SHALON observations of High-Frequency- and Low-Frequency-Peaked BL Lac objects

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Abstract. The BL Lac objects come in two subclasses: the "low-frequency-peaked BL Lac objects" in which the synchrotron peak falls in the IR-optical range and the "high-frequency-peaked BL Lac objects" where it falls in the UV-X-ray bands. 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. Introduction

The gamma-ray sources form a new class of high-energy objects in the Universe, including active galactic nuclei, radio galaxies, galactic binaries, pulsar wind nebulae, in addition to supernova remnants which are assumed to be the origin of cosmic rays for a long time. Exploring the emission mechanism from these objects is a big challenge in astrophysics. Non-thermal nature of emission inherently needs multiwavelength observations to study the phenomena, involving astronomers working in other wavelength.

The γ-astronomical researches are carrying out with SHALON mirror Cherenkov telescope at the Tien-Shan high-mountain observatory (3340 m a.s.l.). During the period 1992 - 2012, SHALON has been used for observations of metagalactic and galactic sources [1, 2, 3]; 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, 4].

2. 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 γ-quanta in 1992 year using Whipple telescope [6]. The search was initiated by the detection of some Active Galactic Nuclei, including Mkn 421 by EGRET [7]. Since the first detection this source has been observed by the number of independent groups using different methods of registration of γ-initiated showers: Whipple [8], HEGRA [9, 10, 11],...
**Figure 1.** from left to right: The SED of Mrk 421 (see text). Mkn 421 $\gamma$-ray integral spectrum and the source image at energy range of $> 0.8$ TeV by SHALON.

**Figure 2.** from left to right: The SED of Mrk 501 (see text). Mkn 501 $\gamma$-ray integral spectrum and the source image at energy range of $> 0.8$ TeV by SHALON.

SHALON [1, 2, 3], CAT [27, 28], TACTIC [17], HESS [20], MAGIC [21], CELESTE [18], STACEE [19], CASA-MIA [16], CYGNUS [14], Tibet [15], Telescope Array [12, 13]. Recently Mkn 421 was detected by Fermi LAT [4]. Presently this source is also systematically 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 from modern and archival observations [4, 5] and models (see [4, 5]). An image of $\gamma$-ray emission from Mkn 421 obtained with SHALON is shown in Fig. 1. The averaged for the whole period of observation since 1994 integral $\gamma$-ray flux above 800 GeV was estimated as $(0.63 \pm 0.05) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$. Within the range $1 - 10$ TeV, the integral energy spectrum is well described by the power law with index $k_\gamma = -1.87 \pm 0.11$ (fig. 1).

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 $(1.01 \pm 0.25) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$ and $(0.96 \pm 0.2) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$, respectively. The similar variations of the flux over the average value was also observed with the telescopes of Whipple, HEGRA, TACTIC, HESS (60°–67°), MAGIC (45°).

**3. Markarian 501**

The detection of Mkn 421 as metagalactic VHE $\gamma$-ray source initiated a search for VHE emission from several other active galactic nuclei of blazar type. This led to the detection of BL Lac objects Mkn 501 ($z = 0.034$) by Whipple in 1995 [22]. In contrast to Mkn 421, EGRET had not detected this source, as significant source of $\gamma$-rays [23]. 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, 3], HEGRA [30, 31], TACTIC [25, 26] CAT [27, 28, 29],
Mkn 180 γ-ray integral spectrum and the source image at energy range of > 0.8 TeV by SHALON.

Mkn 180 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 integral γ-ray flux in 1997 and Aug. 2006 by SHALON telescope was estimated as $(1.21 \pm 0.13) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}$ and $(2.05 \pm 0.23) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}$, 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 quit 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 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 [5] and VERITAS, MAGIC, Whipple [5].

4. 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 γ-ray emission have been found. Recently, optical - TeV/GeV correlation was also found. Mkn 180 was detected in TeV γ rays by MAGIC during an optical high state [33] (Fig. 3). Earlier, Mkn 180 had been observed...
by HEGRA [34] and Whipple [35] but were only able to derive flux upper limits, and EGRET did not detect the source [36, 37]).

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° to 34°. After the standard analysis, a clear excess corresponding to a 10.5σ [38] 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 800 GeV is $(0.65 \pm 0.09) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}$ (Fig. 3). An image of γ-ray emission from Mkn 180 by SHALON telescope is shown in Fig. 3, right. Figure 3 presents spectral energy distribution of the γ-ray emission from Mkn 180 by SHALON in comparison with other experiment data HEGRA [34], MAGIC [33], EGRET [36, 37], Whipple [35], Fermi LAT [39] and with theoretical predictions from [33, 40, 41].

5. OJ 287

OJ 287 ($z=0.306$ [42]) is an low-frequency peaked BL Lac objects. It is one of the most studied blazars which spectrum has been well measured through radio [47, 48, 49] to X-ray bands [43, 44, 45, 46] for radio studies and for optical. The most outstanding characteristic of OJ 287 is its 12 year period, which is discovered in optical range [44] 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 emissions of the same electrons (also refered as "synchrotron self-Compton model [50]). OJ 287 has been detected with GeV emissions by EGRET [51] and Fermi LAT[52]. 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 $< 1.1 \times 10^{-13} \text{cm}^{-2}\text{s}^{-1}$. 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 [38] was determined. The measured integral energy spectrum of OJ 287 can be well described by a power law with the index $-1.43 \pm 0.18$. The observed integral flux above 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 shown in Fig. 4.

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 $6.2\sigma$ [38]) with the softer energy spectrum with a power law with the index $-1.96\pm0.16$. Figure 4 presents spectral energy distribution [53] of the γ-ray emission from OJ 287 by SHALON in comparison with other experiment data MAGIC [53], EGRET [51], and with theoretical predictions from [52] and also [53]. The open triangles at TeV energies on Fig. 4 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.

6. Conclusion

In this paper we have presented the observation results for four blazar-type sources: Mkn 421, Mkn 501, Mkn 180 and OJ 287. The integral spectra, images and spectral energy distribution in all broad energy range are shown for all sources under discussion. The significant variations of TeV flux was observed from Mkn 421, Mkn 501, which is correlated with those in GeV energy range by Fermi LAT. The spectrum and flux of Mkn 180 have been measured by SHALON. These results are in agreement with studies of Mkn 180 reported by MAGIC. For the first time, OJ 287 blazar was successfully detected with SHALON telescope at TeV energies through the different state of this source. The large multiwavelength coverage can give the opportunity
to study of spectral energy distributions of these sources from radio to γ-ray energy and to investigate the different mechanisms of emission.

References
[1] Sinitsyna V G et al., 1999 Nucl. Phys. B (Proc. Suppl.) 75A 352; 2001, 97 215; 2003, 122 247, 409; 2006, 151 108; 2008, 175-176 463; 2009, 196 442.
[2] Sinitsyna V G 2006 Rad. Phys. and Chem. 75 880
[3] Sinitsyna V G et al. 2009 J. Phys. Soc. Jpn., Suppl. A 78 192
[4] Abdo A A et al. 2010 Astrophys. J. 716 30
[5] Abdo A A et al. 2011 Astrophys. J. 727 129
[6] Schubell M S et. al. 1996 Astrophys. J. 460 644
[7] Thompson D J et al. 1995 Astrophys. J. Suppl. 101 209 259
[8] McEnery J E et. al. 1997 Proc. 25th Int. Cosmic Ray Conf. Durban, 3
[9] Petry D et al. 1996 Astron. & Astrophys. 311 L13
[10] Petry D et al. 1997 Towards a Major Atmospheric Cherenkov Detector-V. Ed. De Jager 3 241
[11] Karle A D et al. 1995 Astropart. Phys. 4 1
[12] Aiso S et al. 1997 Proc. 25ICRC Durban 3 261
[13] Yamamoto Y et al. 1999 Proc. 26ICRC, Salt Lake City 3 386
[14] Alexandreas D E et al. 1993 Astrophys. J. 418 832; 1993 Proc. 23ICRC Calgary 1 373
[15] Amenomori M et. al. 1997 in Proc. 25ICRC Durban 3 297; 1999 Proc. 26thICRC Salt Lake City 3 418; 2005 Proc. 29th ICRC Pune 4 211
[16] Borione A et. al. 1995 Proc 24th ICRC Rome 2 503
[17] Rannot R C et al. 2005 Proc. 29th ICRC Pune 4 355
[18] Brion E. et al. 2005 Towards a Major Atmospheric Cherenkov Detector-VII. ed. B. Degrange, 117
[19] Carson J E et al. 2005 Proc. 29th ICRC Pune 4 415
[20] Horns D et al. 2005 Proc. 29th ICRC Pune 4 319
[21] Mazin D et al. 2005 Proc. 29th ICRC Pune 4 327
[22] Weekes T C et al. 1999 Prep. Ser. 4811
[23] Kataoka J et al. 1999 Astrophys. J. 514 138
[24] Benbow W et al. 2005 in Proc. 29th ICRC Pune 4 303
[25] Bhat C L et al. 1997 Towards a Major Atmospheric Cherenkov Detector-V. ed. De Jager, 196
[26] Yadav K K 2009 Proc. of Rencontres de Moriond 173
[27] Djuanatti-Atai A et al. 1997 ibid. 21
[28] Iacoucci L, Nuss E 1998 in Proc. 16ECRS 363
[29] Punch M et al., 1997 in Proc. 25th ICRC Durban 3 253
[30] Petry D et al. 1997 in Proc. 25th ICRC, Durban 3 241
[31] Bradbury S M et al. 1997 Astron. &Astrophys. 320 L15
[32] Catanese M et al. 1999 in Proc. 26th ICRC, Salt Lake City 3 301
[33] Albert J et al. 2006 Astrophys. J. 648 L105
[34] Aharonian F et al. 2004 Astron. &Astrophys. 421 529
[35] Horan D et al. 2004 Astrophys. J. 603 51
[36] Fichtel C E et al. 1994 ApJS 93 125
[37] Hartman R C et al. 1999 ApJS 123 79
[38] Li T-P and Ma Y-Q, 1983 Astrophys. J. 272 317
[39] Abdo A A et al. 2009 Astrophys. J. 707 1310
[40] Costamante L, Ghisellini G 2002 Astron. &Astrophys. 384 56
[41] Fossati G et al. 2000 Astrophys. J. 541 166
[42] Stickel M, Frie J W, Kuehr H 1989 Astron. Astrophys. S 80 103
[43] Tateyama C E et al. 1999 Astrophys. J. 520 27
[44] Valtaoja E et al. 2000 Astrophys. J. 531 744
[45] Gabuzda D C, Gmez J L, 2001 Mon. Not. R. Astron. Soc. 320 L49
[46] Tateyama C E, Kingham K A 2004 Astrophys. J. 608 149
[47] Idesawa E et al. 1997 Publ. Astron. Soc. Jpn. 49 631
[48] Issobe N et al. 2001 Publ. Astron. Soc. Jpn. 53 79
[49] Seta H et al. 2009 Publ. Astron. Soc. Jpn. 61 1011
[50] Ghisellini G, et al. 1998 Mon. Not. R. Astron. Soc. 301 451
[51] Hartman R C et al. 1999 ApJS 123 79
[52] Abdo A A et al. 2009 Astrophys. J. 700 597; 2010 Astrophys. J. 715 429
[53] Hayashida M et al. 2009 Proc. of 31st ICRC, Lodz