SHALON observations of
Active Galactic Nuclei
at red shift from $z=0.0179$ to $z=1.375$

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Very high energy gamma-ray emission of metagalactic sources

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. We present results of long term observations of FSRQ: among them are known object 3c454.3 (z=0.859), high-red shifted quasar 1739+522 (4c+51.37) (z=1.375) and 4c+31.63 (z=0.295), 4c+55.17 (z=0.896) as well as BL Lac type object OJ 287 (z=0.306) which was recently detected by SHALON Cherenkov telescopic system. Also we present the observation results of known BL Lacs Mkn 421 (z=0.031), Mkn 501 (z=0.034) and Mkn 180 (z=0.046). A number of variability periods in different wavelengths including VHE gamma rays were found.
SHALON sky-map catalogue of $\gamma$-quantum sources 800 GeV – 100 TeV (2013)
A ROSAT HRI image of the region around the galaxy NGC 1275 at the centre of the Perseus galaxy cluster. The contour lines show the radio structure as given by VLA observations. The maxima of the X-ray and radio emission coincide with the active nucleus of NGC 1275. In contrast, the X-ray emission disappears almost completely in the vicinity of the radio lobes.

A Chandra X-ray image of NGC 1275 at the centre of the Perseus galaxy cluster. The contour lines show the TeV structure by SHALON observations.
In 1996 year a new metagalactic source are detected by SHALON in TeV energies. This object was identified with Seyfert galaxy NGC 1275 (z=0.0179). The γ-ray emission from the position of NGC 1275 was detected above 800 GeV with a statistical significance of 31.4σ (for 271.2 hours). The integral γ-ray flux for this source is found to be \((0.78\pm0.05)\times10^{-12}\text{ cm}^{-2}\text{s}^{-1}\) at energies of > 800 GeV. The energy spectrum of NGC 1275 at 0.8 to 20 TeV can be approximated by the power law \(F(>E_0) \propto E^{k_γ}\), with \(k_γ = -2.24 \pm 0.09\). The variations of the γ-ray flux on the year scale are no more than 20% of average value.

Overall spectral energy distribution of NGC 1275. The TeV energy spectrum of NGC 1275 from SHALON, 15 year observations in comparison with other experiments: Fermi LAT’09-11, MAGIC’10-11 and upper limits: EGRET’95, Whipple’06, Veritas’09 and models.

The available high and very high energy data for NGC 1275 are well fitted in CM model with three components (Colafrancesco S et al. 2010), in which the most energetic and smaller blob produces a synchrotron self-Compton emission observed at γ-ray energies red curve).

The Seyfert galaxy NGC 1275 has been also observed with Tibet Array (>5TeV) and Veritas telescope at energies about 300 GeV at 2009. The radio-galaxy NGC 1275 has been recently detected by Fermi as a source of high-energy γ-rays. NGC 1275 was recently detected at energies >100 GeV with MAGIC in observations of 2010 – 2011 yy.
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. Presently this source is systematic studied by different experiments: VERITAS, SHALON, TACTIC, HESS, MAGIC. Mkn 421 is being intensively studied since 1994 by SHALON. As is seen from figure the SHALON results for this known $\gamma$-source are consistent with the data by best world telescopes. An image of $\gamma$-ray emission from Mkn 421 is also shown. The integral averaged for the period 1994 to 2011 $\gamma$-ray flux above 0.8 TeV 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 $F(>E_\gamma) \propto E_k^{k_\gamma}$, with $k_\gamma = -1.87 \pm 0.11$. 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 ($60^\circ - 67^\circ$), MAGIC ($45^\circ$).
The detection of Mkn 421 as metagalactic VHE γ-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. In contrast to Mkn 421, EGRET had not detected this source, as a significant source of γ-rays. So Mkn 501 was the first object to be discovered by as γ-ray source from the ground. An image of γ-ray emission from Mkn 501 by SHALON telescope is also shown. The integral average γ-ray flux above 0.8 TeV was estimated as $(0.86 ± 0.06) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$ and the power index of the integral spectrum is $k_\gamma = -1.87 ± 0.13$. The significant increase of Mkn 501 flux was detected in 1997 with the VHE ground telescopes all over the world. The integral γ-ray flux in 1997 and 2006 by by SHALON telescope was estimated as $(1.21 ± 0.13) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$ and $(2.05 ± 0.23) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$, respectively that is comparable with flux of powerful galactic source Crab Nebula by SHALON.

The 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 $(3.41 ± 0.70) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$. This increase is correlated with the flaring activity at lower energy range in observations of Fermi LAT and VERITAS, MAGIC, Whipple.
Mkn 180 is a known extragalactic source of high frequency peaked BL Lac type \((z = 0.045)\). As the VHE \(\gamma\)-ray emitting AGNi 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].

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, 2011 and 2012, for a total of 71.0 hours, at zenith angles ranging from 25° to 34°. After the standard analysis, a clear excess corresponding to a 14.5\(\sigma\) [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

\[
F(E > 0.8\text{TeV}) = (0.65 \pm 0.09) \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}.
\]
3c 382 has been detected by SHALON at TeV energies (in observations of 2009 - 2012 years) with a statistical significance of $7.8\sigma$.

The integral $\gamma$-ray flux above 0.8 TeV was estimated as $(0.95\pm0.20)\times10^{-12}$ cm$^{-2}$s$^{-1}$. The energy spectrum of $\gamma$-rays in the observed energy region from 800 GeV is described by the power law with the index $k_\gamma = -1.08\pm0.11$.

The observations of 3c 382 at the high energies with FermiLAT have gave only the upper limit in the range 0.1-100 GeV.
4C+31.63, at redshift $z = 0.295$, is the example of blazar class of objects.

4C+31.63 was observed by SHALON in the 2012 at the clear moonless nights, for a total of 13.5 hours, at zenith angles ranging from 12° to 35° (Li&Ma). After the standard analysis, a clear excess corresponding to a $5.6\sigma$ was determined.

$$I_{4c+31.63}(>0.8\text{TeV}) = (0.72 \pm 0.22) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$$

In observations of 2012 year a new metagalactic source are detected by SHALON in TeV energies. This object was identified with FSRQ type source 4c+31.63, previously detected at high energies with Fermi LAT.

Spectral energy distribution of the gamma-ray emission from 4C+31.63 by SHALON (open triangles) in comparison with the experimental data at high energies by Fermi LAT (2011).
Spectral energy distribution [53] of the γ-ray emission from OJ 287 by SHALON in comparison with other experiment data EGRET [54], Fermi/LAT [55, 56], MAGIC [53] and with theoretical predictions from [55, 56] and also [53]. The open triangles at TeV energies are SHALON spectrum of OJ287; an upper limit at > 0.8 TeV corresponds to SHALON observations in 1999, 2000; the black triangles are the gamma-ray spectrum at the increased flux period of 2010. OJ 287 is the weakest extragalactic source observed by SHALON.

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 < 1.1×10^{-13} cm^{-2}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 6.9 σ [40] was determined. The observed integral flux is

\[ F(E > 0.8\text{TeV}) = (0.26 \pm 0.07) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}. \]

The flux increase over the detected average flux was found at 14,15 November and 4, 5 December 2010 with value of

\[ F(E > 0.8\text{TeV}) = (0.63 \pm 0.15) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}. \]

(statistical significance of 6.2 σ [40]) with the softer energy spectrum with a power law with the index -1.96±0.16.
3C 454.3, at redshift $z = 0.859$, is a well-known example of blazar class of objects.

Spectral energy distribution of the gamma-ray emission from 3C454.3 by SHALON (open triangles) in comparison with other experiment data, Fermi/LAT (2009 - 2011); upper limits by MAGIC (2010).

In 1998 year a new metagalactic source are detected by SHALON in TeV energies. This object was identified with FSRQ type source 3C454.3.

3C 454.3 was observed by SHALON in the period from 1998 to 2012, for a total of 61 hours, at zenith angles ranging from $18^\circ$ to $35^\circ$. After the standard analysis, a clear excess corresponding to a $12.2\sigma$ was determined.

$I_{3c454.3(>0.8\text{TeV})} = (0.43\pm0.07) \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$
Spectral energy distribution of the gamma-ray emission from 4C+55.17 by SHALON (open triangles) in comparison with the experiment data by EGRET, Fermi LAT (2011).

In 2012 year a new metagalactic source are detected by SHALON in TeV energies. This object was identified with FSRQ type source 4c+55.17, previously detected at high energies with EGRET and Fermi LAT.

4C+55.17, at redshift $z = 0.896$, is the radio-loud active galaxy classified as a FSRQ.

4C+55.17 was observed by SHALON in the period from 2012 and 2013 at the clear moonless nights, for a total of 23 hours, at zenith angles ranging from $13^\circ$ to $35^\circ$ (Li & Ma). After the standard analysis, a clear excess corresponding to a $7.8\sigma$ was determined.

$I_{4c+55.17}(>0.8\text{TeV}) = (0.93 \pm 0.23) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$
1739+522, at redshift $z = 1.375$, is a powerful example of blazar class of objects.

1739+522 was observed by SHALON in the period from 1999 to 2012, at the clear moonless nights, for a total of 114 hours, at zenith angles ranging from 14° to 35° (Li&Ma). After the standard analysis, a clear excess corresponding to a 14.2σ was determined.

$$I_{1739+522}(>0.8\text{TeV}) = (0.49 \pm 0.05) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$$

Spectral energy distribution of the gamma-ray emission from 1739+522 by SHALON (open triangles) in comparison with other experiment data Fermi/LAT (2009 - 2011).

In 1999 year a new metagalactic source are detected by SHALON in TeV energies. This object was identified with FSRQ type source 1739+522 (4c+51.37).
References