estimated distances are very approximate and are model-dependent.

If the BLR were to emit only one line at energy E_0, the optical depth for a γ-ray photon of energy E through the region of size R filled with isotropic soft photon field of column density $N_{\rm ph}$ would be $\tau_{\gamma\gamma}(E,E_0) = \sigma_{\gamma\gamma}(s)\ \tau_{\rm T}/\sigma_{\rm T} = N_{\rm ph}\sigma_{\gamma\gamma}(s)$, where

$$\tau_{\rm T} = N_{\rm ph}\sigma_{\rm T} = \frac{L_{\rm line}\sigma_{\rm T}}{4\pi R c E_0} = 110 \frac{L_{\rm line,45}}{R_{18}} \frac{10\ {\rm eV}}{E_0}, \qquad (2)$$

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[1] We defined $Q = 10^x Q_x$ in cgs units.

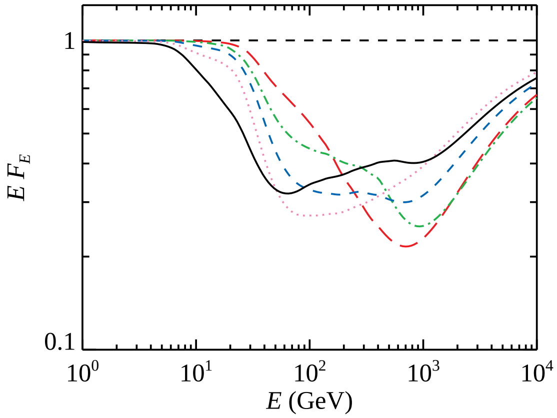

Figure 3. Examples of the photon spectrum transmitted through the BLR of various ionizations and optical depths. The incident spectrum (dashed black line) is taken as a power-law of photon index $\Gamma = 2$. The total photon column density corresponds to $\tau_{\rm T} = 10$ in all cases. Transmission function $\exp(-\tau_{\gamma\gamma}(E))$ for different $\log\xi$ is shown by different lines: 0.5 (red long-dashed), 1.0 (green dot-dashed), 1.5 (blue short-dashed), 2.0 (pink dotted), 2.5 (black solid).

$\sigma_{\rm T}$ is the Thomson cross-section, $L_{\rm line}$ is the line luminosity, $s = EE_0/(m_{\rm e}c^2)^2$ and $\sigma_{\gamma\gamma}$ is the angle-averaged cross-section for photon-photon pair production (see, e.g. Gould & Schréder 1967; Zdziarski 1988). Note, that $\sigma_{\gamma\gamma}$ has threshold $s = 1$ (i.e. at $E_{\rm thr} = 19.2\ {\rm GeV}/(E_0/13.6\ {\rm eV})$) and has a peak of about $\sigma_{\rm T}/5$ at $E \approx 3.5\ E_{\rm thr}$.

The BLR spectrum, of course, contains many lines and recombination continua. One can introduce the cross-section weighted with the photon distribution:

$$\overline{\sigma}_{\gamma\gamma}(E) = \frac{1}{N_{\rm ph}} \int_{s>1} \sigma_{\gamma\gamma}(s) N_{\rm ph}(E_0) {\rm d}E_0, \qquad (3)$$

where $N_{\rm ph} = \int N_{\rm ph}(E_0) dE_0$. The spectrum transmitted through the BLR is attenuated as $\propto \exp(-\tau_{\gamma\gamma}(E))$, where $\tau_{\gamma\gamma}(E) = \tau_{\rm T}\overline{\sigma}_{\gamma\gamma}(E)/\sigma_{\rm T}$, and $\tau_{\rm T}$ is computed using Equation (2) replacing $L_{\rm line}$ by $L_{\rm BLR}$ and E_0 by the mean photon energy of the BLR:

$$\overline{E} = \frac{1}{N_{\rm ph}} \int E_0 N_{\rm ph}(E_0) {\rm d}E_0. \qquad (4)$$

As an illustration we present the results of absorption of a power-law spectrum by the BLR of different ionizations in Fig. 3 fixing the total BLR photon column density at $N_{\rm ph} = 1.5 \times 10^{25}\ {\rm cm}^{-2}$, which corresponds to $\tau_{\rm T} = 10$. For the considered $\tau_{\rm T}$, the flux drops at most by a factor of 3–4.5 depending on ξ, corresponding to the maximum optical depth of about 1.1–1.5. Note that the transmitted spectrum in the range from 30 GeV to 1 TeV has nearly the same slope as the intrinsic one at larger ξ, because the opacity is nearly constant in this range. The opacity drops at energies above 1 TeV and the spectrum recovers. We see that the He II LyC breaks at 5 GeV are more pronounced at high ionizations $\log\xi > 1.5$, while the H LyC breaks are seen at any $\log\xi$. This allowed Poutanen & Stern (2010) to introduce a simpler double-absorber model for γ-ray opacity, where the BLR spectrum is replaced by the strongest emission features of H and He II LyC. For low ionization, one can even consider only a single absorber due to the H LyC.

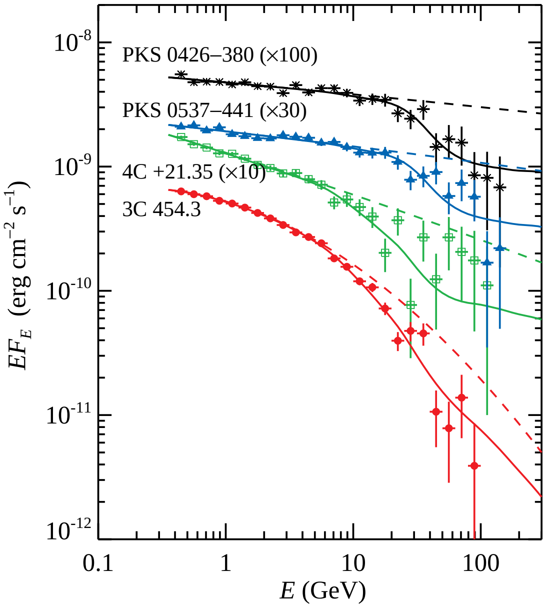

Figure 4. The redshift-corrected *Fermi*/LAT spectra of individual bright blazars and their best-fit model of the log-normal distribution with absorption by the BLR (with $\log\xi = 1.5$). The dashed lines show the same log-normal distributions without absorption.

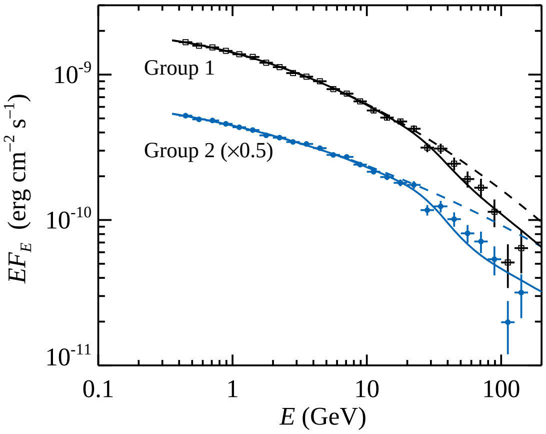

Figure 5. Same as Fig. 4, but for the stacked rest-frame spectra for the two samples of blazars from Table 1 for 1740 days of *Fermi* observations.

4. RESULTS

4.1. *Detection of GeV breaks*

The results of the spectral fits for 3C 454.3, all objects of Group 2 and for the stacked spectra are presented in Table 2 and some of them are shown in Figs. 4 and 5. The best-fit model for all objects except 3C 454.3 and 4C +21.35 is that of the BLR emission with lower ionization degree $\log\xi = 1.5$. In this ionization state, the contribution by He II absorption is small and one can see from Table 2 that the double absorber model H+He II LyC does not improve the fits with respect to the single H LyC absorber. This means that in most spectra there is no sign of He II LyC absorption. The exceptions are 3C 454.3 and 4C +21.35 (PKS 1222+21) where the presence of He II absorption is detected at $\sim 3\sigma$ level. The best-fit model for absorber in these sources is BLR emission with $\log\xi = 2.5$. In the stacked spectra of both groups, the situation is similar: the addition of

Table 2
Spectral Properties of Blazars

Object	lognorm	lognorm+H LyC[a]		lognorm+H&He II LyC[b]		lognorm+log ξ=1.5[c]		lognorm+log ξ=2.5[d]		
	χ^2/dof[e]	χ^2/dof[e]	$\tau_{\rm H}$[f]	χ^2/dof[e]	$\tau_{\rm HeII}$[g]	χ^2/dof[e]	$\tau_{\rm T}$	χ^2/dof[e]	$\tau_{\rm T}$	Significance[h]
3C 454.3	55.0/21	38.3/20	4.4±1.0	28.1/19	0.94±0.3	29.6/20	14.0±4.2	25.8/19	8.8 ±1.7	5.5σ
PKS B1424−418	23.0/23	19.0/22	2.0±1.0	19.0/19	<0.3	18.0/20	6.1±2.9	23.8/20	<4.2	…
PKS 0426−380	42.3/23	27.5/22	3.8±0.7	27.5/21	<0.4	22.9/22	9.6±1.7	36.4/22	6.3± 2.6	4.5σ
PKS 1502+106	30.5/21	22.5/20	3.2±1.2	22.5/19	<0.17	21.1/20	9.0±3.3	30.2/20	1.5±1.3	3σ
PKS 0537−441	46.0/23	34.1/22	$3.2^{+1.5}_{-1.0}$	34.1/21	<1.4	29.3/22	9.1±1.5	40.6/22	5.5±2.6	4σ
PKS 0454−234	35.7/23	28.7/22	3.7±1.5	27.5/21	<0.4	28.2/22	10.6±4.5	34.1/22	4.2±3.4	2.5σ
4C +21.35	35.7/22	33.1/21	3.3±2.3	25.5/20	$1.8^{+1.0}_{-0.5}$	33.4/21	25^{+14}_{-21}	23.8/21	11.2±2.5	3.5σ
PKS 1510−08	20.0/21	20.0/20	<0.5	20.0/19	<0.5	20.0/20	<1.4	20.0/20	<0.9	…
4C +55.17	66.0/21	57.9/20	3.1±1.2	57.0/19	<0.8	57.0/20	7.9±2.7	58.0/20	5.6±1.2	…
Group 1	44.0/23	36.8/22	1.0±0.35	36.4/21	<0.05	30.2/22	3.4±1.0	44.0/22	<1.2	3.5σ
Group 2	65.6/23	42.6/22	2.0±0.4	42.6/21	<0.1	31.6/22	6.2±1.1	52.9/22	2.9±1.2	6σ
Group 3 (BL Lacs)	35.4/22	33.7/21	0.37±0.3	33.7/20	<0.1	…	…	…	…	…

[a] The lognormal distribution with a single H LyC absorber.

[b] The lognormal distribution with a double absorber by H and He II LyC.

[c] The lognormal distribution with absorption provided by the BLR spectrum with ionization parameter $\log\xi = 1.5$ (see Sect. 3 and Poutanen & Stern 2010).

[d] Same as case c, but for $\log\xi = 2.5$.

[e] The number of degrees of freedom (dof) differs because the spectra are cut at the first bin with negative flux.

[f] Optical depth $\tau_{\rm T}$ due to H LyC only.

[g] Optical depth $\tau_{\rm T}$ due to He II LyC only.

[h] The significance of χ^2 reduction of the best-fit model with respect to the fits with lognormal function.

He II does not change χ^2 significantly.

The typical optical depth, $\tau_{\rm T}$, for the best-fit BLR emission model (mostly with $\log\xi = 1.5$) was measured to between 4 and 20. This corresponds to the maximum optical depth of about 0.4–2.2 (see blue dashed line in Fig. 3) and the flux reduction at ∼100 GeV by a factor of 1.5–9. To estimate the absorption optical depth that is contributed by H and He II emission only, one can consider corresponding optical depths from single- or double-absorber models (see Table 2, columns 4 and 6).

Spectra of the six from the nine brightest (above 5 GeV) blazars demonstrate clear absorption breaks dominated by the H LyC absorption. The significance of these breaks ranges from 2.5σ to $5.5\ \sigma$. The typical optical depth by H LyC only is $\tau_{\rm H}\ \sim$2–4, which can be converted directly to the column density of LyC (plus Lyα) photons on the line of sight to the γ-ray emitting region $N_{\rm ph,HLyC} = \tau_{\rm H}/\sigma_{\rm T} \approx (3-6)\times 10^{24}$. The stacked spectrum of Group 2 (which does not include 3C 454.3) has 6σ significance of the break. This is the most confident and the most conservative demonstration that the H LyC absorption in bright blazars is a very typical phenomenon. Previously Poutanen & Stern (2010), Stern & Poutanen (2011), and recently Tanaka et al. (2013) revealed this absorption in individual sources. However, in first and in the last papers a less conservative assumption of a power law null hypothesis was used.

As for the GeV breaks associated with He II absorption (now with a more accurate Pass 7 effective area), they get a status of a rare phenomenon. There are indications of such breaks in two objects: 3C 454.3 (3σ) and 4C +21.35 (almost 3σ), see Fig. 4.

4.2. *Significance of the breaks*

Detection of the breaks due to H LyC absorption has high significance. The amplitude of the spectral deviation from the null hypothesis is factor of 2 in the case of the stacked spectrum (Group 2) and factor of 3 in the case of PKS 0426−380. This is much above possible systematic errors like uncertainties in the response function.

The breaks due to He II LyC are much weaker than was claimed before (Ackermann et al. 2010; Abdo et al. 2011; Stern & Poutanen 2011) mostly because of the difference between Pass 6 and Pass 7 detector response functions. A sharp rise in the Pass 6 effective area (see Fig. 1) made the spectral break observed at 2–3 GeV sharper and more significant. However, we believe that the breaks observed in two objects, 3C 454.3 and 4C +21.35, are real. First, now there is no any feature in the LAT response function at the corresponding energy. Second, deviation of the spectra in the rest-frame range 5–20 GeV from the extrapolation of the lognormal function fitted to the data below 5 GeV reach at least 50% (see Fig. 4), much above the uncertainty in the LAT response. It should be noted that the 3σ significance level is quite serious in this case, because the detection of the effect does not include "hidden trials" like thresholds adjustments and sample manipulation. This significance is also very conservative as it was measured for the lognormal null hypothesis, not a power-law. For 3C 454.3, we do not expect systematical errors associated with the background subtraction or source confusion due to exceptionally high γ-ray brightness. 4C +21.35 is weaker and there could be some systematics, e.g., an underestimated soft background: the soft part of the spectrum could be lower and the spectrum could then be fitted with a narrower lognormal distribution without absorption. Therefore, the He II absorption break in 4C +21.35 needs further studies.

In order to prove the presence of the GeV breaks in FSRQ, we checked whether the breaks appear also in the comparison spectra (see Fig. 6), where they are not expected. We see that the stacked BL Lac spectrum (Group 3) is well described by a power-law (with some deviations because of imperfectness of the response function) without any breaks (except possibly at 100 GeV). The upper limits on the opacity due to H or He LyC are significantly below the detected opacity in the bright blazars (see Table 2). The "empty" sky spectrum also

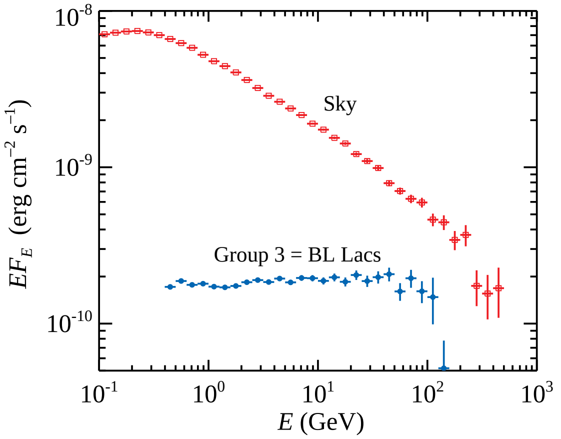

Figure 6. Spectral energy distribution of the "empty" sky is shown by red open squares. The stacked spectrum of four brightest BL Lacs (Group 3: Mrk 421, 3C 66A, S5 0716+714 and PKS 2155−304) is shown by blue circles. Neither of the spectra show any signs of absorption by H or He LyC in the range 2–20 GeV.

does not show any signs of the breaks in the 2–20 GeV range. Thus, inaccuracies in the detector response are unlikely to affect our conclusions.

We also made a simple test whether a different null hypothesis for the underlying spectrum would remove the necessity of the breaks. Instead of the log-normal function, we assumed, following the referee's suggestion, a biquadratic function $EF(E) \propto \exp[-A\ln^2(E/E_{\rm peak}) - B\ln^4(E/E_{\rm peak})]$, which has the same number of free parameters as our log-normal distribution with BLR absorption. This ad hoc function gives a slightly better fit with $\chi^2/{\rm dof} = 20/19$ for 3C 454.3, but a much worse fit with $\chi^2/{\rm dof} = 41/22$ for the Group 2 spectrum (see Table 2). Interestingly, a fit for 3C 454.3 gives $A \approx 0$, so that the spectral curvature is fully determined by the quartic term; what is the physical meaning of such a model is a mystery to us.

5. DISCUSSION AND SUMMARY

Our main results can be formulated as follows.

- We find that the 20 GeV breaks due to H LyC are ubiquitous. They are statistically significant in the majority of the bright blazars as well as in the stacked redshift-corrected spectra.
- The 5 GeV breaks due to He II LyC remain significant only in two objects.
- A more complicated function describing the underlying spectrum can change the significance of the break existence. An ad hoc biquadratic function of $\ln E$ gives a slightly better fit that the physically justified lognormal function with the BLR absorption for 3C 454.3, but a much worse fit for the stacked blazar spectrum. Thus this model does not eliminate the need for the break.
- Breaks are not seen in the stacked redshift-corrected BL Lac spectrum or the spectrum of the "empty" sky.
- The presence of the breaks associated with absorption by UV photons implies that at least some fraction of the γ-rays are produced within the BLR.

The presence of He II LyC absorption in 3C 454.3 is not surprising. This object is exceptional in all its components: the γ-ray emission from the jet reaches luminosities in excess of 2×10^{50} erg s^{-1} (Abdo et al. 2011), the accretion disk emits $L_{\rm d} \sim 10^{47}$ erg s^{-1} (Bonnoli et al. 2011), the BLR 3×10^{45} erg s^{-1} (Pian et al. 2005), and luminosity in Lyα only is $L_{{\rm Ly}\alpha} \sim 10^{45}$ erg s^{-1} (Wills et al. 1995). Here we can expect that the ionization degree is high and the photon-photon optical depth is substantial.

The second object that shows He II LyC absorption is 4C +21.35. That case is important because this FSRQ has been detected during a flare in the 70–400 GeV range by MAGIC (Aleksić et al. 2011) and the coexistence of the absorption break and VHE emission is difficult to understand in a single emission zone scenario, because the multi-hundred GeV photons would have trouble escaping from the BLR. The γ-ray luminosity of 4C +21.35 is smaller than in 3C 454.3, 10^{48} erg s^{-1} during flares (Tanaka et al. 2011), but the accretion disk is almost as luminous with $L_{\rm d} \approx 5\times10^{46}$ erg s^{-1} (Tavecchio et al. 2011). On the other hand, the BLR luminosity is significantly smaller 5×10^{44} erg s^{-1} (Wang et al. 2004; Fan et al. 2006; Tanaka et al. 2011) with Lyα producing $\sim 10^{44}$ erg s^{-1}, i.e. ten times less than in 3C 454.3. A much lower BLR luminosity implies that the opacity for 100 GeV photons is smaller, because BLR size scales roughly as $R_{\rm BLR} \approx 10^{18} L_{\rm d,47}^{1/2}$ cm (Kaspi et al. 2007; Bentz et al. 2009) and the opacity as $\tau_{\rm T} \propto L_{\rm line}/L_{\rm d}^{1/2}$ (see Equation (2) and Poutanen & Stern 2010). Thus in 4C +21.35, the optical depth through the BLR is expected to be 5–7 times smaller than in 3C 454.3. This might be the reason why VHE emission is detected in 4C +21.35, but not in a much stronger source 3C 454.3.

For a given object having both the measurement of the line luminosity and the estimation of the BLR size, we can obtain an expected value for the opacity $\tau_{\rm T}$ using Equation (2), i.e. assuming that the BLR emission is isotropic and γ-rays have to penetrate through the whole BLR. For 3C 454.3 with $L_{\rm d,47} \sim 1$ and $L_{{\rm Ly}\alpha,45} \sim 1$, we get the opacity from H LyC/Lyα of $\tau_{\rm H} \sim 100$, while for 4C +21.35 we have $\tau_{\rm H} \approx 15$. We see, however, for both objects the observed value is $\tau_{\rm H}$ ∼2–5 (Table 2), much below the expectation. What are the possible solutions for this discrepancy? We can propose at least two solutions:

- The size of the H LyC/Lyα emission region is larger than that measured from reverberation mapping using C IV (Kaspi et al. 2007) and Hβ lines (Bentz et al. 2009). We note that no Lyα variability was detected in any of the quasars analyzed by Kaspi et al. (2007) supporting this picture. This would immediately reduce the expected γ-ray opacity, which scales inversely proportionally with the size.
- Alternatively, if the BLR is flat (Shields 1978; Decarli et al. 2011), i.e. elongated alone the accretion disk, the γ-ray opacity is much reduced (e.g. Lei & Wang 2014). In this case, the threshold energy, which depends on the maximum interaction angle between the BLR photons and the γ-rays, should be a factor of two larger (i.e. ∼40 GeV instead

of ∼20 GeV) contradicting the data. However, if in addition a few BLR clouds are situated along the jet axis outside the γ-ray emitting region, they would produce enough photons to collide head-on with the γ-rays to make a break at 20 GeV.

- Finally, the γ-ray emitting region can be extended and its location can change depending on the luminosity, with less GeV absorption during the strong flares (Stern & Poutanen 2011; Pacciani et al. 2014). The VHE emission does not need to be produced in exactly the same place as the GeV emission. This can explain the fact that we see both GeV breaks as well as >100 GeV emission in 4C +21.35 (but not necessarily at the same time).

How then these models compares with the results on He II absorption? Photoionization models predict that luminosity in He II LyC/Lyα is typically ∼10% of the hydrogen one (Tavecchio & Ghisellini 2008; Poutanen & Stern 2010). Thus, taking the same BLR size and geometry and using four times larger photon energy gives $\tau_{\rm He} \sim \tau_{\rm H}/40$. In that case, the He II absorption would be negligible. On the other hand, reverberation mapping shows that He II lines are produced closer to the black hole that e.g. Hβ (Peterson & Wandel 1999), implying a higher photon density *inside* the zone of complete He ionization and a larger $\tau_{\rm He}$. However, if the γ-ray emitting region is slightly outside of that region the opacity is reduced. Again in this situation the break energy should be higher, but the quality of the data do not allow us to reject a hypothesis that the He II break energy is actually two times larger than the fiducial (rest-frame) 5 GeV value. Thus we do not see an obvious contradiction between the fact that the γ-rays are produced outside (or at the edge) of He II LyC emitting region and the presence of the break.

In general, the situation with the H LyC absorption strongly dominating over He II LyC absorption seems more natural than the picture presented by Abdo et al. (2010) and Poutanen & Stern (2010), where a few GeV breaks look more prominent than those at ∼20 GeV. Now the statement of Poutanen & Stern (2010) that the jet emission takes place in the inner (higher ionization) regions of BLRs should be modified: the gamma-ray emission site lies within the normal H II BLR region. This fact does not change the main astrophysical implications of photon-photon absorption of the jet gamma-ray emission, this particularly implies that the jet is already accelerated within a parsec distance from the black hole and therefore the Blandford-Znajek mechanism (Blandford & Znajek 1977; Komissarov et al. 2007) is responsible for the jet launching and the BLR dense photon field can provide conditions for energy dissipation via photon breeding (Stern & Poutanen 2006, 2008).

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REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJ, 699, 817
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 710, 1271
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, ApJ, 733, L26
Ackermann, M., Ajello, M., Baldini, L., et al. 2010, ApJ, 721, 1383
Aleksić, J., Antonelli, L. A., Antoranz, P., et al. 2011, ApJ, 730, L8
Bentz, M. C., Walsh, J. L., Barth, A. J., et al. 2009, ApJ, 705, 199
Blandford, R. D. & Znajek, R. L. 1977, MNRAS, 179, 433
Bonnoli, G., Ghisellini, G., Foschini, L., Tavecchio, F., & Ghirlanda, G. 2011, MNRAS, 410, 368
Decarli, R., Dotti, M., & Treves, A. 2011, MNRAS, 413, 39
Fan, Z., Cao, X., & Gu, M. 2006, ApJ, 646, 8
Gould, R. J. & Schréder, G. P. 1967, Physical Review, 155, 1404
Harris, J., Daniel, M. K., & Chadwick, P. M. 2012, ApJ, 761, 2
Kallman, T. & Bautista, M. 2001, ApJS, 133, 221
Kaspi, S., Brandt, W. N., Maoz, D., et al. 2007, ApJ, 659, 997
Komissarov, S. S., Barkov, M. V., Vlahakis, N., & Königl, A. 2007, MNRAS, 380, 51
Laor, A., Fiore, F., Elvis, M., Wilkes, B. J., & McDowell, J. C. 1997, ApJ, 477, 93
Lei, M. & Wang, J. 2014, PASJ, 66, 7
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Pacciani, L., Tavecchio, F., Donnarumma, I., et al. 2014, 790, 45
Peterson, B. M. & Wandel, A. 1999, ApJ, 521, L95
Pian, E., Falomo, R., & Treves, A. 2005, MNRAS, 361, 919
Poutanen, J. & Stern, B. 2010, ApJ, 717, L118
Shields, G. A. 1978, in Proc. of the Pittsburgh Conference on BL Lac Objects, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh), 257
Stern, B. E. & Poutanen, J. 2006, MNRAS, 372, 1217
Stern, B. E. & Poutanen, J. 2008, MNRAS, 383, 1695
Stern, B. E. & Poutanen, J. 2011, MNRAS, 417, L11
Tanaka, Y. T., Cheung, C. C., Inoue, Y., et al. 2013, ApJ, 777, L18
Tanaka, Y. T., Stawarz, Ł., Thompson, D. J., et al., 2011, ApJ, 733, 19
Tavecchio, F., Becerra-Gonzalez, J., Ghisellini, G., et al. 2011, A&A, 534, A86
Tavecchio, F. & Ghisellini, G. 2008, MNRAS, 386, 945
Wang, J.-M., Luo, B., & Ho, L. C. 2004, ApJ, 615, L9
Wills, B. J., Thompson, K. L., Han, M., et al. 1995, ApJ, 447, 139
Zdziarski, A. A. 1988, ApJ, 335, 786