High-energy TeV observations of gamma-ray blazars Mkn 421, Mkn 501, Mkn 180 and OJ 287

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Abstract: The radio-loud active galactic nuclei having the radio emission arising from a core region rather than from lobes are often referred to as "blazars" and include BL Lacertae (BL Lac) objects, flat spectrum radio quasars. We present a results of long term observations of known blazars of BL Lac type objects Mkn 421 and Mkn 501, as well as Mkn 180 and OJ 287 which was recently detected by SHALON Cherenkov telescope system. The integral average gamma-ray fluxes of Mkn 180 and OJ 287 are (0.65 ± 0.09) × 10⁻¹² cm⁻² s⁻¹ and (0.26 ± 0.07) × 10⁻¹² cm⁻² s⁻¹ respectively. The integral average gamma-ray fluxes of Mkn 421 and Mkn 501 were found as (0.63 ± 0.05) × 10⁻¹² cm⁻² s⁻¹ and (0.86 ± 0.06) × 10⁻¹² cm⁻² s⁻¹ respectively. The spectra and images of these blazars are obtained. Also, spectral energy distributions are presented. Extreme variability in different wavelengths including VHE gamma rays is the most distinctive feature of BL Lac. For example, the significant increase of Mkn 501 flux was detected in 1997 with the VHE ground telescopes all over the world. A number of significant increases had been detected from Mkn 421 and Mkn 501 on the year time-scales. These observations are carrying out with SHALON mirror telescopes at the Tien-Shan high mountainous Observatory of P.N. Lebedev Physical Institute.

Keywords: Active Galactic Nuclei; BL Lacs; Mkn 421; Mkn 501; Mkn 180; OJ 287.

1 Introduction

The γ-astronomical researches are carrying out with SHALON mirror Cherenkov telescope at the Tien-Shan high-mountain observatory. During the period 1992 - 2011, SHALON has been used for observations of metagalactic and galactic sources [1, 2]; among them are the known blazars Mkn 421, Mkn 501, Mkn 180 and OJ 287. The observation results of high-frequency peaked BL Lac object: Mkn421 (z = 0.031), Mkn501 (z = 0.034), Mkn 180 (z = 0.045) and low-frequency peaked BL Lac object OJ 287 (z=0.306) are presented with integral spectra, images and spectral energy distributions combined with those in all broad energy range [1, 2, 3].

Markarian 421

The BL Lac Mkn 421 was detected as the first and the nearest (z = 0.031) metagalactic source of blazar type of TeV energy gamma-quanta in 1992 year using Whipple telescope [4]. The search was initiated by the detection of some Active Galactic Nuclei, including Mkn 421 by EGRET [5]. Since the first detection this source has been observed by the number of independent groups using different methods of registration of gamma-initiated showers: Whipple [6], HEGRA [7, 8, 9], SHALON [1, 2], CAT [28, 29], TACTIC [18], HESS [21], MAGIC [22], CELESTE [19], STACEEE [20], CASA-MIA [17], CYGNUS [12, 13], Tibet [14, 15, 16], Telescope Array [10, 11]. Recently Mkn 421 was detected by Fermi LAT [3]. Presently this source is also systematic studied by different experiments (fig. 1).

Mkn 421 is being intensively studied since 1994 by SHALON. Figure 1 shows the spectral energy distribution of Mkn 421 by SHALON in comparison with other experiment data and models (see [3]). An image of gamma-ray emission from Mkn 421 obtained with SHALON is shown in Fig. 2. The averaged for the whole period of observation since 1994 integral gamma-ray flux above 0.8 TeV was estimated as (0.63 ± 0.05) × 10⁻¹² cm⁻² s⁻¹. Within the range 1 - 10 TeV, the integral energy spectrum is well described by the power law $F(>E_\gamma) \propto E_\gamma^{-\alpha}$, with $\alpha = -1.87 \pm 0.11$ (fig. 2).

Extreme variability in different wavelengths including VHE gamma rays on the time-scales from minutes to years is the most distinctive feature of BL Lac objects. The increase of the flux over the average value was detected in 1997 and 2004 observations of Mkn 421 by SHALON and estimated to be (1.01 ± 0.25) × 10⁻¹² cm⁻² s⁻¹ and (0.96 ± 0.2) × 10⁻¹² cm⁻² s⁻¹, respectively. The white area around the SHALON data (see fig. 1) shows the range
V. G. Sinitsyna et al. TEV observations of γ-ray blazars MKN421, MKN501, MKN180 and OJ287

Figure 1: The spectral energy distribution of Mrk 421 from modern and archival observations [3]. TeV range is represented with integral spectrum by SHALON (black points) in comparison with other very high energy experiments (grey points) [3].

Figure 2: left: The Mkn 421 observational results by SHALON; γ-quantum integral spectrum; right: The source image at energy range of >0.8 TeV.

Markarian 501

The detection of Mkn 421 as metagalactic VHE gamma-ray source initiated a search for VHE emission from several other active galactic nuclear of blazar type. This led to the detection of BL Lac object Mkn 501 (z = 0.034) by Whipple in 1995 [23]. In contrast to Mkn 421, EGRET had not detected this source, as significant source of gamma rays [24]. So Mkn 501 was the first object to be discovered by as gamma-ray source from the ground. Then, Mkn 501 had been confirmed as a source of VHE gamma-rays by the SHALON [1, 2], HEGRA [31, 32], TACTIC [26, 27], CAT [28, 29, 30], HESS [25] and CASA-MIA [33]. At GeV energy range Mkn 501 was detected by Fermi LAT [3]. At figure 3 the SHALON results for this gamma-source are presented together with the data telescopes of Whipple, HEGRA, TACTIC, HESS, MAGIC (grey points) (see [3]). An image of gamma-ray emission from Mkn 501 by SHALON telescope is shown in Fig. 4. The integral average gamma-ray flux above 0.8 TeV was estimated as $(0.86 \pm 0.06) \times 10^{-12} \, cm^{-2} s^{-1}$ and the power index of the integral spectrum is $k_{\gamma} = -1.85 \pm 0.11$.

Mkn 501 shows the significant flux variability in the different energy ranges. The significant increase of Mkn 501 flux was detected in 1997 and 2006 with the VHE ground telescopes all over the world. The variations of the spectrum are shown with the white area on figure 3. The integral gamma-ray flux in 1997 and Aug. 2006 by SHALON telescope was estimated as $(1.21 \pm 0.13) \times 10^{-12} \, cm^{-2} s^{-1}$ and $(2.05 \pm 0.23) \times 10^{-12} \, cm^{-2} s^{-1}$, respectively that is comparable with flux of powerful galactic source Crab Nebula by SHALON. The flux increase at the end of Aug. 2006 followed the quiet period from May to July 2006. The last flaring state of Mkn 501 at the very high energies was detected in the SHALON observational period between...
Figure 5: The spectral energy distribution of Mrk 180 from modern and archival observations [3, 35]. TeV range is represented with integral spectrum by SHALON in comparison with other experiments [35, 36, 37].

Figure 6: The Mkn 180 observational results by SHALON: \( \gamma \)-quantum integral spectrum and The source image at energy range of \( > 0.8 \) TeV. March and June 2009. The flux increase was detected at 23-24 April and 23-25 May with average flaring flux of \( (3.41 \pm 0.70) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} \). This increase is correlated with the flaring activity at lower energy range in observations of Fermi LAT [34] and VERITAS, MAGIC, Whipple (see [34]).

Markarian 180

Mkn 180 is a known extragalactic source of high frequency peaked BL Lac type at a redshift of \( z = 0.045 \). As the VHE -ray emitting Active Galactic Nuclei are variable in flux in all wavebands the correlations between low energy emission (for example X-ray) and gamma-ray emission have been found. Recently, optical - TeV/GeV correlation was also found. Mkn 180 was detected in TeV \( \gamma \) rays by MAGIC during an optical high state [35] (Fig. 5). Earlier, Mkn 180 had been observed by HEGRA [36] and Whipple [37] but were only able to derive flux upper limits, and EGRET did not detect the source [38, 39]). Mkn 180 was observed by SHALON in 2007, 2009, 2010 and 2011, for a total of 52.3 hours, at zenith angles ranging from 25\(^\circ\) to 34\(^\circ\). After the standard analysis, a clear excess corresponding to a 10.5\( \sigma \) [40] was determined. No evidence for flux variability was found. The measured integral energy spectrum of Mkn 180 can be well described by a power law with the index \(-2.16 \pm 0.15\). The observed integral flux above 0.8TeV is \( F(E > 0.8 TeV) = (0.65 \pm 0.09) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} \) (Fig. 6). An image of gamma-ray emission from Mkn 180 by SHALON telescope is shown in Fig. 6. Figure 5 presents spectral energy distribution of the \( \gamma \)-ray emission from Mkn 180 by SHALON in comparison with other experiment data HEGRA [36], MAGIC [35], EGRET [38, 39], Whipple [37], Fermi LAT [41] and with theoretical predictions from [35, 42, 43].

OJ 287

OJ 287 (\( z=0.306 \) [44]) is an low-frequency peaked BL Lac objects (LBLs). It is one of the most studied blazars which spectrum has been well measured through radio [49, 50, 51] to x-ray bands [45, 46, 47, 48] for radio studies and for optical. The most outstanding characteristic of OJ 287 is its 12 year period, which is discovered in optical range [46] 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 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 (IC) emissions of the same electrons (also referred as "synchrotron self-Compton (SSC) model" [52]). OJ 287 has been detected with GeV emissions by EGRET [54] and Fermi/LAT [55, 56]. 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 gamma-ray flux from the position of OJ 287, but only an upper limit of < 1.1 × 10^{-13} cm^{-2} s^{-1}. In observations of 2008, 2009 and 2010 (31.2 hours in total) the weak gamma-ray flux was detected. An excess corresponding to a 6.9σ [40] was determined. The measured integral energy spectrum of OJ 287 can be well described by a power law with the index −1.46 ± 0.18. The observed integral flux above 0.8 TeV is \( F(E > 0.8 TeV) = (0.26 ± 0.07) \times 10^{-12} cm^{-2} s^{-1} \). An image of gamma-ray emission from OJ 287 by SHALON telescope is shown in Fig. 8.

The flux increase over the detected average flux was found at 14.15 November and 4, 5 December 2010 with value of (0.63 ± 0.15) × 10^{-12} cm^{-2} s^{-1} (statistical significance of 6.2σ [40]) with the softer energy spectrum with a power law with the index −1.96 ± 0.16. Figure 7 presents spectral energy distribution [53] of the gamma-ray emission from OJ 287 by SHALON in comparison with other experiment data MAGIC [53], EGRET [54], and with theoretical predictions from [55, 56] and also [53]. The black points at TeV energies on Fig. 7 are SHALON spectrum of OJ287; an upper limit at > 0.8 TeV corresponds to SHALON observations in 1999, 2000. The grey area is the gamma-ray spectrum at the increased flux period of 2010. OJ 287 is the weakest extragalactic source observed by SHALON.

References