TeV gamma-rays from the region of Perseus Cluster

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Abstract. The results of 20-year observations of the Perseus cluster centering on the NGC 1275 including IC 310 radio galaxy and extragalactic supernova SN 2006gy at energies 800 GeV - 45 TeV by the SHALON telescope are presented. It was found, that the TeV γ-ray emission at energies > 800 GeV has an extended structure with a distinct core centered at the NGC 1275 nucleus and well correlates with the photon emission regions viewed in X-rays by Chandra and anti-correlates with radio-structures. Also, the variations of TeV γ-ray flux both at year- and day- scales were found. The obtained data indicate that the part of TeV γ-ray emission is generated by relativistic jets in the nucleus of NGC 1275. Whereas, the presence of an extended structure around NGC 1275 and the slow rise of the γ-ray flux is the 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.

1. Introduction
The Perseus galaxy cluster with the central galaxy NGC 1275 has long been considered as an ideal candidate both for studying the physics of relativistic jets from Active Galactic Nuclei and for revealing the feedback role of the central galaxy. Here, we present the results of twenty-year investigations of the NGC 1275 and its surroundings, including IC 310 radio galaxy and extragalactic supernova SN 2006gy, obtained at 0.8 - 50 TeV with SHALON telescope [1, 2, 3, 4].

The SHALON instrument consists of two imaging atmospheric Cherenkov telescopes located in Tien-Shan mountains at an altitude of 3340 m above the sea level [1, 2, 3, 4]. It is designed for observations of γ-ray sources in the energy range from 800 GeV to 100 TeV. Each of the telescopes has a composite mirror with an area of 11.2 m². The detector has the largest field of view > 8° among similar instruments. It allows the background from charged cosmic-ray particles and the atmospheric transparency to be continuously monitored simultaneously with the observations of γ-ray sources. It gives the reduction of systematic uncertainties, related to the changes in atmospheric parameters, below 10% and increases the rejection factor of background events separation from γ-rays. [1, 5]. The accuracy of the determination of the coordinates of the γ-ray shower source in SHALON experiment is ~ 0.07°, and it is improved by a factor of 10 after additional processing (see [3, 5]) using deconvolution algorithm [6]. The SHALON method of selection of γ-ray showers from the background cosmic-ray showers allows the rejection of 99.93% of the background events. The minimum detectable integral flux of γ-rays at 1 TeV is 2.1 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}. In the energy range from 1 - 50 TeV the minimum detectable flux falls to the value of 6 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} [1, 2]. The SHALON experiment has been in operation since 1992 providing the long-term observations of many different types of sources that are of interest for many areas of astroparticle physics.
Figure 1. left to right: The image of NGC 1275 by SHALON in 0.8 - 45 TeV γ-rays (grey scale); the red contours indicate the image of NGC 1275 in X-ray (1.5–3.5 keV) by Chandra [9] the black contours are the radio structures by VLA (332 MHz) [10]; Spectral energy distribution of the γ-ray emission from NGC 1275 by SHALON (△ and ▲) in comparison with experimental data and models; Light curve for NGC1275. The fluxes are presented in arbitrary units: for X-ray data is in the units of $7 \times 10^{-12}$ erg cm$^{-2}$s$^{-1}$; High energy year fluxes from Fermi LAT, data from COS-B and EGRET upper limits are in $1.67 \times 10^{-7}$ cm$^{-2}$s$^{-1}$; Very high energy year integral fluxes from SHALON observations (red triangles) are in the units of $7 \times 10^{-13}$ cm$^{-2}$s$^{-1}$.

2. NGC 1275 at very high energies

NGC 1275 is a powerful source of radio and X-ray emission, surrounded by extended filamentary structures historically aroused great interest owing to both its position at the center of the Perseus cluster and its possible "feedback" role [7] which revealed with X-ray detection of hot gas shells and cavities that spatially coincide with the radio structures (Fig. 1) extending from the central, active part of the AGN.

The long-term studies of NGC 1275 and its surroundings in the SHALON experiment were started at the 1996 year and has been intensively studied since then [2, 3]. SHALON observations yield the detection of very high energy γ-ray emission from NGC 1275 [1, 2, 3, 4]. The 289.8 hours of moonless observations were collected in the different years from 1996 to 2016. Gamma-ray emission from NGC 1275 was detected by SHALON at energies above 800 GeV at the 33.7σ determined according to Li&Ma [8] with the average integral flux $(7.8 \pm 0.5) \times 10^{-13}$ cm$^{-2}$ s$^{-1}$.

The γ-ray energy spectrum in the observed energy range 800 GeV - 45 TeV is well described by:

$$dF/dE = (6.9 \pm 0.09) \times 10^{-13} \times E^{-2.61 \pm 0.16} \times \exp(-E/28 \pm 9 \text{ TeV}) \text{ cm}^{-2} \text{ sec}^{-1} \text{ TeV}^{-1}$$

with $\chi^2/DoF = 0.94$ (with DoF = 9). (see Fig. 1, △).

In order to find the mechanisms of generation of very high energy emission in the source the correlation of the emission regions in the wide energy range including radio, X-rays and TeV γ-rays should be established.

In Fig. 1 an TeV emission map of NGC 1275 by SHALON is overlaid with ones in X-rays and radio. In X-rays and TeV γ-rays, both, the images of Perseus cluster center demonstrate a circular symmetric structure with the distinct emission from the position of NGC 1275 core. The X-ray surface brightness maxima around the core are coincides with maxima of TeV flux to the east and west of the nucleus of NGC 1275. The clearly seen minima in the X-rays and in the TeV γ-rays to the north and south from NGC 1275 coincides with outer radio lobes (black lines) which are further surrounded with bright X-ray arc regions. The interpretation is that the intense emission from these rims comes from the shells surrounding the radio lobes [9].

To analyze the emission originated at NGC 1275 core, we extracted the component corresponding to the region of NGC 1275 of 32" in size. Gamma-ray emission associated with the central region of NGC 1275 was detected at energies above 0.8 TeV at a 13.5σ [8] with an average integral flux $(3.26 \pm 0.30) \times 10^{-13}$ cm$^{-2}$ s$^{-1}$. Fig. 1 shows the spectral energy distributions of NGC 1275 (△) and its central region (▲) by SHALON (1996 - 2012, 2015, 2016) [3] with the Fermi LAT (2009 - 2011) [11]; 8 year catalogue [12] and other experimental data (see refs in [3]).

The data about TeV γ-rays from NGC 1275 have been collected in SHALON experiment.
since 1996, and the intensity of NGC 1275 was found to be variable in the very high energies (see Fig.1). The SHALON telescope has detected four short-time (within five days) increases of the TeV $\gamma$-ray flux [3] in the entire time of observations of NGC 1275, and a light curve shows a slow TeV $\gamma$-ray flux increase after the 2001 year. The archive light curves at radio [13], X-ray data [14, 15] and Fermi LAT year fluxes at $E > 100$ MeV [16] are presented in Fig. 1 together with NGC 1275 $\gamma$-ray fluxes by SHALON. The red triangles indicate the integral fluxes from the SHALON data averaged over each year of observations. In case of the flare localization, two points are presented: open triangles are the fluxes averaged over the observation year, and red ones are the flux without the flaring period.

3. SN 2006gy
The flux increase was detected from the region NGC 1275 in autumn 2006. The detailed analysis yielded the detection of the new object identified with the extragalactic supernova SN 2006gy that is about 0.46° away from NGC 1275 (see details in [17]). Observations were done in Sep.- Dec. of 2006 and then during the winter of 2007. No flux increase was found in Sep. observations. In the flare, detected at Oct. 22, the flux increased 6 times from the NGC 1275 average flux and stayed on this level all Oct. moonless period. The $\gamma$-ray flux for SN 2006gy is $I(> 0.8\text{TeV}) = (3.71 \pm 0.65) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}$. Follow-up observations in Nov., Dec. period shown that the flux of SN 2006gy had dropped to a level of $(0.69 \pm 0.17) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}$. The results of 2007 observations revealed no TeV $\gamma$-ray emission from the region of SN 2006gy.

4. IC 310
The radio galaxy IC 310 is located in the Perseus Cluster at 0.37° from its central galaxy, NGC 1275. IC 310 is known as a head-tail radio galaxy which radio morphology consists of a bright "head", located at the core of the galaxy, and "tail" of a radio lobe pointing away from the center of the cluster (Fig. 2, left). In X-rays IC 310 looks as a point source at the position of the radio "head" [18] and its luminosity suggests that this galaxy contains an active nucleus. IC 310 has been systematically observed by SHALON telescope in 1996 - 2016 years for a total of 170 hours and it was detected at $> 0.8$ TeV at level of 19.8$\sigma$ [8] with the average integral flux $(0.89 \pm 0.09) \times 10^{-13} \text{cm}^{-2}\text{s}^{-1}$ (see [17] for details). The differential spectrum of $\gamma$-rays from IC 310 in the 0.8 - 40 TeV energy range is well fitted with a hard power law with an exponential cutoff $dF/dE = (0.83 \pm 0.09) \times 10^{-12} \times E^{-1.56 \pm 0.16} \times \exp(-E/11.5 \pm 3 \text{ TeV}) \text{ TeV}^{-1} \text{ cm}^{-2}\text{s}^{-1}$ (see Fig. 2, right). The variations of TeV $\gamma$-ray flux on the day-scale were detected in the periods of SHALON observations at Nov. 2003, Nov. - Dec. 2004, Oct. 2005, Oct. 2007 and Nov. 2008.

IC 310 image in TeV $\gamma$-rays by SHALON is overlaid in Fig. 2 with radio emission map from WENSS [19] and X-ray image from ROSAT [18]. The main TeV $\gamma$-ray emission region of IC 310 corresponds to the galaxy core visible in X-rays and coincides with the "head" of the radio structure. The detection of TeV $\gamma$-rays from the core of IC 310 galaxy and the day scale flux variability point out the origin of this emission in the relativistic outflow from the active nucleus.
5. Conclusion

The results of twenty-year-long observations of the Perseus cluster centering on NGC 1275 at energies 800 GeV - 45 TeV by the SHALON are presented. The characteristics of IC 310 radio galaxy and extragalactic supernova SN 2006gy accompanying the investigation of NGC 1275 are obtained. The emission regions of TeV $\gamma$-rays observed by SHALON from NGC 1275 well correlate with ones viewed in X-rays by Chandra and anti-correlate with radio-structures. This TeV $\gamma$-ray emission recorded by SHALON has an extended structure with a distinct core centered at the source’s position. The emission component corresponding to the core of NGC 1275 was fully identified. Also, the variations of TeV $\gamma$-ray flux both at year- and day- scales were found. The data obtained at very high energies indicate that a part of this emission is generated by relativistic jets in the nucleus of NGC 1275. But, the presence of an extended structure around NGC 1275 and the slow rise of the $\gamma$-ray flux 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.

6. References

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