SHALON observations of Active Galactic Nuclei at red shift from $z = 0.0179$ to $z = 2.979$

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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 Flat Spectrum Radio Quasars (FSRQ) and BL Lacertae (BL Lac) objects. During the period 1992 - 2015, SHALON has been used for observations of the metagalactic sources NGC1275, Mkn421, Mkn501, Mkn180, 3c382, 4c+31.63, OJ 287, 3c454.3, 4c+55.17, 1739+522. We present results of long term observations of FSRQ: among them are known object 3c454.3, high-red shifted quasar 1739+522 as well as BL Lac type objects. The observation results are presented with integral spectra, images and spectral energy distributions for each of sources at energies $> 800$ GeV. A number of variability periods in different wavelengths including VHE $\gamma$-rays were found.

Introduction

High and very high energy $\gamma$-rays have come to play an important role in the study of Active Galactic Nuclei (AGNi). A big number of AGNi have been detected through the MeV to TeV energies. The long term SHALON observations yielded data on AGNi of different type at energy range of $800$GeV - $100$ TeV (Table 1). The redshifts of AGNi observed by SHALON range from $z=0.0179$ to $z=2.979$. Some of these AGNi were discovered at TeV energies by SHALON. The results on fluxes, spectral energy distributions and images are shown here and [1, 2, 3, 4, 5].

Perseus Cluster and NGC 1275 ($z = 0.018$)

Among observed AGNi and the proximal one is NGC 1275 of Perseus Cluster. Long-term studies of the central galaxy in the cluster, NGC 1275, are being carried out in the SHALON experiment. Results on NGC 1275 fluxes, spectral energy distribution, detailed images and detailed analysis of data to reveal the processes produce TeV $\gamma$-ray emission are shown in as in Fig. 1, within these Proceedings and [2]. The TeV images of the galaxy and its surroundings, and the variability of TeV flux indicate that the part of TeV emission is generated by relativistic jets in the nucleus of NGC 1275 itself. Whereas, the extended structures around NGC 1275 is evidence of the interaction of cosmic rays and magnetic fields generated in the jets at the galactic center with the gas of the Perseus cluster.
The catalogue of and extragalactic γ-ray sources by SHALON with parameters for spectrum fitting in form of power low with exponential cutoff $F(>E) \propto E^{k_s} \times \exp(-E/E_{\text{cutoff}})$.

| Sources    | Observable flux$^a$ | $k_s$ | $E_{\text{cutoff}}$, TeV | Distance, kpc | Type       |
|------------|---------------------|-------|---------------------------|---------------|------------|
| NGC 1275   | (0.78 ± 0.05)       | −2.18 ± 0.12 | 32 ± 7                   | 0.018         | Seyfert    |
| Mkn 421    | (0.63 ± 0.05)       | −1.51 ± 0.18 | 10 ± 3                   | 0.031         | BL Lac     |
| Mkn 501    | (0.86 ± 0.06)       | −1.48 ± 0.15 | 11 ± 3                   | 0.034         | BL Lac     |
| Mkn 180    | (0.65 ± 0.09)       | −1.84 ± 0.15 | 7.3 ± 2.2                | 0.046         | BL Lac     |
| 3c382      | (0.91 ± 0.14)       | −1.05 ± 0.11 | 21 ± 7.0                 | 0.0578        | BLR G      |
| 4c+31.63   | (0.73 ± 0.16)       | −1.13 ± 0.16 | 10.4 ± 3.2               | 0.295         | FSRQ       |
| OJ 287     | (0.26 ± 0.07)       | −1.14 ± 0.11 | 9.5 ± 1.2                | 0.306         | BL Lac     |
| 3c454.3    | (0.43 ± 0.07)       | −0.52 ± 0.12 | 6.2 ± 1.0                | 0.859         | FSRQ       |
| 4c+55.17   | (0.90 ± 0.16)       | −1.40 ± 0.15 | 5.4 ± 2.1                | 0.896         | FSRQ       |
| 1739+522   | (0.49 ± 0.05)       | −0.50 ± 0.18 | 6.1 ± 1.2                | 1.375         | FSRQ       |
| B2 0242+43 | (0.58 ± 0.20)       | −        | −                        | 2.243         | FSRQ       |
| B2 0743+25 | (0.37 ± 0.16)       | −        | −                        | 2.979         | FSRQ       |

$^a$ Integral flux at energy > 800 GeV in units of $10^{-12} \text{cm}^{-2}\text{s}^{-1}$

Mkn 421 ($z = 0.031$), Mkn 501 ($z = 0.034$) and Mkn 180 ($z = 0.046$)

The observation results of known BL Lacs Mkn 421, Mkn 501 and Mkn 180 are obtained (see Fig. 1 and [1, 3]). The integral spectra, images and spectral energy distributions at energies above 800 GeV are obtained for the each of the sources.

A number of variability periods in different wavelengths including VHE γ-rays were found. For example, 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 and VERITAS, MAGIC, Whipple.

Mkn 180 was observed by SHALON in 2007, 2009 - 2014, for a total of 81 hours. After the standard analysis, a clear excess corresponding to a 18.5σ [6] was detected. No evidence for flux variability was found. Mkn 180 spectrum fitting parameters are in the table 1.

Data from SHALON observations are shown together with ones from experiments (see Fig. 1).

3c 382 ($z = 0.0578$)

3c 382 is a typical Broad Line Radio Galaxy (BLRG). Its radio structure shows several quasar-like features. The core is bright and there is a narrow jet with the compact hotspot with the lobe opposite the jet. In contrast to blazars, the jets in BLRGS are not pointing directly toward the observer, so the relativistic beaming effects and jet dominance are only moderate, so it became possible to investigate both the accretion disk and the jet. In our observations we are mainly aimed on the searches for TeV γ-rays form 3c 382 and the comparison with estimations.

3c 382 has been detected by SHALON at TeV energies (in observations of 2009 - 2014 years, 43.1 hours in the total [1, 4]) with a significance [6] of 9.5σ (Fig. 1, table 1). TeV image of 3c382 is correlated with the structures visible in radio energies by VLA (refs. in [1]) The observations of 3c382 with Fermi LAT have gave only an upper limit in the range 0.1 - 100 GeV (Fig. 1).

4c+31.63 ($z = 0.295$)

In observations of 2012 a new source was detected by SHALON in TeV energies. This object was identified with FSRQ type source 4c+31.63 at redshift $z = 0.295$. 4c+31.63 was observed by
Figure 1. Spectral energy distributions of the γ-ray emission from AGNi observed by SHALON.

SHALON in the 2012 - 2014 for a total of 39.3 hours [1]. The γ-ray emission from the position of 4c+31.63 was detected above 800 GeV with a statistical significance[6] of 8.6σ. Energy spectrum
Figure 2. Spectral energy distributions of the $\gamma$-ray emission from AGNi observed by SHALON.

parameters are shown in the table 1. 4c+31.63 was previously detected at high energies with Fermi LAT. The image of 4c+31.63 in TeV $\gamma$-ray by SHALON telescope is shown in Fig. 2.

**OJ 287 ($z = 0.306$)**
The most outstanding characteristic of BL Lac object OJ 287 is its 12 year period, which is discovered in optical range 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. OJ 287 has been detected with GeV emissions by EGRET and Fermi LAT (refs. in [1, 3]).

In observations of 2008, 2009 and 2010 (31.2 hours in total) the weak γ-ray flux was detected [1, 3]. An excess corresponding to a 6.9σ [6] was determined (see table 1). OJ 287 is the weakest extragalactic source observed by SHALON. The image of γ-ray emission from OJ 287 by SHALON telescope is shown in Fig. 2.

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 [6]).

Fig. 2 presents spectral energy distribution of the γ-ray emission from OJ 287 by SHALON [1, 3] in comparison with other experiments (refs. in [1, 3]). The Δ at TeV energies on Fig. 2 are SHALON spectrum of OJ 287; an upper limit at > 0.8 TeV corresponds to SHALON observations in 1999, 2000: ▲ present the γ-ray spectrum at the increased flux period of 2010.

3c454.3 \((z = 0.859)\)

In 1998 year a 3c454.3 had been detected by SHALON at TeV energies [5] with 14.3σ [6]. The integral γ-ray flux, energy spectrum parameters are presented in the table 1. The TeV γ-ray emission map is presented in Fig. 2. Recently, 3c454.3 has detected with Fermi LAT at energies 200 MeV - 300 GeV (refs. in [1]). The spectrum by Fermi is fitted with a broken power-law with photon indices \(\Gamma_{\text{low}} = 2.27 \pm 0.3\), \(\Gamma_{\text{high}} = 3.5 \pm 0.05\) with an average flux of \(\sim 3 \times 10^{-6} \text{cm}^{-2}\text{s}^{-1}\), for energies \(> 100\text{MeV}\). 3c454.3 shows the significant flux variability in the different energy ranges including high and very high energies. The last significant flaring state of 3c454.3 at TeV energies was detected in the SHALON observational period of Nov. - Dec. 2010. The flux increase was detected at 02-04 Dec. with flux of \((3.41 \pm 0.70) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}\). This increase is correlated with the flares at lower energy range in observations of Fermi LAT (refs. in [1]).

4c+55.17 \((z = 0.896)\)

4c+55.17, at redshift \(z = 0.896\), is the radio-loud active galaxy classified as a FSRQ. This object was previously detected at high energies with EGRET and Fermi LAT with unusually hard MeV-GeV γ-ray spectrum. 4c+55.17 was observed by SHALON in the period from 2012 - 2014 for a total of 49.6 hours [1]. After the standard analysis, a clear excess corresponding to a 8.4σ [6] was determined with integral flux and the observed energy spectrum are shown in table 1 and Fig. 2. Also, the image of 4c+55.17 at TeV energies is obtained by SHALON (see Fig. 2).

1739+522 \((4c+51.37) \,(z = 1.375)\)

One more remote metagalactic γ source of FSRQ type was detected by SHALON in 1999 and is being intensively studied since then [1, 5]. This object was identified with the 1739+522 (with 15.1σ [6] at \(E > 0.8\) TeV). Energy spectrum parameters are shown in the table 1. The image of 4c+51.37 at TeV energies by SHALON is presented at Fig. 2. The 100 MeV - 100 GeV γ-ray emission from 1739+522 was detected with Fermi LAT with 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 index \(\Gamma = 2.5 \pm 0.04\) (refs. in [1])

B2 0242+43 and B2 0743+25 \((z > 2)\)

It was shown in [7] at \(E \sim 10\)th GeV - TeV the γ-ray spectra of high-redshift sources begin to be attenuated by the still poorly known EBL photon field due to the \(\gamma + \gamma \rightarrow e^+e^-\) process. So, to estimate the cosmic γ-ray horizon two very high-redshifted sources from first and second Fermi LAT AGN catalogue are observed by SHALON in autumn-winter period of 2014 year.

B2 0242+43, at \(z = 2.243\), is the radio-loud active galaxy classified as a FSRQ. B2 0242+43 was observed by SHALON in the 2014 y. for a total of 14 hours. An excess corresponding to a 4.8σ [6] was determined with integral flux shown in table 1 also the unexpected high-level
flux increase up to the twice over the detected in average was observed at end of November. The surroundings of B2 0242+43 of 20' size in radius doesn’t contain any candidate for the TeV-emission as some powerful over the wide wavelength range variable sources that could be the sources of the flares detected in the observation period. The list of nearby sources includes two weak radio-objects and one X-ray source didn’t confirmed after their detection [8, 9].

B2 0743+25, at z = 2.979, is the FSRQ from Fermi LAT catalogues. B2 0743+25 was observed by SHALON in the period of 2014 for 10 hours. The integral $\gamma$-ray flux (see table 1) was determined with the significance of 3.9$\sigma$. The analysis of the region of 20’ size around B2 0743+25 was performed in order to find close powerful sources that could be resolved as this distant quasar [9, 10]. Among the nearby sources no candidate for the TeV-emission were found as four of quasar objects which were not recognized in radio, X-ray or MeV-GeV energies [10].

Further observations and investigations of B2 0242+43, B2 0743+25 and area around these objects are undertaken to establish the reliable source of TeV $\gamma$-ray emission.

Conclusion
The results presented here is a brief summary of the results on long-term observations of AGNi from the SHALON telescope such as spectral energy distributions and images. A number of variability periods in different wavelengths including VHE $\gamma$-rays were found. All data from SHALON observations are compared with ones from experiments at high and very high energies.

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