

Extragalactic Background Light expected from photon-photon absorption on spectra of distant Active Galactic Nuclei

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Abstract. Extragalactic background radiation blocks the propagation of TeV gamma-ray over large distances by producing e^+e^- pairs. As a result, primary spectrum of gamma-source is changed, depending on spectrum of background light. So, hard spectra of Active Galactic Nuclei with high red shifts allow the determination of a EBL spectrum. The redshifts of SHALON TeV gamma-ray sources range from 0.018 to 1.375 those spectra are resolved at the energies from 800GeV to 30 TeV. Spectral energy distribution of EBL constrained from observations of Mkn421 ($z=0.031$), Mkn501 ($z=0.034$), Mkn180 ($z=0.046$), OJ287 ($z=0.306$), 3c454.3 ($z=0.859$) and 1739+522 ($z=1.375$) together with models and measurements are presented.

1 Introduction

The cosmological processes, connecting the physics of matter in Active Galactic Nuclei will be observed in the energy spectrum of electromagnetic radiation. The understanding of mechanisms in active galactic nuclei requires the detection of a large sample of very high energy gamma-ray objects at varying redshifts. The detection of the very high energy γ -ray sources at the redshifts $z=0.0179$ to $z=1.375$ with SHALON telescope gives an opportunity to constrain extragalactic background light (EBL) density, based on modification to gamma-ray spectra and thus it will help to reconstruct the the cosmological history of the EBL.

2 SHALON telescope

The γ -astronomical researches are carrying out with SHALON [1–9] mirror Cherenkov telescope at the Tien-Shan high-mountain observatory (fig. 1). The SHALON mirror telescopic system consists of composed mirror with area of 11.2 m^2 . It is equipped with 144 photomultipliers receiver with the pixel of 0.6° and the angular resolution of the experimental method of $< 0.1^\circ$. It is essential that our telescope has a large matrix with full angle $> 8^\circ$ that allows us to perform observations of the supposed astronomical source (ON data) and background from extensive air showers (EAS) induced by cosmic ray (OFF data) simultaneously. Thus, the OFF data are collecting for exactly the same atmospheric thickness, transparency and other experimental conditions as the ON data.

An additional selection of electron-photon showers among the net cosmic rays EAS becomes possible through

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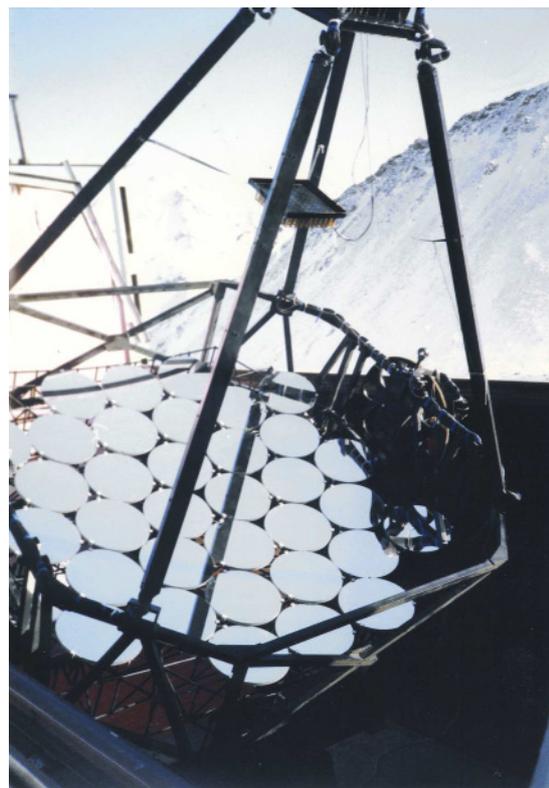


Figure 1. SHALON telescope.

an analysis of a light image which, in general, emerging as an elliptic spot in light receiver matrix. The selection of gamma-initiated showers from the background of proton showers is performed by applying the following criteria:

Table 1. The catalogue of metagalactic γ -ray sources observed by SHALON.

Sources	Observable flux ^a	k_γ ^b	Distance ^c	z	Type
NGC 1275	(0.78 ± 0.05)	-2.24 ± 0.09	71	0.018	Seyfert
SN2006 gy	(3.71 ± 0.65)	-3.13 ± 0.27	83	0.019	SN
Mkn 421	(0.63 ± 0.05)	-1.87 ± 0.11	124	0.031	BL Lac
Mkn 501	(0.86 ± 0.06)	-1.87 ± 0.13	135	0.034	BL Lac
Mkn 180	(0.65 ± 0.09)	-2.16 ± 0.15	182	0.046	BL Lac
3c382	(0.95 ± 0.20)	-1.08 ± 0.11	247	0.0578	BLRG
OJ 287	(0.26 ± 0.07)	-1.43 ± 0.18	1070	0.306	BL Lac
3c454.3	(0.43 ± 0.07)	-0.85 ± 0.07	5489	0.859	FSRQ
1739+522	(0.49 ± 0.05)	-0.93 ± 0.09	9913	1.375	FSRQ

^a Integral flux at energy $> 800\text{GeV}$ in units of $10^{-12}\text{cm}^{-2}\text{s}^{-1}$ ^b Power index in case of power fit of observable data^c Distance in Mpc

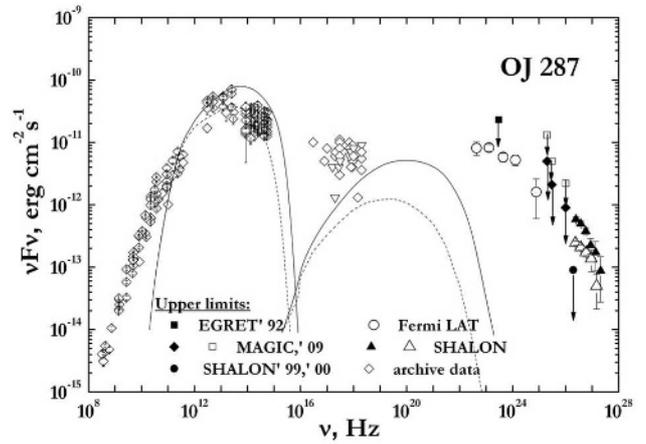
- $\alpha < 20^\circ$;
- $length/width > 1.6$;
- the ratio $INT0$ of Cherenkov light intensity in pixel with maximum pulse amplitude to the light intensity in the eight surrounding pixels exceeds > 0.6 ;
- the ratio $INT1$ of Cherenkov light intensity in pixel with maximum pulse amplitude to the light intensity in the in all the pixels except for the nine in the center of the matrix is exceeds > 0.8 ;
- $distance$ is less than 3.5 pixels.

Our analysis of the distributions of listed shower image parameters suggests that the background is rejected with 99.92% efficiency (see Refs. [2, 3, 5, 7–9]), whereas the amount of background showers to the selected gamma-showers does not exceed of 10%.

The γ -astronomical researches are carrying out with SHALON [1] mirror Cherenkov telescope since 1992. During the period 1992 - 2012 SHALON has been used for observations of extragalactic sources of different type. Among them are known BLLac-type sources Mkn 421, Mkn 501, Mkn 180, OJ 287; Seyfert Galaxy NGC 1275; Broad Line Radio Galaxy 3c 382; and Flat Spectrum Radio Qusars: 3c 454.3; 1739+522 (4c+51.37). [2–8]. Our method of the data processing is described in [1–4, 9]. Some representative results on fluxes, spectra are shown in Table 1 and also in [2–8] and Figures in these proceedings.

3 OJ 287

OJ 287 ($z=0.306$ [11]) is an low-frequency peaked BL Lac objects. It is one of the most studied blazars which spectrum has been well measured through radio [12–14] to X-ray bands [15–18] for radio studies and for optical. The most outstanding characteristic of OJ 287 is its 12 year period, which is discovered in optical range [16] and has also been confirmed in the x-ray band. OJ 287 is supposed to be a binary black hole system in which a secondary black

**Figure 2.** The spectral energy distribution of OJ 287 (see text).

hole passes the accretion disk of the primary black hole and produces two impact flashes per period. The spectral energy distributions of blazars consist of two broad peaks. The first, lower frequency peak is due to the synchrotron emissions of relativistic electrons in the jet. It is supposed, that the second, higher frequency peak is to be due to the Inverse Compton emissions of the same electrons (also referred as "synchrotron self-Compton model [19]). OJ 287 has been detected with GeV emissions by EGRET [20] and Fermi LAT[21]. It has also been proposed to be a TeV source.

OJ 287 was observed by SHALON in 1999, 2000, 2008, 2009 and 2010, for a total of 47.3 hours, at zenith angles ranging from 22° to 34° . The observations of 1999 and 2000 years does not reveal a γ -ray flux from the position of OJ 287, but only an upper limit of $< 1.1 \times 10^{-13}\text{cm}^{-2}\text{s}^{-1}$ (fig. 2). In observations of 2008, 2009 and 2010 (31.2 hours in total) the weak γ -ray flux was detected. An excess corresponding to a 6.9σ [10] was determined. The measured integral energy spectrum of OJ 287 can be well described by a power law with the index -1.43 ± 0.18 (fig. 3). The observed integral flux above

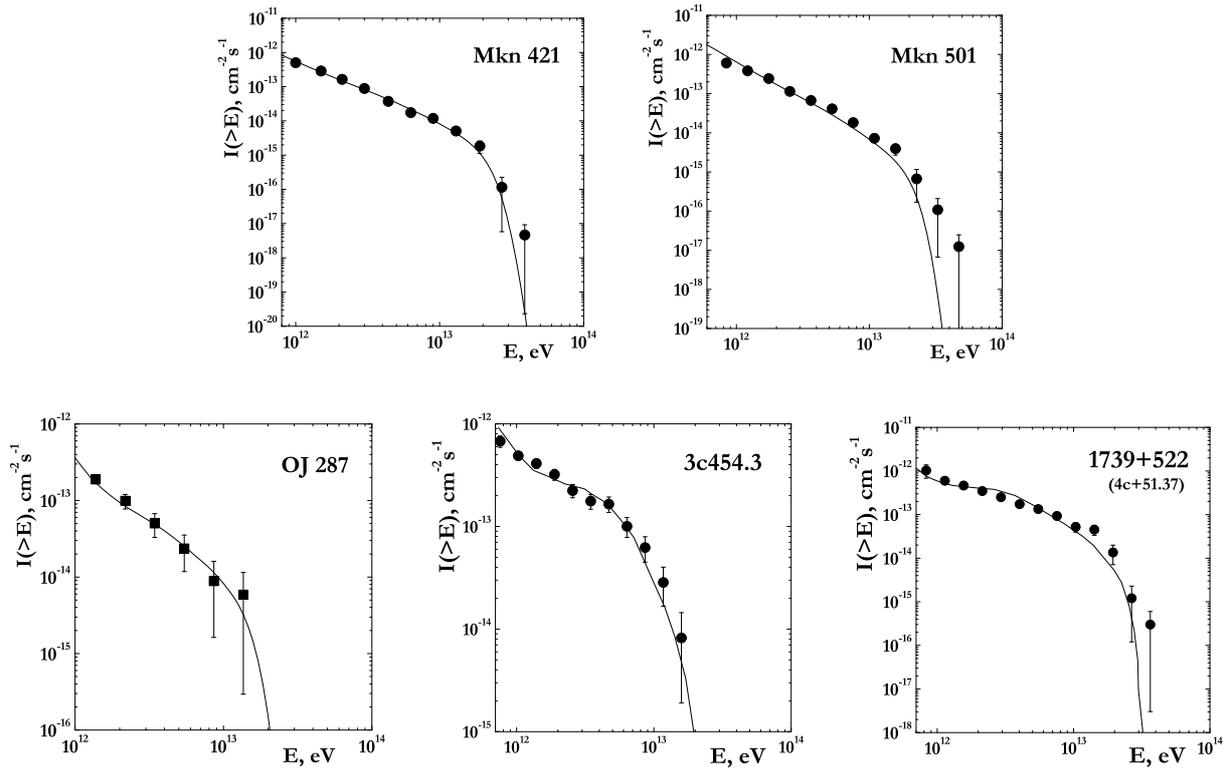


Figure 3. The integral energy spectra for Mkn 421, Mkn 501, OJ287, 3c454.4 and 1739+522 measured by SHALON (black points) together with spectra attenuated by EBL (lines, see text).

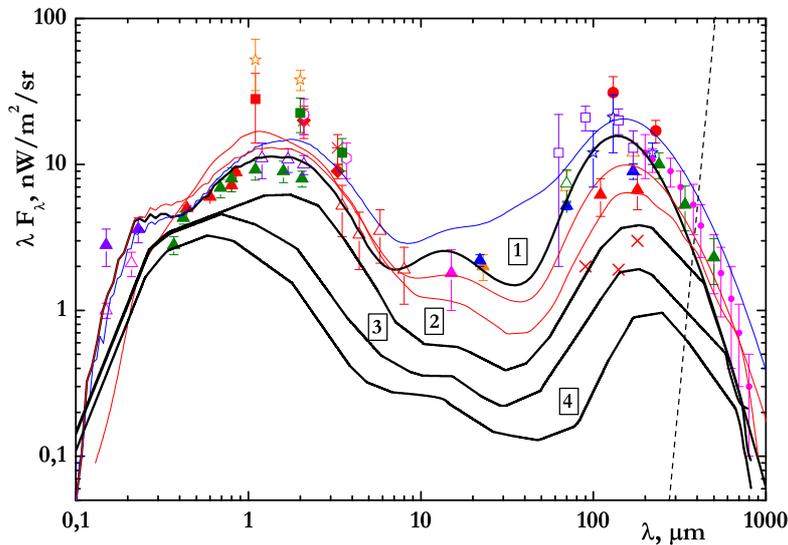


Figure 4. Spectral energy distribution of EBL: measurements [30] and models [31–34] and EBL shape constrained from observations of the extragalactic sources by SHALON:

1 - Mkn 421 ($z=0.031$), Mkn 501 ($z=0.034$); 2 - OJ287 ($z=0.306$); 3 - 3c454.3($z=0.859$); 4 - 1739+522 ($z=1.375$).

800 GeV is $(0.26 \pm 0.07) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$. An image of γ -ray emission from OJ 287 by SHALON telescope is also obtained.

The flux increase over the detected average flux was found at 14,15 November and 4, 5 December 2010 with value of $(0.63 \pm 0.15) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$ (statistical significance of 6.2σ [10]) with the softer energy spectrum with a

power law with the index -1.96 ± 0.16 . Figure 2 presents spectral energy distribution [22] of the γ -ray emission from OJ 287 by SHALON in comparison with other experiment data MAGIC [22], EGRET [20], and with theoretical predictions from [21] and also [22]. The open triangles at TeV energies on Fig. 2 are SHALON spectrum of OJ287; an upper limit at > 0.8 TeV corresponds to SHALON observations in 1999, 2000. The black triangles present the γ -ray spectrum at the increased flux period of 2010. OJ 287 is the weakest extragalactic source observed by SHALON.

4 3c454.3

In 1998 year a new metagalactic source 3c454.3 ($z=0.859$) had been detected by SHALON at TeV energies [2–7]. The integral gamma-ray flux above 0.8 TeV was estimated as $(0.43 \pm 0.07) \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$ (Table 1, Fig. 3, bottom line). Within the range 0.8 - 9 TeV, the integral energy spectrum is well described by the single power law $I(> E_\gamma) \propto E_\gamma^{-0.85 \pm 0.07}$ (fig. 3). Also, the spectrum by SHALON within the energy range 0.8 - 17 TeV can fitted with a power-law spectrum with exponential cut-off.

The measured flux value is consistent with the upper limit $0.84 \times 10^{-11} \text{ cm}^{-2}\text{s}^{-1}$ obtained by Whipple telescope at energy more than 0.5 TeV [23–26]. Taking into account that the spectrum from 3c454.3 measured by EGRET in the energy range from ~ 30 MeV to 50 GeV can be approximated as $E^{-1.2}$ [27].

Recently, 3c454.3 has detected with Fermi LAT at energies 200 MeV - 300GeV [28]. The spectrum by Fermi is fitted with a broken power-law with photon indices $\Gamma_{low} = 2.27 \pm 0.3$, $\Gamma_{high} = 3.5 \pm 0.05$ with an average flux of $\sim 3 \times 10^{-6} \text{ photons cm}^{-2}\text{s}^{-1}$, for energies $> 100 \text{ MeV}$.

5 1739+522

One more remote metagalactic gamma - source was detected by SHALON in 1999 and is being intensively studied since then [2–7]. This object was identified with the active galactic nucleus 1739+522. This the most distant object (with redshift $z=1.375$) is also the most powerful: its integral gamma-ray flux is found to be $(0.49 \pm 0.05) \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$ at energies of > 0.8 TeV. Within the range 0.8 - 7 TeV, the integral energy spectrum is well described by the single power law $I(> E_\gamma) \propto E_\gamma^{-0.93 \pm 0.09}$ (fig. 3, bottom line). Also, within the energy range 0.8 - 35 TeV the average integral spectrum can fitted with a power-law spectrum with exponential cut-off.

The average gamma-flux measured by EGRET telescope of Compton Observatory (CGRO) in the range ~ 30 MeV to 50 GeV is about $2 \times 10^{-8} \text{ cm}^{-2}\text{s}^{-1}$ with integral spectrum index about -1.2 [27]. The high energy γ -ray emission from 1739+522 was detected with Fermi LAT [29] in the range 100 MeV - 100 GeV with an average flux of $F(> 1 \text{ GeV}) = (2.5 \pm 0.2) \times 10^{-9} \text{ cm}^{-2}\text{s}^{-1}$ and power-law with photon indices $\Gamma = 2.5 \pm 0.04$ [29]

According to our analysis, the energy spectra of distant quasars 3c454.3 ($z=0.859$) and 1739+522 ($z=1.375$):

$F_{3c454.3}(> E_\gamma) \propto E_\gamma^{-0.85 \pm 0.07}$ and $F_{1739+522}(> E_\gamma) \propto E_\gamma^{-0.93 \pm 0.05}$ differ from those of the known blazars Mkn 421 ($z=0.031$) and Mkn 501 ($z=0.034$): $F_{Mkn 421}(> E_\gamma) \propto E_\gamma^{-1.87 \pm 0.11}$ and $F_{Mkn 501}(> E_\gamma) \propto E_\gamma^{-1.85 \pm 0.11}$. Hence, the average energy spectrum of the nearest metagalactic sources differs from spectra of remote objects 1739+522 and 3c454.3 within the energy range $10^{12} - 10^{13}$ eV. This observation of distant quasars does not contradict to unified energy spectrum $F(> E_\gamma) \propto E_\gamma^{-1.2 \pm 0.1}$.

6 Extragalactic Background Light

As the TeV gamma rays can be absorbed due to interaction of low-energy photons of Extragalactic Background Light (EBL), the observations of active galactic nuclei can also be used for the study background light from UV to far infrared and even cosmic microwave background. TeV gamma-rays, radiated by distant sources, interact with photons of background via $\gamma + \gamma \rightarrow e^+e^-$ resonant process, then relativistic electrons can radiate gamma-ray with energies less than of primary gamma-quantum. As a result, primary spectrum of gamma-source is changed, depending on spectrum of background light. So, a hard spectra of AGNi with high red shifts of 0.03 - 1.8 allow the determination an absorption by EBL and thus its spectrum.

The redshifts of SHALON very high energy gamma-ray sources range from $z=0.018$ to $z=1.375$. Among them bright enough AGNi of BLLac type Mkn421, Mkn 501 and FSRQ type 3c454.3, 1739+522 (4c+51.37) those spectra are resolved in the TeV energy band from 800 GeV up to ~ 20 -50 TeV. The fit of a simple power law function to the observational data presented in Table 1. Also, the measured spectra can be fitted by a power law with an exponential cutoff: $F(> E) \propto E^{-\gamma} \times \exp(-E/E_{cutoff})$ with hard power indices of about $\gamma \sim 1.55$ for Mkn 421 and Mkn 501 and $\gamma \sim 0.6$ for 3c454.3 and 1739+522. The value of E_{cutoff} ranges from 11 ± 2 TeV for Mkn 421, Mkn 501 and to 7 ± 2 TeV for distant sources.

It has mentioned that the observed spectra are modified by γ -ray attenuation, i.e. $F_{observed}(E) = F_{intrinsic}(E) \times \exp(-\tau(E, z))$ where $\tau(E, z)$ is optical depth for pair creation for a source at redshift z , and at an observed energy E . According to the definition of the optical opacity the medium influences on the primary source spectrum at $\tau \geq 1$, but for $\tau < 1$ the medium is transparent, so the measuring of source spectrum in the both range of τ can give the intrinsic spectrum of the source to constrain the EBL density. The optical depth for sources at redshifts from 0.031 to 1.375 was calculated with assumption of EBL shapes shown in Fig. 4. We used the EBL shape from Best-fit model and Low-SFR model [33] (see Fig. 4 thick black line 1 corresponds to Low-SFR model) to calculate the attenuated spectrum of Mkn 421 and Mkn 501 in assumption of simple power low intrinsic spectrum of the source with spectrum index of $\gamma = 1.5$, taken from the range of $\tau < 1$. The result is shown at Fig. 3 with line; the black squares are observational data for Mkn 421 and Mkn 501. The shapes of EBL density constrained from the spectra of the high redshift sources OJ287 ($z=0.306$), 3c454.3 ($z=0.859$)

and 1739+522 (1.375) are shown in Fig. 4 with curves 2, 3 and 4, respectively. For these sources the slope of intrinsic spectrum is taken $\gamma = 0.9 - 1.2$. The attenuated spectra for OJ287, 3c454.3 and 1739+522 are also presented at Fig. 3 (thin lines) together with observational data.

Observations of distant metagalactic sources have shown that the Universe is more transparent to very high-energy γ -rays than previously believed.

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