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Very high-energy γ-ray emission from high-redshift blazars

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ABSTRACT

Aims. We study the possible detection of and properties of very high-energy (VHE) γ-ray emission (in the energy band above 100 GeV) from high redshift sources.

Methods. We report on the detection of VHE γ-ray flux from blazars with redshifts $z > 0.5$. We use the data from the *Fermi* telescope in the energy band above 100 GeV and identify significant sources via cross-correlation of arrival directions of individual VHE γ rays with the positions of known *Fermi* sources.

Results. There are thirteen high-redshift sources detected in the VHE band by the *Fermi*/LAT telescope. The present statistics of the *Fermi* signal from these sources is too low for a sensible study of the effects of suppression of the VHE flux by pair production through interactions with extragalactic background light photons. We find that the detection of these sources with ground-based γ-ray telescopes would be challenging. However, several sources, including BL Lacs PKS 0426-380 at $z = 1.11$, KUV 00311-1938 at $z = 0.61$, B3 1307+433 at $z = 0.69$, as well as a flat-spectrum radio quasar 4C +55.17 at $z = 0.89$, should be detectable by HESS-II, MAGIC-II, and CTA. A high-statistics study of a much larger number of VHE γ-ray sources at cosmological distances would be possible with the proposed high-altitude Cherenkov telescope 5@5.

Key words. galaxies: active – BL Lacertae objects: general – quasars: general – gamma rays: galaxies

1. Introduction

Gamma-ray emission from distant blazars is suppressed by the effect of pair production through interactions of these γ rays with the low-energy photons forming the extragalactic background light (EBL; Gould & Schreder 1967; Kneiske et al. 2004; Stecker et al. 2006; Mazin & Raue 2007; Franceschini et al. 2008; Gilmore et al. 2012). This prevents observations of high-redshift sources using the technique of imaging the Cherenkov emission produced through γ-ray-induced air showers, used by the ground-based Cherenkov telescopes HESS, MAGIC, and VERITAS (Aharonian et al. 2008). Most of the very high-energy (VHE) γ-ray loud blazars detected by these telescopes are situated in the local Universe, at several hundred megaparsec distances, in the redshift range $z \sim 0{-}0.2$[1]. Only one source at redshift $z > 0.5$, 3C 279, was detected by the MAGIC telescope during a flaring episode (Albert et al. 2008). Another source at redshift 0.444, 3C 66A, was detected by VERITAS (Acciari et al. 2009). One more relatively high redshift source, PG 1553+113 (at $z > 0.4$, reported by Danforth et al. 2010) was detected by MAGIC and VERITAS (Albert et al. 2007a; Orr 2011).

Measurement of the effect of suppression of the VHE γ-ray flux from low-redshift blazars is commonly used for the estimation of the density of the EBL in the local Universe (Kneiske et al. 2004; Stecker et al. 2006; Mazin & Raue 2007; Franceschini et al. 2008; Gilmore et al. 2012). Constraints on the EBL density and spectral characteristics, extracted from the VHE blazar observations, are useful for understanding the cosmological evolution of galaxies. Observations of the suppressed VHE γ-ray emission from blazars at non-negligible redshifts can provide not only a measurement or constraint of the EBL density in the local Universe, but also new information on the cosmological evolution of the EBL, which is largely uncertain.

Observations of high-redshift sources in the VHE band would also provide valuable information on the cosmological evolution of the VHE γ-ray loud blazars and, more generally, on γ-ray emitting active galactic nuclei (AGNs), which is also highly uncertain. This information is important, in particular, for an understanding of the origin of extragalactic γ-ray background (Abdo et al. 2010a; Neronov & Semikoz 2012). Most of the VHE γ-ray emitting blazars at zero redshift belong to a high-energy peaked BL Lac (HBL) subclass of the blazar population. Negative cosmological evolution of this subclass was reported based on the observations in the visible and X-ray band (Giommi et al. 1999). Such puzzling evolution is, apparently, opposite to the general positive evolution of blazars and radio galaxies (BL Lac parent AGN population) with the cumulative power of the sources increasing as $(1+z)^k$, $k > 0$ (Hodge et al. 2009; Sadler et al. 2007; Smolcic et al. 2009). Independent verification of this hypothesis using γ-ray observations would be possible only if a significant amount of VHE emitting blazars could be detected in the redshift range $z \sim 0.5{-}1$.

Taking into account the importance of the study of the VHE γ-ray emission from distant AGN, we report here on the detection of VHE γ-ray signals from sources at redshifts $z > 0.5$ by

[1] http://tevcat.uchicago.edu

the Large Area Telescope (LAT) on board the *Fermi* satellite (Atwood et al. 2009). The effective area of LAT, about 1 m^2, is several orders of magnitude smaller than that of the ground-based γ-ray telescopes, so that LAT has detected very few photons from the brightest extragalactic VHE γ-ray sources in ~4 years of observations. However, an extremely low level of the background (including the residual cosmic ray background and Galactic/extragalactic γ-ray background) makes even signal from only a few photons in the energy band above 100 GeV significant. This fact has been used by Neronov et al. (2010, 2011) for the search of extragalactic VHE γ-ray sources via the analysis of clustering of VHE γ-rays on the sky, based on the method first proposed by Gorbunov et al. (2005). In this paper we use the correlation of arrival directions of VHE γ-rays detected by *Fermi* with the positions of high-redshift blazars to identify high-redshift sources of VHE γ-rays and to study their spectral characteristics.

2. Data selection and data analysis

For our analysis we have used *Fermi* Pass 7 data within the time window from August 4, 2008, up to September 9, 2013. We have considered two sub-classes of the ULTRACLEAN events (evclass = 4' in the photon selection routines): the event from the classes 65 311 and 32 543. Those classes have the best angular resolution in *Fermi*, corresponding to a superclean class in pass 6 data for $E > 100$ GeV.

Using the method of Gorbunov et al. (2005) we correlated the arrival directions of photons with $E > 100$ GeV with positions of the sources listed in the two-year *Fermi* catalogue (Nolan et al. 2012) with high Galactic latitude $|b| > 10°$. This analysis is similar to one done for the 1 FGL catalogue by Neronov et al. (2011), where a catalogue of 75 objects with $E > 100$ GeV was obtained. There are 1359 front and 1135 back converted photons at high Galactic latitude $|b| > 10°$ and $E > 100$ GeV in the selected data.

We have measured the PSF for the selected events via the correlation of photon arrival directions with the sky positions of known γ-ray blazars. The size of the 68% containment circle for the event classes 65 311 and 32 543 is 0.08° for front photons and 0.21° for back photons with energies above 100 GeV. In order to keep the analysis methods consistent with those used by Neronov et al. (2011), we use 0.1° and 0.2° distance bins for correlation analysis using front and back photons.

We took all high Galactic latitude *Fermi*/LAT sources with known redshifts and selected high redshift sources with $z > 0.5$. The original second *Fermi* catalogue (Nolan et al. 2012) does not contain information on the redshift of many sources. Instead, we have considered the redshifts listed in the 13th Veron catalogue of BL Lacs (Veron-Cetty & Veron 2010) and in the Rome blazar catalogue of Massaro et al. (2007). We cross-checked the information on the source redshifts with the *Fermi* AGN catalogue (Abdo et al. 2010b) and with the information given in the NED[2] and SIMBAD[3] databases. In this way, out of 423, we selected 122 *Fermi* BL Lacs with $z > 0.5$.

For the 122 selected BL Lacs we found 9 photons correlating with 8 objects within 0.1 degree, while a total background of 0.24 was expected. The probability that this signal occurred by chance was $P \sim 6 \times 10^{-12}$. The 8 sources contributing to the correlation are listed in the upper part of the Table 1. Within 0.2 degrees from the source positions, (but outside the 0.1 degree region of the sources) the expected background was 0.64 photons, while 7 photons were observed from 6 additional BL Lacs.

One of these six additional sources was KUV 00311-1938, with two associated photons. The chance coincidence probability for the two photons to arrive within 0.2 degrees from the source position was 1.7×10^{-5}, which corresponds to a 4σ detection of the source above 100 GeV. The chance coincidence probability for the remaining 5 photons to arrive within 0.2° from other BL Lacs was $P \sim 6 \times 10^{-4}$. We list these sources in the lower part of Table 1 (last five lines), but one should remember that they might, in principle, be fake detections due to the chance coincidence of the background photon arrival directions.

From the 361 flat spectrum radio quasars (FSRQ) we selected 322 objects with $z > 0.5$. Within 0.1 degree from these objects we found 5 photons from 5 different sources, while a total background of 0.7 was expected. The probability that this happened by chance was $P \sim 7\times10^{-4}$. Again, these objects were given lower priority in Table 1, similar to that for the case of BL Lacs with photons only associated within 0.2 degrees. We did not consider correlations with FRSQ objects within larger angles because of the high level of chance coincident background. The complete list of sources with redshift $z > 0.5$ which correlate with the arrival directions of the VHE γ rays in LAT is shown in Table 1.

For the spectral and timing analysis presented in Figs. 1–16, we have used the *Fermi* Science Tools[4]. We have calculated the source spectra using two complementary techniques: the likelihood analysis and the aperture photometry methods. The two methods give consistent results. The likelihood method being more reliable at low energies (0.1−10 GeV) where the LAT instrument has a relatively wide point spread function (PSF). The aperture photometry method enables to properly take into account the Poissonian statistics of the signal at low photon count rates in the 10–300 GeV range.

The following setup was used for the spectral extraction: P7CLEAN_V6 event class in combination with the zenith angle cut at 105 degrees. We adopted the energy dependance of the *Fermi*/LAT PSF suggested by Taylor et al. (2011), and the size of the photon extraction region was changed according to it. More precisely, the photons were extracted from the region two times larger than the $\theta_{\rm PSF}$, predicted by the expression from Taylor et al. (2011), while the spectral model for the analysis included all sources from the 2FGL catalogue (Nolan et al. 2012) within the circle of a $3\theta_{\rm PSF}$ radius. During the aperture photometry analysis the source counts were extracted from the circle of 1° in radius, whereas the background was collected from the ring with the outer radius of 4° around the source region. The source counts were afterwards corrected for the PSF, whose angular profile was precomputed with the *gtpsf* tool.

3. Properties of individual high-redshift sources

In this section we study in more detail the spectral and timing properties of the high-redshift VHE γ-ray sources listed in Table 1 to understand if some of the lower significance sources in Table 1 among the FSRQs and the two BL Lacs listed in the last two rows of the table could possibly be random coincidences of arrival directions of the VHE γ rays with the source positions on the sky. We also investigate the possibility for the detection of these sources using ground-based γ-ray telescopes.

[2] http://ned.ipac.caltech.edu/

[3] http://simbad.u-strasbg.fr/simbad/

[4] http://fermi.gsfc.nasa.gov/ssc/data/analysis/

Table 1. High-redshift blazars emitting in the energy band $E > 100$ GeV.

	Name	RA	Dec	Type	z	N_{30-100}	$N_{0.1}$	$N_{0.2}$	E_{max}	L/L_{Mrk421}	P
1	PKS 0139-09	25.358	–9.479	BLL	0.733	3	1	0	138	28	1.5E-03
2	PKS 0426-380	67.168	–37.939	BLL	1.111	19	2	0	134	595	1.7E-06
3	B2 0912+29	138.968	29.557	BLL	1.521(?)	9	1	0	126	680	1.9E-03
4	PMN J0953-0840	148.261	–8.672	BLL	0.590	5	1	0	120	107	1.4E-03
5	Ton 116	190.803	36.462	BLL	1.065(?)	15	1	0	114	468	2.1E-03
6	PG 1246+586	192.078	58.341	BLL	0.847(?)	20	1	0	104	289	1.6E-03
7	B3 1307+433	197.356	43.085	BLL	0.691	4	1	0	104	94	1.3E-03
8	BZB J1436+5639	219.240	56.657	BLL	0.680	5	1	0	106	48	2.5E-03
9	PKS 1424+240	216.75	23.800	BLL	0.6035	46	4	2	248	28	3.0E-13
10	4C +55.17	149.409	55.383	FSRQ	0.899	19	1	0	141	527	2.8E-03
11	PKS 1124-186	171.768	–18.955	FSRQ	1.048	6	1	0	108	336	1.5E-03
12	TXS 1720+102	260.685	10.227	FSRQ	0.732	0	1	0	187	19	2.8E-03
13	PKS 1958-179	300.238	–17.816	FSRQ	0.652	4	1	0+1	119	14	3.4E-03
14	PKS 2142-75	326.806	–75.603	FSRQ	1.138	1	1	0	135	62	2.5E-03
15	1RXS 005447.2-245532	13.695	–24.925	AGU	0.610	–	1	0	–	22	1.0E-03
16	KUV 00311-1938[1]	8.393	–19.359	BLL	0.610	14	0	2	152	121	1.7E-05
17	B3 0133+388[2]	24.135	39.100	BLL	0.750	29	0	1	108	453	1.2E-02
18	RGB J0250+172	42.658	17.203	BL	1.100(?)	4	0	1	358	179	1.1E-02
19	PKS B1130+008	173.190	0.574	BLL	0.678	1	0	1	140	24	6.4E-03
20	S4 1250+53	193.300	53.020	BLL	0.550	4	0	1	145	58	6.8E-03
21	S4 1749+70	267.137	70.098	BLL	0.770	10	0	1	110	69	1.0E-02

Notes. Columns $N_{0.1}$ and $N_{0.2}$ give the numbers of VHE photons within an angular distance of 0.1° and 0.2° from the source position. P is the chance coincidence probability for the VHE photons to be found within the 0.1° or 0.2° circles from the source. The labels "f" and "b" mark photons which are pair converted in the front and back layers of the LAT detector. Column N_{30-100} gives the number of photons associated with the source in the lower energy band 30−100 GeV. E_{max} is the maximum energy of photon associated with the source. $L/L_{Mrk\ 421}$ is the source 100−300 GeV luminosity (EBL and redshift corrected) in units of Mrk 421 (Albert et al. 2007b), computed based on the power law approximation of the source spectra, depicted in Figs. 1−16. Question marks denote the sources with uncertain redshift. [(1)] Detected by HESS (Becherini et al. 2012). [(2)] Detected by MAGIC (Mazin et al. 2012).

3.1. Firm detections

3.1.1. PKS 0139-09

The redshift of this source has been obtained through spectroscopic measurements (Stocke et al. 1997). At the same time, the SIMBAD database entry for the source gives a redshift of 1.03, based on the data from the SDSS photometric catalogue (Abazajian et al. 2009). The detection of absorption lines at redshift $z \approx 0.5$ (Healey et al. 2008; Plotkin et al. 2010; Stickel et al. 1991) for this source imposes a lower limit on its redshift, so that in any case the source belongs to the $z > 0.5$ source sample in which we are interested in this paper.

The upper panel of Fig. 1 shows the light curve of the source in the energy band above 1 GeV. From this light curve, one can see that the source behaviour is stable on the time scale of almost four years of *Fermi* exposure. The lower panel of the same figure shows the source spectrum in the 0.3−300 GeV energy range. The spectrum is accurately described by a simple power law, suppressed at high-energies through absorption on the EBL. The model spectrum shown in Fig. 1 is calculated assuming a source redshift of 0.733 and using the EBL model of Franceschini et al. (2008). The 100−200 GeV band source flux is consistent with the expectation based on the Franceschini et al. model.

Of course, the statistics of the *Fermi* signal is largely insufficient for a sensible study of the details of the shape of the spectrum in the 100 GeV band, which is determined by the effects of propagation through the EBL. Such a study would be possible only with a ground-based γ-ray telescope, which provides a much larger collection area for γ rays and, consequently, much higher source signal statistics. The lower panel of Fig. 1 shows a comparison of the measured source spectrum with the sensitivity limits of different existing and future ground-based γ-ray telescopes. Unfortunately, the model source flux is below the sensitivity limit of the HESS-II telescope, which will start operation in 2012. The estimate of the HESS-II sensitivity shown in this plot has been taken from Masbou (2010). The sensitivity curve found in Masbou (2010) is given in terms of the integral flux. Conversion of the sensitivity into the differential flux sensitivity depends on the slope of the source spectrum. Figure 1 shows three different differential sensitivity curves corresponding to three different values of the slope of the source spectrum. One can see that within the energy range covered by HESS-II, the spectrum is steep, with a slope close to $\Gamma = 4$, such that the source flux is below the HESS-II sensitivity level, and thus not expected to be detectable.

The expected performance of the next-generation ground-based γ-ray telescope CTA is not better than that of HESS-II for energies below 100 GeV. Because of this, the prospects for the source detection with CTA are also not promising. Contrary to this, however, the sensitivity of a ground-based γ-ray telescope optimized for the 10 GeV energy band, 5@5 (Aharonian et al. 2000) is sufficient for the source detection in the energy range above 10 GeV and up to the sharp EBL-induced cut-off at 100 GeV. The difference in the performance of 5@5 and CTA in the 10−100 GeV energy band turns out to be crucially important for the possibility of the study of VHE γ-ray emission from this high-redshift source.

3.1.2. PKS 0426-380

This bright BL Lac is situated at a redshift of $z = 1.11$ (Heidt et al. 2004). The source is strongly variable in the GeV energy band (see Fig. 2, upper panel). Several active episodes, during

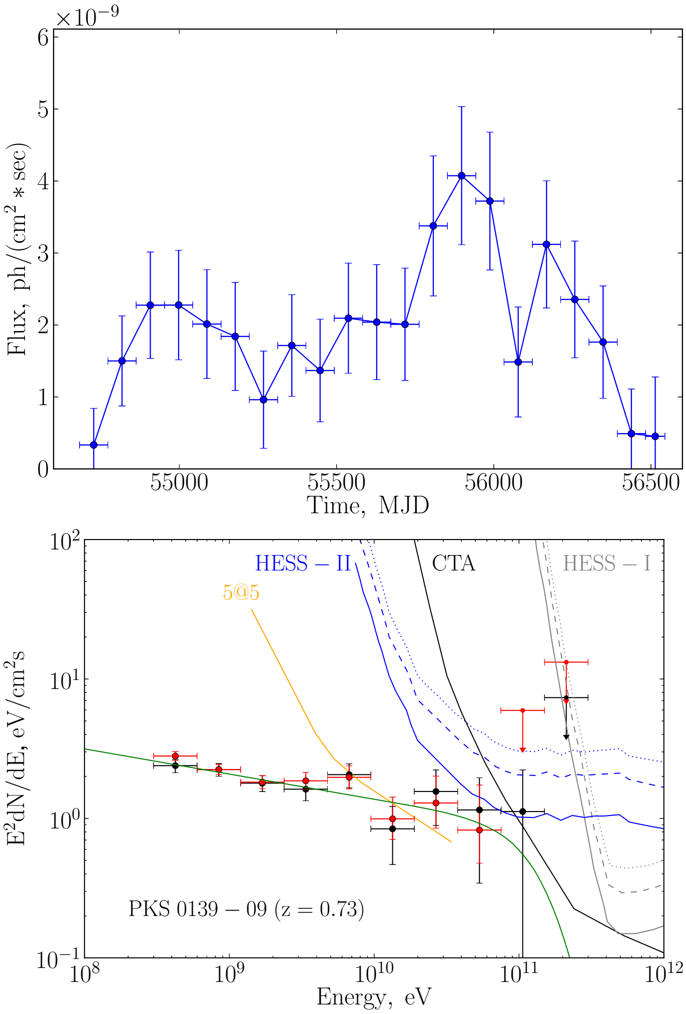

Fig. 1. Light curve (*top*) and spectrum (*bottom*) of PKS 0139-09 at redshift $z = 0.733$. Green curve in the bottom panel shows a power-law-type model spectrum absorbed on the EBL from Franceschini et al. (2008). Also shown in the bottom panel are sensitivity curves of different ground based γ-ray telescopes: 5@5 (Aharonian et al. 2000), HESS-I and HESS-II (Masbou 2010), and CTA (CTA Consortium 2011). The solid sensitivity curves for HESS-I and HESS-II correspond to spectral index of $\Gamma = 2$, dashed – to $\Gamma = 3$, and dotted – to $\Gamma = 4$. Black and red data points in the lower panel show the spectrum extracted using the likelihood analysis and aperture photometry method, respectively.

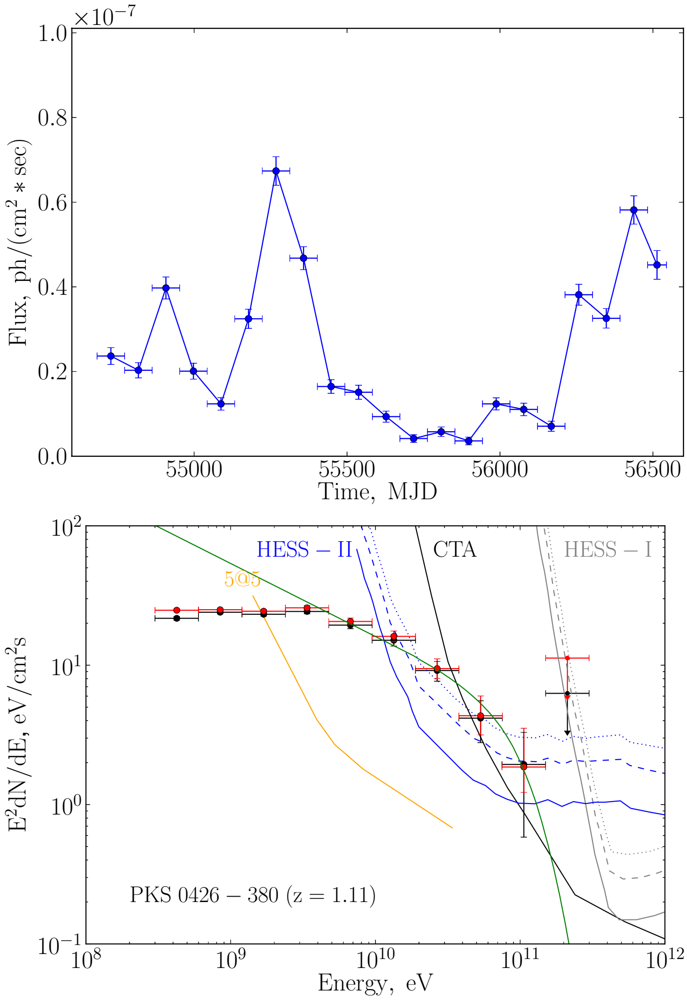

Fig. 2. Light curve (*top*) and spectrum (*bottom*) of PKS 0426-380 at the redshift $z = 1.11$. Notations are the same as in Fig. 1.

which the flux increased by up to an order of magnitude, have been observed during the four years of *Fermi's* operation.

The source spectrum averaged over the whole observation period extends as a soft power law with $\Gamma > 2$ well into the 100 GeV energy band at the level of $\sim 10^{-11}$ erg/cm^{2}s (see Fig. 2, lower panel). At this flux level, the source should be readily detectable in the 30−100 GeV energy range with the HESS-II telescope and, in the future, with CTA.

We have verified that the source flux did increase by a factor of ∼2−3 during the flaring activities without any significant change in its spectral shape. This implies that the detectability of the source from the ground should be facilitated if the next ground-based observations are triggered during the next increased activity episode (which could be traced based on the *Fermi* monitoring of the source).

3.1.3. B2 0912+29

The SIMBAD database ascribes a redshift $z = 1.521$ to the source, with a reference to the SDSS photometric survey (Abazajian et al. 2009), but stating that the redshift is spectroscopic. At the same time, the NED database does not ascribe a redshift to the source.

The source spectrum can be described by a relatively hard power law with slope $\Gamma \simeq 2$, which continues up to ∼200 GeV. The observed spectrum shown in Fig. 3 is in reasonable agreement with a power law model suppressed at high energies by absorption on the EBL.

The bottom panel of Fig. 3 shows a comparison of the sensitivity of the MAGIC telescope in stereo operation mode (Colin et al. 2009) with the level of the source flux for different assumed values of the slope of the power law spectrum Γ. One can see that the source flux is right at the limit of sensitivity of the MAGIC instrument and, among the discussed ground-based telescopes, only the 5@5 Cherenkov facility has the possibility to detect it with certainty.

3.1.4. PMN J0953-0840

This hard-spectrum BL Lac object is located at the redshift $z > 0.590$ (Shaw et al. 2013). The source flux in the ≳100 GeV band makes this source a good target for observations with existing

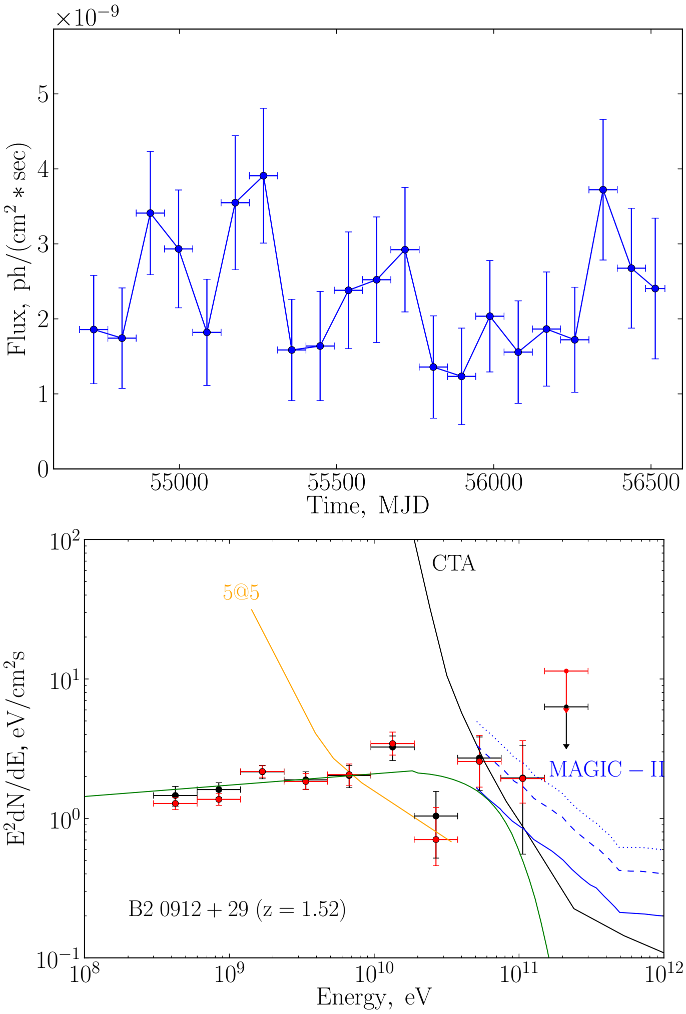

Fig. 3. Light curve (*top*) and spectrum of B2 0912+29 at the supposed redshift $z = 1.521$. Notations are the same as in Fig. 1. Blue curves show the sensitivity of the MAGIC telescope in the stereo observation mode (from Colin et al. 2009) for different source spectral indices – $\Gamma = 2$ (solid), $\Gamma = 3$ (dashed), and $\Gamma = 4$ (dotted).

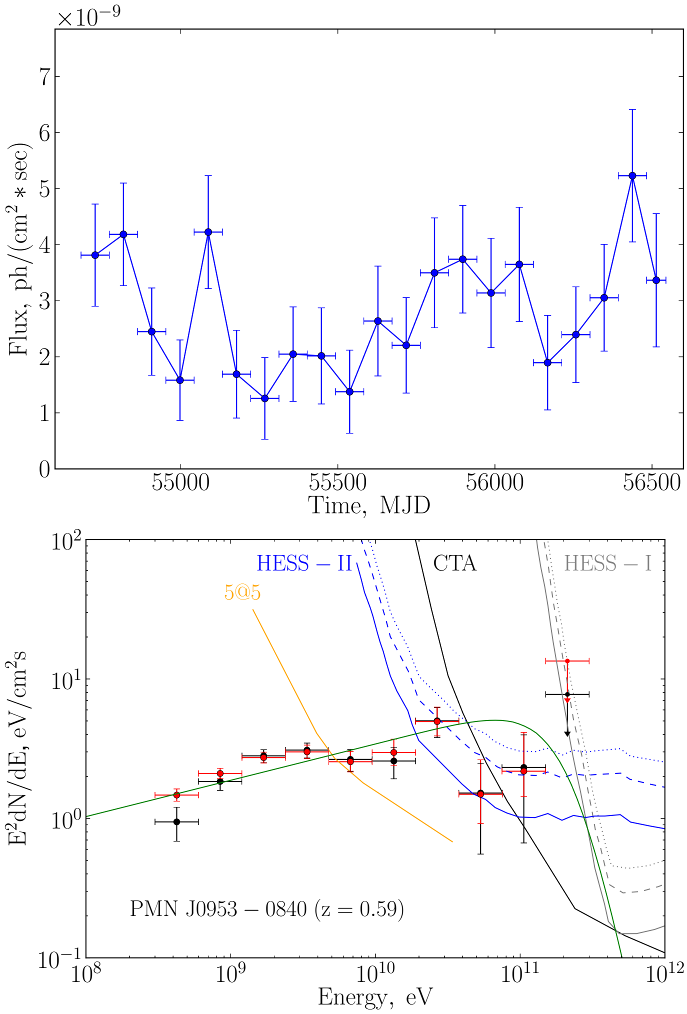

Fig. 4. Light curve (*top*) and spectrum of PMN J0953-0840 at the supposed redshift $z = 0.590$. Notations are the same as in Fig. 1.

HESS-II and future CTA telescopes. Approximation of the spectrum with a power law suggests that the source should be detectable with HESS-II right above few tens of GeVs; further lowering of the detection energy would require a specially optimized for ∼10 GeV domain instrument, such as 5@5.

The ource light curve above 1 GeV does not show any prominent flares; PMN J0953-0840 demonstrates rather stable behaviour in this energy band. This means that there is no need to wait for the flaring episodes to detect this source with the ground-based telescopes, although they would facilitate the detection.

3.1.5. Ton 116

The redshift of the source cited in the NED database is $z = 1.065$, with a reference to the SDSS measurement (Abazajian et al. 2009). At the same time, the *Fermi* AGN catalogue (Abdo et al. 2010b) list this source as having an unknown redshift. The source exhibits a hard spectrum with slope $\Gamma \simeq 1.7$ (see Fig. 5), so that in spite of the high redshift of the source, the flux in the 100 GeV energy range should be at the level detectable by MAGIC and, in the future, by CTA. The source spectrum is expected to become very steep just above 100 GeV, so that its signal in MAGIC and CTA would be dominated by the contribution from the lowest energy bin just at the threshold energy of the instrument. It is not clear what quality of measurement of the shape of the spectrum in the VHE band could be achieved for such a situation. A proper study of the shape of the spectrum and of the effect of the EBL on it could be done only with a dedicated instrument with a very low energy threshold, like 5@5. From Fig. 5 one can see that the 5@5 instrument would be able to detect the source starting from the energy of ≃10 GeV.

3.1.6. PG 1246+586

The source redshift listed in both the NED and SIMBAD databases is $z = 0.847$ with a reference to SDSS (Abazajian et al. 2009). In the *Fermi* AGN catalogue the source redshift is considered as unknown (Abdo et al. 2010b). The source exhibits a steady behaviour, remaining stable over the four years of *Fermi* monitoring (see the top panel of Fig. 6) and the source spectrum is hard with a slope slightly less than $\Gamma = 2$ up to energies above 100 GeV, where the spectrum starts to be affected by the effect of suppression on the EBL (bottom panel of Fig. 6). The sensitivity of the MAGIC telescope would be sufficient for the detection of the source, as would the sensitivity of CTA. Similar to the case of Ton 116, a proper study of the shape of the VHE γ-ray spectrum

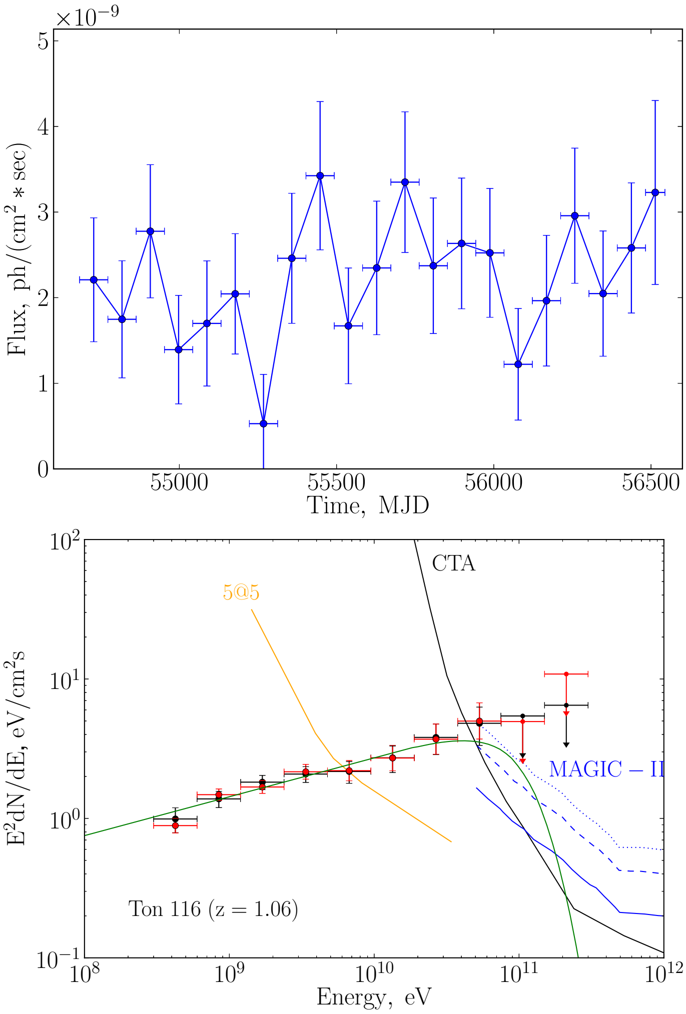

Fig. 5. Light curve (*top*) and spectrum of Ton 116 at the redshift z = 1.065. Notations are the same as in Fig. 3.

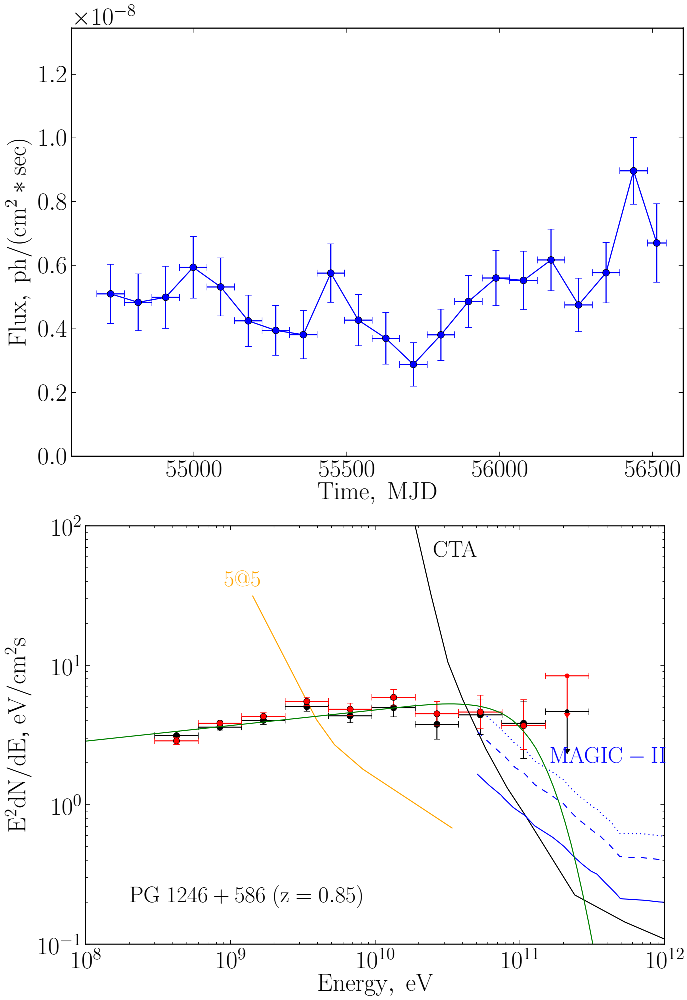

Fig. 6. Light curve (*top*) and spectrum of PG 1246+586 at the redshift z = 0.847. Notations are the same as in Fig. 3.

can be done only with a dedicated low-energy threshold instrument, like 5@5, which would be able to detect the source starting from an energy of ∼10 GeV.

3.1.7. B3 1307+433

The redshift quoted for this source in the NED database is $z = 0.69$, based on the SDSS measurement (Plotkin et al. 2008). At the same time, SIMBAD quotes a redshift of $z = 2.159$, also based on the SDSS data (Abazajian et al. 2009). The spectrum of the source, shown in Fig. 7, is a hard ($\Gamma < 2$) power law up to ∼200 GeV. If the source were at a redshift of 2.159, as mentioned by SIMBAD, the detection above 100 GeV would be in contradiction with the expected level of suppression of the source flux due to the interactions of γ rays with the EBL photons. At a redshift of 0.69, however, the *Fermi* measurement is consistent with the theoretical expectation (see Fig. 7).

Verification of the source spectral properties in the 100 GeV band, therefore, would allow clarification of the issue of the source redshift via observations with the existing ground-based telescopes (MAGIC and VERITAS). However, high-quality measurements of the shape of the spectrum would require a next generation instrument, like CTA and 5@5.

3.1.8. PKS 1424+240

The source PKS 1424+240 is a known TeV-emitting blazar and was discovered by VERITAS (Acciari et al. 2010). The redshift of the source is uncertain: through the analysis of the GeV and TeV data it was constrained to be $z < 0.66$ (Acciari et al. 2010), with an updated estimate of $z = 0.16$ (Prandini et al. 2010), quoted in the NED[5] database. However, recent far-UV observations (Furniss et al. 2013) suggest that the redshift of PKS 1424+240 is $z > 0.6$, so we have included it in our source sample.

The spectrum of the source in the GeV band clearly deviates from power law and becomes soft at energies above 10 GeV. Nevertheless, the source is sufficiently bright to be firmly detected by *Fermi*/LAT above 100 GeV. The derived spectrum smoothly matches with the measurement by MAGIC (Aleksić et al. 2014) (see Fig. 8). Due to the curved shape of the spectrum of the source, the power law fit to the *Fermi* data depicted in Fig. 8 was restricted to the highest energy data points above 5 GeV. In this way the fit accounts only for the high-energy end of the *Fermi* spectrum, providing an approximate guide for its spectrum in the VHE domain, accessible for the Cherenkov instruments. As is seen from Fig. 8, this extrapolation matches well with the MAGIC measurements in 2011 (Aleksić et al. 2014). At the same time the re-observation of the source by

[5] http://ned.ipac.caltech.edu/

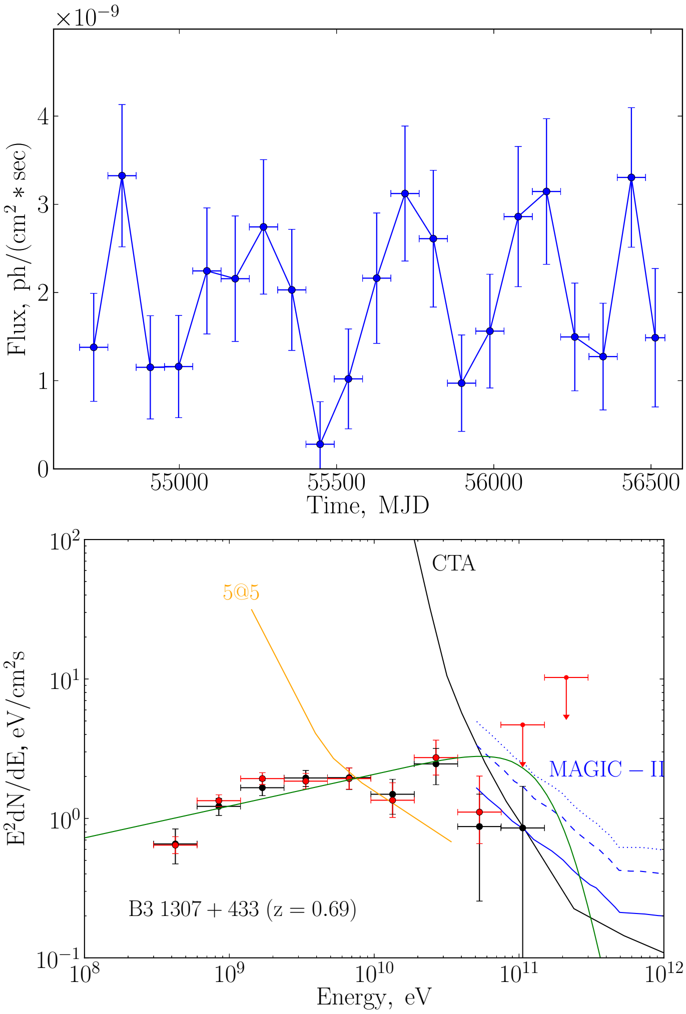

Fig. 7. Light curve (*top*) and spectrum (*bottom*) of B3 1307+433 at the redshift z = 0.69. Notations are the same as in Fig. 3.

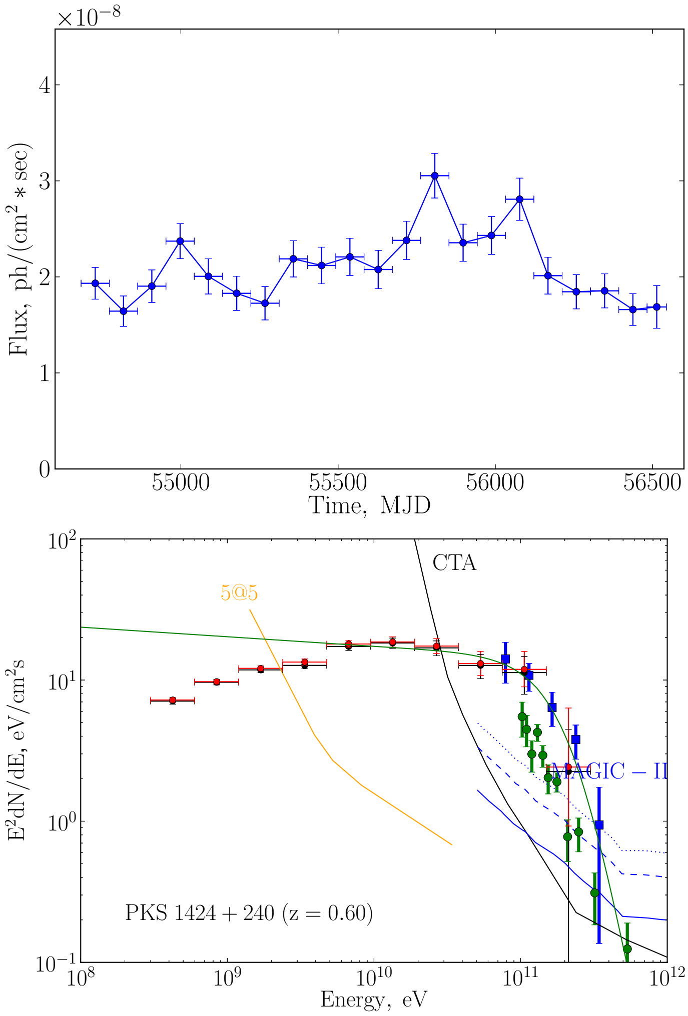

Fig. 8. Light curve (*top*) and spectrum (*bottom*) of PKS 1424+240 at the redshift z = 0.60. Blue squares show the VHE spectrum of the source as measured by MAGIC in 2011 (Aleksić et al. 2014) and green circles show it as seen by VERITAS in 2013 (Archambault et al. 2014). Other notations are the same as in Fig. 3.

VERITAS in 2013 (Archambault et al. 2014) reveals a significantly weaker flux in the VHE domain (see Fig. 8). The variability in the VHE domain, pointed out in Archambault et al. (2014), seems to be in agreement with the behaviour of the source in the *Fermi* band, seen at the upper panel of Fig. 8: a higher flux in 2011 (during the MAGIC observations) and a gradual decrease of the flux afterwards, which corresponds to the lower source flux, measured by VERITAS in 2013.

Because of its large redshift of $z > 0.6$, the direct γ-ray emission of PKS 1424+240 should be significantly attenuated in interactions with the EBL. This makes this source particularly interesting for EBL constraint projects and a variety of models have already been suggested to explain its SED (e.g. Prandini et al. 2012; Essey & Kusenko 2014).

3.1.9. BZB J1436+5639

This source is located at a redshift of $z > 0.680$ (Shaw et al. 2013). This hard-spectrum blazar is a relatively weak source (see Fig. 9), so the future and existing ground-based γ-ray telescopes should detect the rapidly decreasing part of its spectrum only at the limit of their sensitivity. Better results can be achieved if a low-energy instrument such as 5@5 were used, capable of detecting the source above several tens of GeVs.

The source light curve does not show any significant variability, so the spectrum in Fig. 9 is likely to represent the quiescent flux state. The source detection will be thus facilitated if the source is observed during a flaring period, a phenomena not unusual for BL Lac-type AGN.

3.1.10. KUV 00311-1938

As is mentioned in the previous section, this source is individually detected above 100 GeV with significance 4.5σ. The redshift of this BL Lac, previously believed to sit at a value $z = 0.61$ (Giommi et al. 2005), has been brought into doubt through the failure of further searches to verify the absorption line features. However, a lower limit on its redshift of $z = 0.51$ was obtained, indicating that this source is indeed very distant (Pita et al. 2012). Its spectrum is characterized by a hard power-law-type with $\Gamma < 2$ from 0.3 GeV up to ~200 GeV. The *Fermi* data points in the > 100 GeV band match well with the power law model, suppressed by the absorption on the EBL. The EBL effect is expected to appear mostly above 200 GeV, in the energy band readily accessible by the HESS telescope. The source flux above 100 GeV is sufficiently high for the detection with HESS-II and

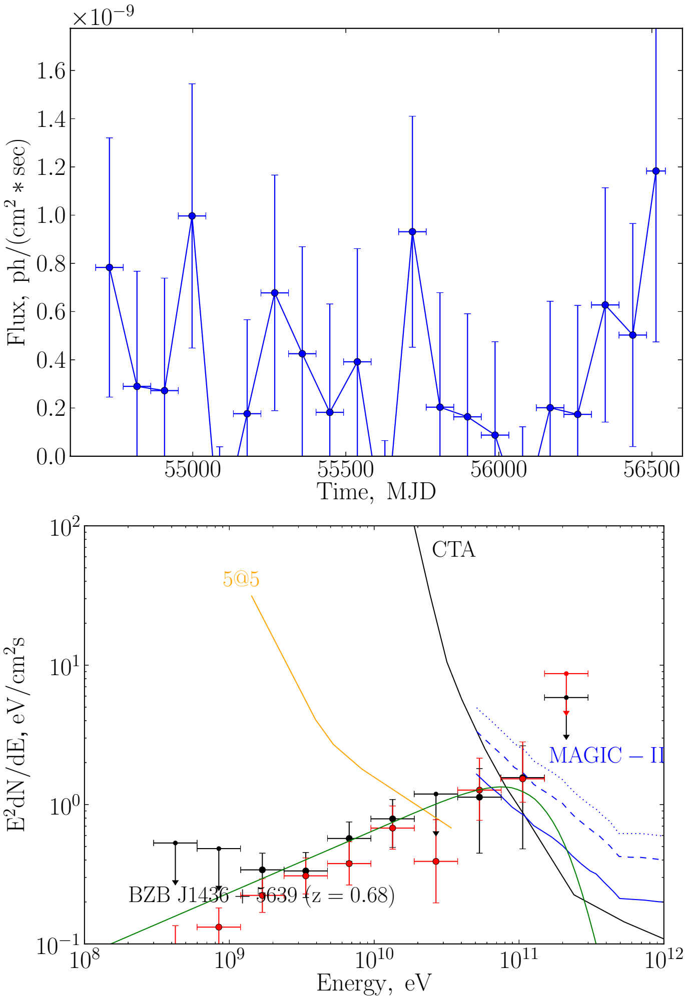

Fig. 9. Light curve (*top*) and spectrum (*bottom*) of BZB J1436+5639 at the redshift $z = 0.69$. Notations are the same as in Fig. 3.

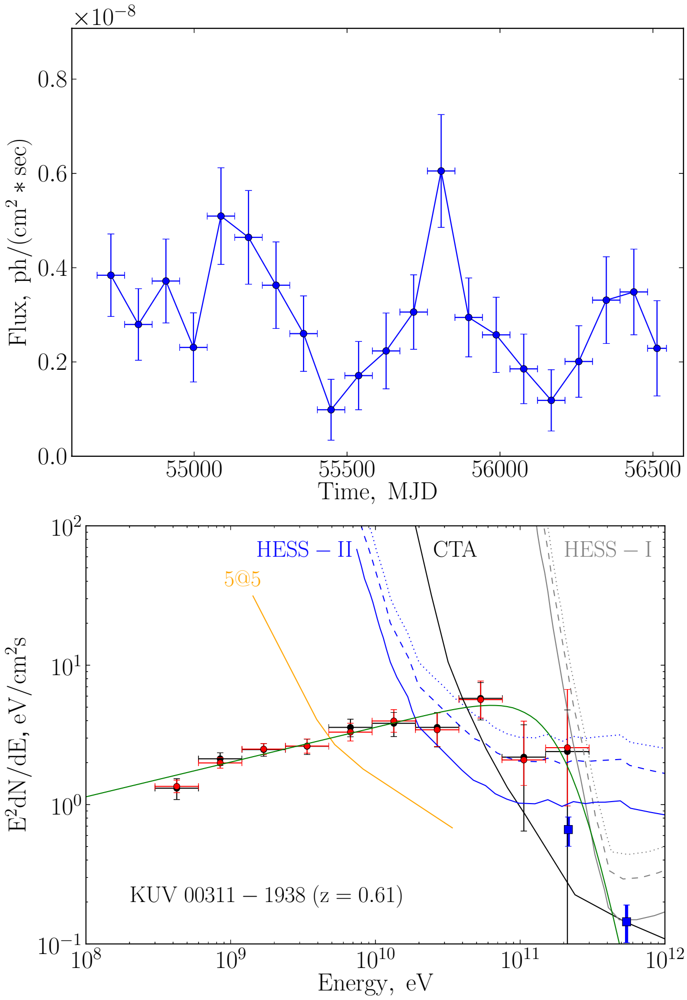

Fig. 10. Light curve (*top*) and spectrum of KUV 00311-1938 at the redshift $z = 0.61$. Blue squares show the VHE spectrum of the source as measured by HESS (Becherini et al. 2012). Other notations are the same as in Fig. 1.

HESS (see Fig. 10). Indeed, this source was recently detected by HESS (Becherini et al. 2012), in accordance with our expectation. One should keep in mind that the HESS data were taken between 2009 and 2011, so they do not exactly correspond to the *Fermi*/LAT measurements, averaged over the 2008–2013 period.

3.2. Possible detections

In this subsection we provide the details on sources for which the correlation of the arrival directions of $E > 100$ GeV photons with their source positions is less significant. We notice that some chance coincidence sources can possibly be singled out based on their spectral characteristics (the extrapolation of the low-energy spectrum to the VHE band is not consistent with the source flux level in the VHE band implied by the detection of the VHE photon). However, this criterion alone cannot be used to firmly reject the source because of the possible existence of peculiar source spectra (e.g. the presence of different emission components in different energy bands).

3.2.1. 4C +55.17

The source 4C +55.17 is from the FSRQ subclass of blazars, i.e. from the subclass which gives only a minor contribution to the set of known VHE γ-ray sources in the local Universe. The appearance of this source, along with the four other FSRQs in the $z > 0.5$ VHE source sample, is perhaps important since it may provide an indication of the higher FSRQ contribution to the VHE γ-ray source population in the cosmological past.

The source's redshift is $z = 0.8955$ (Adelman-McCarthy et al. 2008). The source spectrum is softer than $\Gamma = 2$ for GeV energies and above, as expected from FSRQs which have on average softer spectra than BL Lacs (see Fig. 11). An extrapolation of the $E < 100$ GeV band spectrum into the VHE band is consistent with the estimate of the VHE flux of the source based on the detected VHE photon. This indicates that the VHE γ-ray emission from the source is real. However, detection of the source from the ground would be a challenging task for the existing ground-based telescopes like MAGIC (see Fig. 11). Indeed, a recent attempt to detect this source with the VERITAS telescope (Furniss & McConville 2013) using data over the 2010–2013 period, has resulted only in upper limits, as demonstrated in Fig. 11. At the same time, the source should be readily detectable by the next-generation instruments CTA and 5@5 (Fig. 11).

3.2.2. PKS 1124-186

As with 4C +55.17, PKS 1124-186 also belongs to the FSRQ class, but is a more distant object, with a redshift of $z = 1.048$

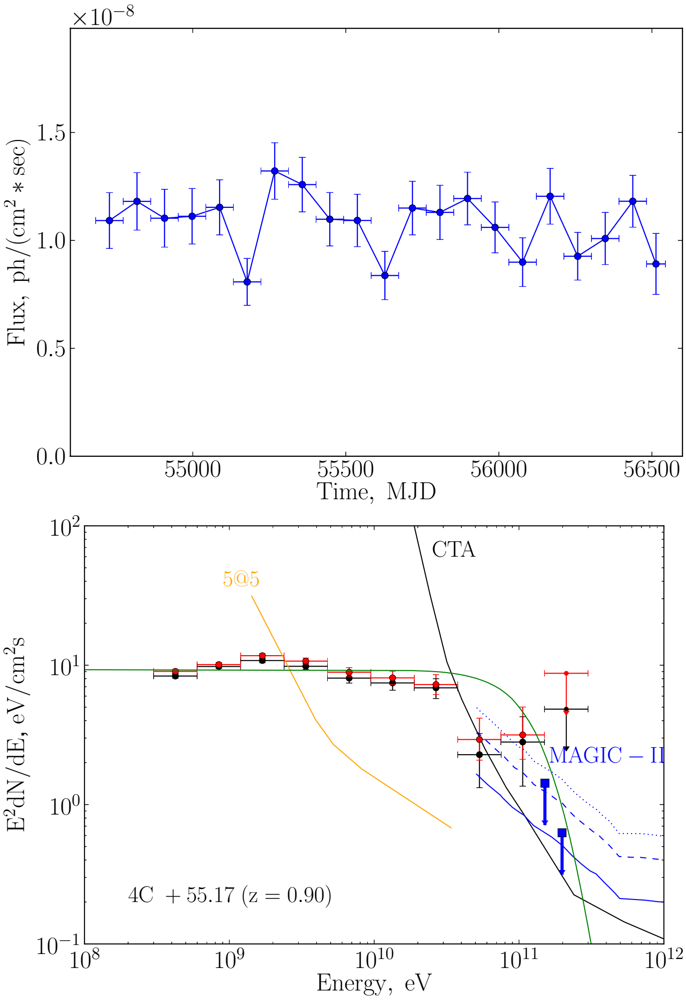

Fig. 11. Light curve (*top*) and spectrum (*bottom*) of 4C +55.17 at the redshift $z = 0.8955$. The VHE part of the spectrum, measured by VERITAS (Furniss & McConville 2013), is marked by the blue squares. Other notations are the same as in Fig. 3.

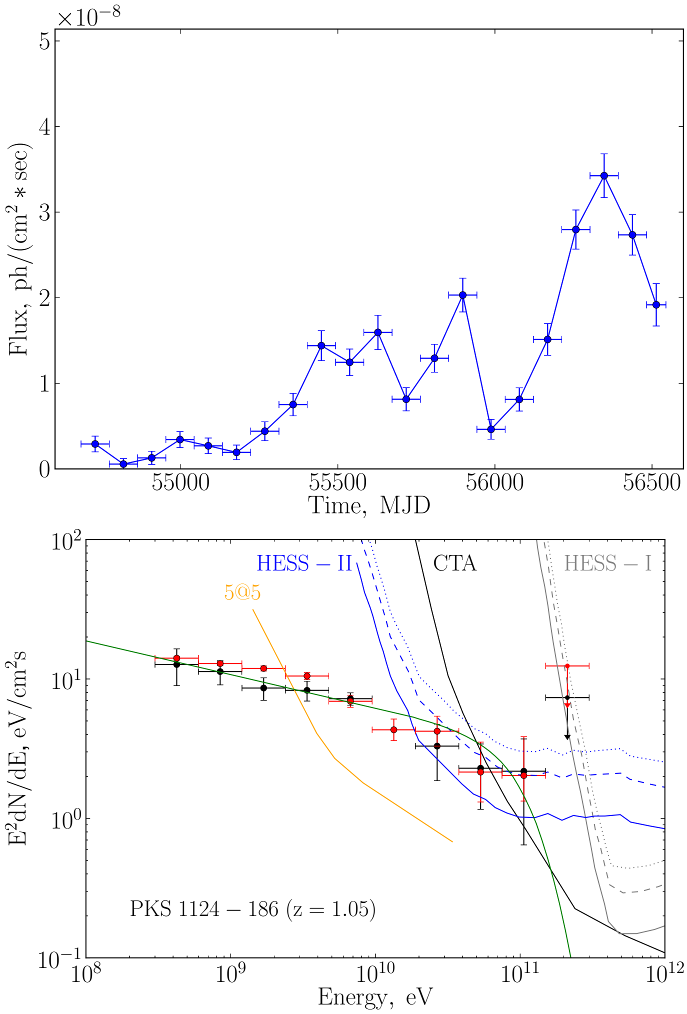

Fig. 12. Light curve (*top*) and spectrum (*bottom*) of PKS 1124-186 at redshift $z = 1.048$. Notations are the same as in Fig. 3.

(Barkhouse & Hall 2001). Being an FSRQ, this source has a peak in its spectrum situated at energies $\lesssim$100 MeV, so the ground-based Cherenkov instruments can probe only the decreasing branch of the spectrum, absorbed on the EBL (see Fig. 12). The source is close to the sensitivity limits, but should still be detectable by the HESS-II and future CTA instruments. If realized, the 5@5 telescope should be capable of detecting the source from energies $\lesssim$10 GeV, providing a much better measurement of the source spectrum.

The light curve of PKS 1124-186 shows a trend towards the increase of the flux over the period of the *Fermi*/LAT observations. This suggests that the detection of the source will be simplified in the coming years by the increase of the source flux in the $\gtrsim$100 GeV energy band.

3.2.3. TXS 1720+102

This is another representative of the FSRQ subpopulation in the high-z VHE source sample. The source is at a redshift $z = 0.732$ (Afanasiev et al. 2005). Its spectrum is softer than $\Gamma = 2$ in the energy band below 100 GeV. The overall source flux level is somewhat low compared to e.g. 4C +55.17, so that the source would be just barely detectable by MAGIC, VERITAS, and/or CTA (see Fig. 13) The $E > 100$ GeV data are consistent with the extrapolation of the lower energy power law attenuated by the EBL (see Fig. 13). As one can see, the >100 GeV did not appear at the spectrum in Fig. 13. This is a consequence of using a 1° circle for the spectral extraction with the aperture photometry method. In this case, the fact that the photon was not displaced from the source position is not taken into account and the flux is attributed to the whole extraction circle. This results in a lower signal-to-noise ratio for the source and, correspondingly, to the upper limit at the plot.

3.2.4. PKS 1958-179

The spectral characteristics of this FSRQ at a redshift of $z = 0.65$ (Barkhouse & Hall 2001) appear somewhat peculiar with a soft spectrum below an energy ~30 GeV and possibly a new hard component appearing above the 30 GeV band (see Fig. 14). The statistics of the *Fermi* data is not sufficient to draw definitive conclusions about the existence of two separate components in the spectrum. In principle, a single power law with a photon index of about $\Gamma = 2$ provides a satisfactory fit to the data above an energy of 1 GeV. Within such a spectral model, the detection of the source in the energy band above 100 GeV is consistent with the assumption that the power law extends to the VHE band, if the absorption of the VHE γ rays through interactions with the EBL photons is taken into account. The source could be

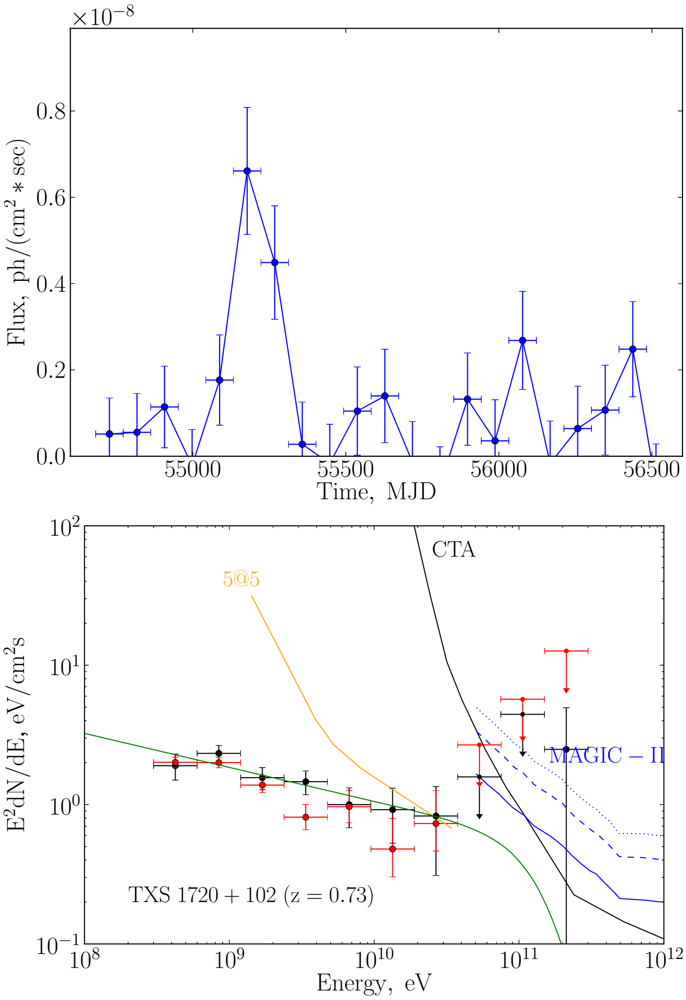

Fig. 13. Light curve (*top*) and spectrum (*bottom*) of TXS 1720+102 at the redshift $z = 0.732$. Notations are the same as in Fig. 3.

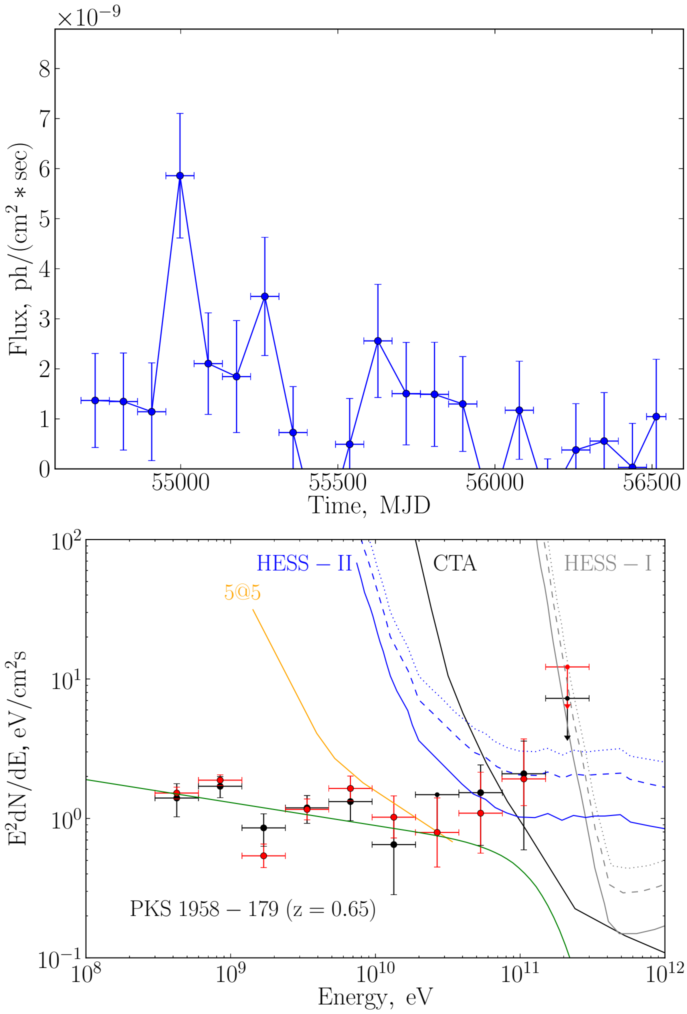

Fig. 14. Light curve (*top*) and spectrum of PKS 1958-179 at the redshift $z = 0.65$. Notations are the same as in Fig. 1.

marginally detectable by ground based γ-ray telescopes, including both existing and future facilities (see Fig. 14).

3.2.5. PKS 2142-75

This FSRQ at $z = 1.139$ (Jauncey et al. 1978) also has a soft time-averaged spectrum in the 0.3−300 GeV energy band, accurately described with a power law (see Fig. 15). During the period of *Fermi* observations, the source has exhibited several pronounced flares (Fig. 15, upper panel). Because of the soft spectrum, the source is below the expected sensitivity limits of the existing and planned ground-based Cherenkov instruments and only marginally accessible for the 5@5 facility, unless the flaring activity spotted by *Fermi*/LAT continues in the future.

3.2.6. RGB J0250+172

Contrary to the soft spectra FSRQs, RGB J0250+172 at $z = 1.1$ (Bauer et al. 2000) is characterized by a hard γ-ray spectrum and is a good candidate for being a real VHE γ-ray source. In NED it is mentioned as a BL Lac object, while in Symbad as a quasar of unknown type. In the *Fermi* Catalogue it is listed as an FSRQ. Taking into account a flat spectrum we assume it is a BL Lac object. However, due to the lower overall flux normalization, the source is only marginally detectable by *Fermi*/LAT, current and next-generation ground-based γ-ray telescopes (see Fig. 16). Unexpectedly, a photon with energy 358 GeV is detected from the source direction. This detection is somewhat puzzling. On the one hand, the estimate of the source flux in the 200−400 GeV band, based on this photon, is consistent with the power law extrapolation of the lower-energy spectrum, without taking into account the EBL-induced suppression of the source flux (see Fig. 16). On the other hand, if the EBL suppression is taken into account, the measured source flux is orders of magnitude above the expected flux from a source at redshift of 1.1. Resolution of this inconsistency might be (a) that the VHE photon from the source direction is a background photons with the chance probability 0.5%, (b) that the energy of this particular photon is overestimated by the LAT data analysis software, (c) that the redshift of the source has not been correctly measured, or (d) that the model calculation of the spectrum is wrong. The last possibility implies that the spectrum might not be formed simply by the suppression of the source flux via absorption on the EBL, but some new processes, such as development of cosmic-ray-induced cascade on the way from the source to the Earth (Essey & Kusenko 2009; Prosekin et al. 2012).

This contradiction could be easily resolved via observation of the source with existing ground-based γ-ray telescope(s) like MAGIC. If the source flux in the 200−400 GeV band is indeed at the level of $\sim 10^{-11}$ erg/(cm^{2}s), it should be readily measurable

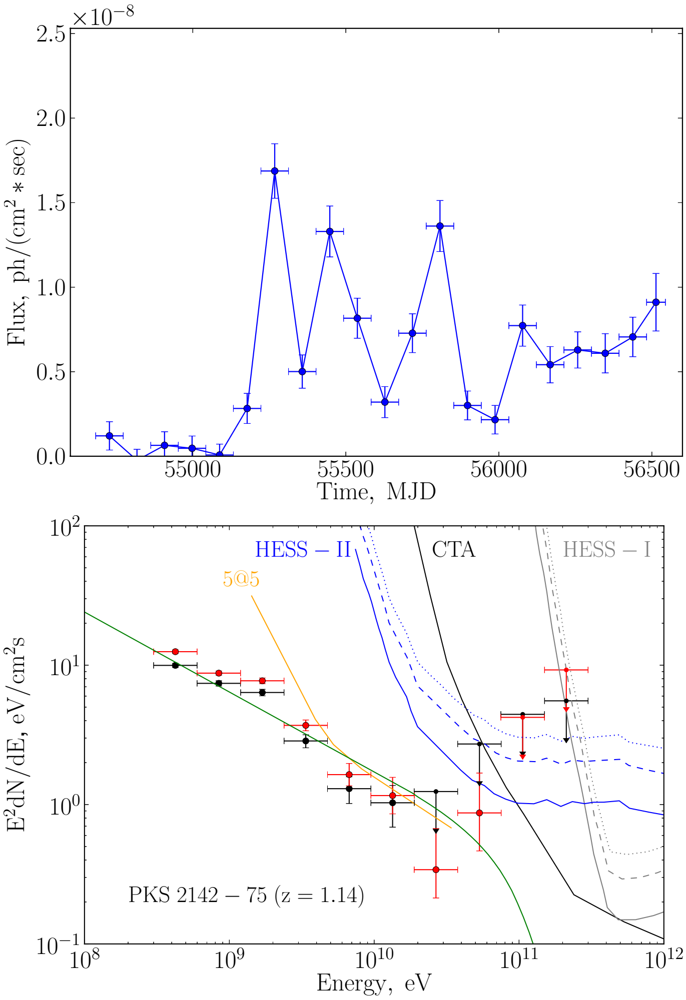

Fig. 15. Light curve (*top*) and spectrum of PKS 2142-75 at the redshift $z = 1.139$. Notations are the same as in Fig. 1.

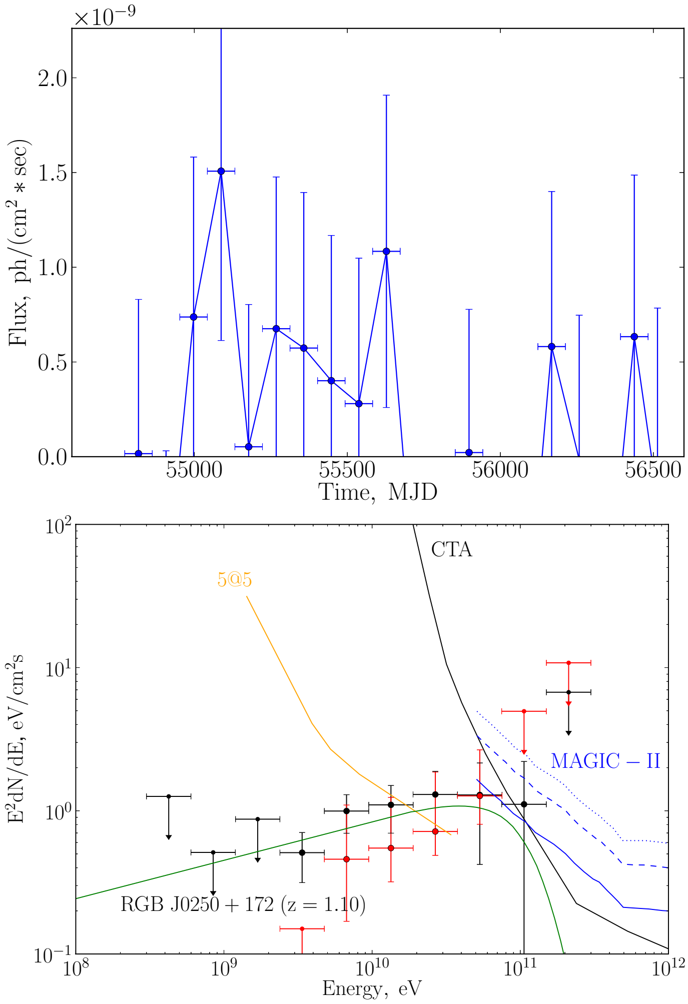

Fig. 16. Light curve (*top*) and spectrum of RGB J0250+172 at the redshift $z = 1.1$. Notations are the same as in Fig. 3.

by MAGIC. If the flux is at the level expected based on the estimate of the model calculation taking into account the EBL suppression, the source is likely not detectable either by MAGIC or by CTA. It would be, however, detectable by 5@5 thanks to the lower energy threshold of the instrument.

4. Discussion

The detection of VHE γ-ray emission at energies above 100 GeV from blazars with redshifts beyond $z = 0.5$ carries important implications for the possibility of studying the cosmological evolution of the blazar population and the overall energy output from the galaxies in the form of the EBL.

Fermi/LAT is able to discover the VHE γ-ray signal from the high-redshift sources and so does not have a capability of studying the details of the spectral characteristics of these high-redshift sources. At the same time, *Fermi's* detections of these sources provides a clear indication of the selection of the high-redshift targets for observations with existing and next-generation ground-based γ-ray telescopes.

In the previous section we compared the *Fermi* flux measurements in the $E > 100$ GeV band with the sensitivity of the ground-based γ-ray telescopes. The results from such comparisons indicate that the flux levels of sources listed in Table 1 are already at or below the sensitivity limit of the current generation ground-based telescopes and are just at the sensitivity limit of the next generation facility CTA. As can be seen from Fig. 11, for the sources like 4C +55.17 the detection of the VHE part of the spectrum is challenging, although next generation telescopes like CTA can hope to detect these objects. This means that Table 1 provides a more-or-less exhaustive list of the high-redshift sources accessible for detection using ground-based γ-ray telescopes.

The situation with the limited capabilities for the detection of high-redshift sources from the ground can, nevertheless, change if a telescope system specially optimized for the reduction of the low-energy threshold, like 5@5 would be realized. In this case most of the sources listed in Table 1 would be detectable by 5@5 already at energies of about 10 GeV, with very high signal statistics. This would allow a high-quality study of the details of the spectral characteristics of the VHE γ-ray emission from high-redshift sources. Lowering the energy threshold with 5@5 would open up the possibility for detecting a much larger number of the high-redshift sources, compared to the just twenty sources listed in Table 1.

The number of high-redshift extragalactic TeV sources that are accessible for the observations with Cherenkov telescopes can be, however, higher if some new propagation effects for VHE γ rays are in action. For example, Essey & Kusenko (2009) suggested that the observed γ-ray spectra of some blazars can be explained in terms of the electromagnetic cascades, initiated by the ultra high-energy protons emitted by them. In this model the

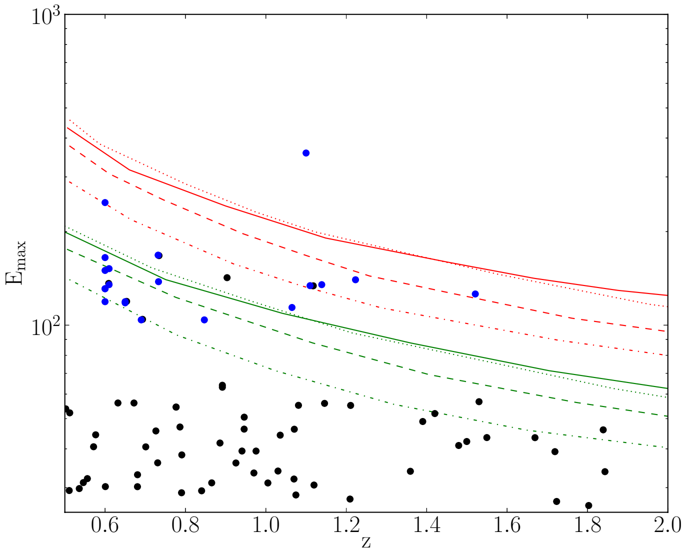

Fig. 17. Energies of VHE photons from BL Lacs and FSRQ as a function of redshift. Black dots represent the results of Abdo et al. (2010), blue dots are this work. Curves correspond to the optical depth $\tau = 1$ (green) and $\tau = 3$ (red) with respect to absorption on the EBL. Solid lines: EBL from Franceschini et al. (2008); dotted lines: EBL from Gilmore et al. (2012); dashed lines: EBL from Finke et al. (2010); dash-dotted lines: EBL from Kneiske et al. (2004).

protons transform their kinetic energy into γ rays all the way towards the observer and, thus, the γ ray absorption on the EBL may be much less significant. In this scenario, the VHE-emitting blazars can potentially be observed from redshifts as high as $z \sim 5{-}8$ (Inoue et al. 2014). Another possibility is that the new physics, such as axions (Mirizzi et al. 2007), is involved, which also allows the sources to be seen from larger distances. All this may increase the number of the observable sources.

Low statistics of the VHE γ-ray signal from the *Fermi* high-redshift blazars does not allow a study of the effect of absorption of γ rays through their interactions with EBL photons on a source-by-source basis. However, the significance of this effect for different models of cosmological evolution of EBL can be evaluated collectively for all twenty sources from Table 1, following the method discussed by Abdo et al. (2010). Figure 17 shows the energies of VHE γ-rays from distant blazars as a function of the source redshift. The data from the previous analysis at lower energies, reported by Abdo et al. (2010), are shown in black in the same figure for comparison. The green/red curves show the energies at which the optical depth with respect to pair production on the EBL is $\tau = 1$ and $\tau = 3$, respectively. This implies a flux suppression by a factor of $\simeq$3 and $\simeq$20. A simple expectation is that there should be no VHE photons from the sources in the upper part of the plot, much beyond the corresponding $\tau = 1$ or $\tau = 3$ curves. From Fig. 17 one can see that this trend of decreasing photon counts beyond the $\tau = 1$ curve holds in the redshift range $z = 0.5{-}1$, with only one photon beyond the solid green curve corresponding to $\tau = 1$ for the Franceschini et al. (2008) model of EBL evolution. At the same time, the trend seems to be broken for redshifts of about $z \gtrsim 1$, where a large number of photons beyond the $\tau = 1$ curve appears. This large number of photons beyond the $\tau = 1$ curve is definitely not due to the larger source number in this redshift range. Table 1 contains sixteen sources at $z < 1$ and six sources at $z \geq 1$. Thus, the larger statistics of photons beyond the $\tau = 1$ curve should be due to a different reason.

One possibility is that the determination of redshifts of the $z \geq 1$ sources listed in Table 1 are not reliable and, in fact, the sources are at lower redshifts. Another possibility is that at least one or two photons in the $z > 1$ part of the diagram might still be from the background and not from the high-redshift sources. This might be the case for the highest energy photon beyond $\tau = 3$ curves, which came from the direction of RGB J0250+172. This photon has a 0.5% probability of being from the background.

If none of these possible explanations holds (this needs to be checked with more data and verification of the redshift measurements), then the over-abundance of the VHE photons beyond the $\tau = 1$ curves in the redshift range $z > 1$ in Fig. 17 should be due to a physical effect. One possibility is that the EBL level at high redshifts is lower, so that the Universe is more transparent to the VHE photons than is implied by the currently existing models. Otherwise, new propagation effects, such as the origin of the γ-ray emission in the ultrahigh-energy cosmic-ray-induced cascade (Essey & Kusenko 2009; Murase et al. 2012; Prosekin et al. 2012; Essey et al. 2010, 2011; Essey & Kusenko 2012; Razzaque et al. 2012; Essey et al. 2012) or even by new physics, like axions (Mirizzi et al. 2007), should be considered.

In the scenario of Essey & Kusenko (2009), ultrahigh-energy protons with energies in the EeV range propagate cosmological distances and lose energy primarily through the proton pair production process. In this case secondary TeV γ-rays are produced by such protons at distances of 100−300 Mpc and easily reach the Earth. For this model to be valid, one needs a relatively low extra-galactic magnetic field with values 0.01−30 fG everywhere on the way of the protons, not only in the voids of the Large Scale Structure of the Universe. Apparently, a support for such a scenario is found in a recent work of Landt (2012), in which absorption lines at the redshift beyond $z = 1$ were found in the spectra of two BL Lacs, PKS 0447-439 and PMN J0630-24. One of these BL Lacs has recently been observed in the VHE band by HESS (Zech et al. 2011). Explanation of the detection of PKS 0447-439 in the VHE band within conventional models would be challenging if the source redshift is indeed $z > 1$ (Prosekin et al. 2012). Thorough verification of the redshift measurement for both PKS 0447-439 and for the $z \geq 1$ sources listed in Table 1 is extremely important for the clarification of consistency/inconsistency of the VHE band detections of the high-redshift sources with the current understanding of the mechanisms of formation of the VHE γ-ray spectra of the sources and of the cosmological evolution of the EBL.

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References

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, VizieR On-line Data Catalog: II/276

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 723, 1082

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, Phys. Rev. Lett., 104, 101101

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJ, 720, 435

Acciari, V. A., Aliu, E., Arlen, T., et al. 2009, ApJ, 693, L104

Acciari, V. A., Aliu, E., Arlen, T., et al. 2010, ApJ, 708, L100

Adelman-McCarthy, J. K., Jennifer, K., Agüeros, M. A., et al. 2008, ApJSS, 175, 297

Afanas'Ev, V. L., Dodonov, S. N., Moiseev, A. G., et al. 2005, Astron. Rep., 49, 374

Aharonian, F. A., Konopelko, A. K., Völk, H. J., & Quintana, H. 2000, Astropart. Phys., 15, 335

Aharonian, F., Buckley, J., Kifune, T., & Sinnis, G. 2008, Rep. Progr. Phys., 71, 096901
Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2014, A&A, 567, A135
Albert, J., Aliu, E., Anderhub, H., et al. 2007a, ApJ., 654, L119
Albert, J., Aliu, E., Anderhub, H., et al. 2007b, ApJ., 663, 125
Albert, J., Aliu, E., Anderhub, H., et al. 2008, Science, 320, 1752
Archambault, S., Aune, T., Behera, B., et al. 2014, ApJ, 785, L16
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Barkhouse, W. A., & Hall, P. B. 2001, AJ, 121, 2843
Bauer, F. E., Condon, J. J., Thuan, T. X., & Broderick, J. J. 2000, ApJSS, 129, 547
Becherini, Y., Boisson, C., Cerruti, M., & H.E.S.S. Collaboration 2012, AIP Conf. Ser., 1505, 490
CTA consortium 2011, Exper. Astron., 32, 193
Colin, P., D. Borla Tridon, E. Carmona, et al. 2009, Proc. the 31st ICRC, Lodz [arXiv:0907.0960]
Danforth, C. W., Keeney, B. A., Stocke, J. T., Shull, J. M., & Yao, Y. 2010, ApJ, 720, 976
Essey, W., & Kusenko, A. 2010, Astropart. Phys. 33, 81
Essey, W., & Kusenko, A. 2012, ApJ, 751, L11
Essey, W., & Kusenko, A. 2014, Astropart. Phys., 57, 30
Essey, W., Kalashev, O., Kusenko, A., & Beacom, J. F. 2010, Phys. Rev. Lett., 104, 141102
Essey, W., Kalashev, O., Kusenko, A., & Beacom, J. F. 2011, ApJ, 731, 51
Essey, W., Ando, S., & Kusenko, A. 2012, Astropart. Phys., 35, 135
Finke, J. D., Razzaque, S., & Dermer, C. D. 2010, ApJ, 712, 238
Franceschini, A., Rodighiero, G., & Vaccari, M. 2008, A&A, 487, 837
Furniss, A., & McConville, W. 2013, Fermi Symposium Proc. – eConf C121028 [arXiv:1303.1103]
Furniss, A., Williams, D. A., Danforth, C., et al. 2013, ApJ, 768, L31
Gilmore, R., Sommerville, R. S., Primack, J. R., & Dominguez, A. 2012, MNRAS, 422, 3189
Giommi, P., Menna, M. P., & Padovani, P. 1999, MNRAS, 310, 465
Giommi, P., Piranomonte, S., Perri, M., & Padovani, P. 2005, A&A, 434, 385
Gorbunov, D. S., Tinyakov, P. G., Tkachev, I. I., & Troitsky, S. V. 2005, MNRAS, 362, L30
Gould, R. J., & Schreder, G. P. 1967, Phys. Rev. Lett., 16, 252
Jauncey, D. L., Wright, A. E., Peterson, B. A., & Condon, J. J. 1978, ApJ, 219, L1
Heidt, J., Tröller, M., Nilsson, K., et al. 2004, A&A, 418, 813
Healey, S. E., Romani, R. W., Cotter, G., et al. 2008, ApJS, 175, 97
Hodge, J. A., Zeimann, G. R., Becker, R. H., & White, R. L. 2009, AJ, 138, 900
Inoue, Y., Kalashev O., & Kusenko, A. 2014, Astropart. Phys., 54, 118
Kneiske, T. M., Bretz, T., Mannheim, K., & Hartmann, D. H. 2004, A&A, 413, 807
Landt, H. 2012, MNRAS, 423, L84
Masbou, J. 2010, Ph.D. Thesis
Massaro, E., Giommi, P., Sclavi, S., et al. 2007, AIP Conf. Proc., 921, 349
Mazin, D., & Raue, M. 2007, A&A, 471, 439
Mazin, D., MAGIC Collaboration, 2012, AIP Conf. Ser., 1505, 186
Mirizzi, A., Raffelt, G. G., & Serpico, P. 2007, Phys. Rev. D, 76, 023001
Murase, K., Dermer, C. D., Takami, H., & Migliori, G. 2012, ApJ, 749, 63
Neronov, A., & Semikoz, D. V. 2012, ApJ, 757, 61
Neronov, A., Tinyakov, P., & Tkachev, I. 2005, JETP, 100, 656
Neronov, A., Semikoz, D. V., & Vovk, Ie., 2010, A&A, 519, L6
Neronov, A., Semikoz, D. V., & Vovk, Ie. 2011, A&A, 529, A59
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Orr, M. 2011, Proc. 32nd ICRC [arXiv:1110.4643]
Plotkin, R. M., Anderson, S. F., Hall, P. B., et al. 2008, AJ, 135, 2453
Plotkin, R. M., Anderson, S. F., Brandt, W. N., et al., 2010, AJ, 139, 390
Pita, S., Goldoni, P., Boisson, C., et al. 2012, AIP Conf. Proc., 1505, 566
Prandini, E., Bonnoli, G., Maraschi, L., Mariotti, M., & Tavecchio, F. 2010, MNRAS, 405, L76
Prandini, E., Becerra-González, J., Lindfors, E., et al. 2012, AIP Conf. Ser., 1505, 647
Prosekin, A., Essey, W., Kusenko, A., & Aharonian, F. 2012, ApJ, 757, 183
Razzaque, S., Dermer, C. D., & Finke, J. D. 2012, ApJ, 745, 196
Sadler, E. M., Cannon, R. D., Mauch, T., et al. 2007, MNRAS, 381, 211
Shaw Michael, S., Romani Roger, W., Cotter Garret, et al. 2013, ApJ, 764, 135
Smolcic, V., Zamorani, G., Schinnerer, E., et al. 2009, ApJ, 696, 24
Stecker, F. W., Malkan, M. A., & Scully, S. T. 2006, ApJ, 648, 774
Stickel, M., Fried, J. M., Kuehr, H., Padovani, P., & Urry, C. M. 1991, ApJ, 374, 431
Stocke, J. T., & Rector, T. A. 1997, ApJ, 489, L17
Taylor, A. M., Vovk, I., & Neronov, A. 2011, A&A, 529, A144
Veron-Cetty, M. P., & Veron, P. 2010, A&A, 518, A10
Zech, A., Behera, B., Becherini, Y. et al. 2011, Proc. 25th Texas Symp. on Relativistic Astrophysics, Heidelberg [arXiv:1105.0840]