Long-term studies of the Cygnus Region and its objects: Cyg X-3 and γCygni SNR

V G Sinitsyna and V Y Sinitsyna
P.N. Lebedev Physical Institute, Russian Academy of Science, Leninsky prospect 53, Moscow, 119991, Russia
E-mail: sinits@sci.lebedev.ru

Abstract. The long-term studies of the Cygnus Region at energies 800 GeV - 100 TeV by SHALON telescope are presented in this paper. The results of twenty-year-long observations of the Cyg X-3 binary at energies 800 GeV - 85 TeV, detected by SHALON in 1995 are presented with images and integral spectra. The 4.8 hour orbital modulation of TeV γ-ray emission of Cyg X-3 was found in SHALON data. A number of high activity period of Cyg X-3 were detected at energies > 800 GeV during the all observation time. The correlation soft X-ray and TeV energy γ-ray fluxes is traced. Additional to Cyg X-3 study data on the TeV sources of Cygnus Region, namely γCygni SNR was obtained with SHALON.

Introduction
SHALON is a high-altitude imaging atmospheric Cherenkov telescope for the detection of very high energy (from 800 GeV to 100 TeV) γ-rays. The γ-astronomical researches are carrying out with SHALON telescope since 1992. During the period 1992 - 2015 SHALON has been used for observations of different galactic and extragalactic objects (see these Proceedings and [1]).

The SHALON observations have yielded the results on different Galactic sources, such as supernova remnants (SNR) of different types and ages, binaries, etc. Among them are: the shell-type SNRs Tycho’s SNR, Cas A, IC 443, γCygni SNR and the plerions Crab, 3C58, Geminga (probably plerion) (see these Proceedings and [1]). For each of sources the observation results are presented with spectral energy distribution by SHALON in comparison with other experiment data and images by SHALON in comparison with data from X-ray and radio-data.

Cygnus Region contains a number of sources of radio and X-ray emission and some of them were detected at high energies. The most powerful have been also supposed to be a GeV-TeV γ-ray emitters. Among them are Cyg X-3 massive binary system (Figs. 1, 2, 3, 4) and the nearby object - γCygni SNR (Fig. 5).

Cygnus X-3
Binary system Cyg X-3 is one of the brightest Galactic X-ray sources, displaying high and low states and rapid variability in X-rays. In addition to being a powerful X-ray source, Cyg X-3 is seen in the infrared and is a strong and variable radio source. It is also the strongest radio source among X-ray binaries and shows both huge radio outbursts and relativistic jets. The radio-activity is closely linked with the X-ray emission and the different X-ray states [2, 3]. Cygnus X-3 is a high mass X-ray binary and microquasar, with a compact object, which is either
Figure 1. Spectral energy distribution of the γ-ray emission from Cyg X-3. △ represent the data from the SHALON Cherenkov telescope. Black points are the archival data from [12].

a neutron star or may be a black hole, and a companion object, which is a Wolf-Rayet star. But Cygnus X-3 shows a short orbital period of 4.8 hours, typical of the low mass binaries. It has been inferred from the modulation of both the X-ray (Fig. 2, right) and infrared emissions. The nature of the compact object is still uncertain. Based on the detections of ultra high energy γ-rays [4, 5], Cygnus X-3 has been proposed to be one of the most powerful sources of charged cosmic ray particles in the Galaxy (Fig. 1).

Cyg X-3 has been regularly observed since a 1995 with SHALON telescope [6] during the 297.6 hours in total. The observations were performed using the standard (for SHALON) technique of obtaining information about the cosmic-ray background and γ-ray-initiated showers in the same observing session. The SHALON method of selecting γ-ray showers from background cosmic-ray showers allow to reject 99.92% of the background showers [1]. The γ-ray source associated with the Cyg X-3 was detected above 800 GeV with a statistical significance [7] of 41.2σ with a average integral γ-ray flux above 800 GeV \( F(E_0 > 800 \text{GeV}) = (6.8 \pm 0.4) \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \) [8, 9, 10, 11]. The energy spectrum of Cyg X-3 at 800 GeV - 85 TeV can be approximated by the power law \( F(E_0) \propto E^{-1.25 \pm 0.10} \).

To securely identify the detected emission with Cyg X-3, a timing analysis to search for the 4.8-hour orbital period of Cyg X-3 was performed (see. Fig. 2, left). We compared the SHALON

Figure 2. left: SHALON and Fermi LAT [13] light curve of Cyg X-3 folded on the orbital period; The dashed line shows the level of averaged integral TeV γ-ray flux by SHALON; right: X-ray light curves folded on the orbital period (see text).
Figure 3. The light curves of Cyg X-3 in wide energy range.

Figure 4. from left to right: The images of Cyg X-3 in flaring periods of 2006, 2009 and 2011 years by SHALON.

light curve folded on the orbital period to the folded > 100 MeV light curve of Cyg X-3 from Fermi LAT together with X-ray data by RXTE/ASM (212 keV), RXTE/PCA (3−15 keV), JEM-X (6−15 keV) and ISGRI (20−40 keV), BATSE (20−100 keV). The folded X-ray, GeV and TeV light curves have the similar asymmetric shape with a slow rise followed by a faster decay. Also, the SHALON and Fermi LAT light curves shifted on about 0.15 in phase and its shape have the local maxima. But, phase of SHALON minimum flux is close the phase of minimum of soft X-ray count rate, shifted by 0.3 in phase.

Extreme variability in different wavelengths including VHE $\gamma$-rays is the remarkable feature of Cyg X-3 (Fig. 3). A number of high activity period of Cyg X-3 were detected with SHALON at energies > 800 GeV during the all period of observation since 1995 year. For example, the images of Cyg X-3 in flaring periods of 2006, 2009 and 2011 years are shown in comparison (Fig. 4). The last two significant increase of very high energy $\gamma$-ray flux have detected in May.
2009 and October 2011, which is correlated with flaring activity at lower energy range of soft X-ray and/or at observations of Fermi LAT [13]. Also, the high TeV γ-ray flux was detected by SHALON during the X-ray flares of the end September and mid of October 2014 observed by MAXI [14]. Earlier, in 1997 and 2003 a comparable increase of the flux over the average value was also observed.

During the period of observations of Cyg X-3 with SHALON 6 significant flux increases were detected at energies above 0.8 TeV. To reveal possible correlation of periods of activity in the TeV energy range with the flares at the low energies the light curves of Swift/BAT (15 - 50keV) $^1$, MAXI (2 - 4 keV) $^1$ [14], RXTE/ASM (3 - 5 keV) $^2$, the fluxes at radio-ranges from RATAN (11.2GHz)[see [15]], AMI-LA (15 GHz) $^3$ and TeV fluxes from SHALON observations were analyzed (Fig. 3). The significant anticorrelation of the fluxes at TeV and hard X-rays and the correlation of very high energy flux and soft X-ray were found. It is note, that TeV flaring activities occur within the 4 - 5 days to strong radio flares (Fig. 3). Probably, it is linked with the powerful ejection from the regions are close to the centers blackhole. This ejection is accompanied with a relativistic shock where the relativistic electrons and magnetic field are generated effectively. Similar relation of TeV and soft X-ray fluxes were found in the 1997 observation period. But the flux increase of 2003 didn’t obey this scheme, it was in the quite period in the soft X-rays. In general, the correlation soft X-ray and TeV energy γ-ray fluxes is traced since 1996 year.

$^\gamma$Cygni SNR

Supernova remnant G78.2+2.1, known as $\gamma$Cygni SNR is a shell-type supernova remnant at a distance of $\sim 1 - 2$ kpc and with the observed diameter of $\sim 1^\circ$. The shell-like features are known in radio- and X-ray energy regions. $\gamma$Cygni SNR is older then Cas A and Tycho’s SNR, its age is estimated as $\sim 5000 - 7000$ yr. [16, 17] and its supposed to be in an early phase of adiabatic expansion. The observations of different age supernova remnants can help to reveal the mechanisms of very high energy cosmic ray acceleration in the SNRs.

During the observations of Cyg X-3 the SHALON field of view contains $\gamma$Cygni SNR as it located in Cygnus Region at $\sim 2^\circ$ SW from Cyg X-3. So due to the large telescopic field of view (≥ 8°) the observations of Cyg X-3 is naturally followed by the tracing of $\gamma$Cygni SNR.

$\gamma$Cygni SNR as a source accompanying to Cyg X-3 is systematically studied with SHALON telescope since 1995 year up to now. The $\gamma$-ray source associated with the $\gamma$Cygni SNR was detected by SHALON [18] above 800 GeV with a statistical significance [7] of 14σ. The average integral $\gamma$-flux above 0.8 TeV: $I_{\gamma\text{CygniSNR}} = (1.27 \pm 0.11) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$ (see [18] for details).

$^1$ http://swift.gsfc.nasa.gov/results/transients/CygX-3/
$^2$ http://xte.mit.edu/asmle/srsrc/cygx3.html
$^3$ http://www.mrao.cam.ac.uk/~guy/cx3/
The energy spectrum of $\gamma$-rays in the observed energy region from 800 GeV to 50 TeV is well described by the power law with exponential cutoff, \( (1.12 \pm 0.11) \times 10^{-12} \times E_{\gamma}^{-0.93 \pm 0.09} \times \exp(-E_{\gamma}/20\text{TeV}) \) Fig. 5, left. The image of $\gamma$Cygni SNR at energies 0.8 - 50 TeV by SHALON is presented in Fig. 5. The analysis of TeV $\gamma$-ray arrival directions reveal two emission regions in $\gamma$Cygni SNR: the main at the South-East part of SNR shell and second one at North. The main contribution of energy flux gives the South-East region of SNR shell. Also, TeV $\gamma$-ray emission regions correlate with the North-West and South-East parts of the shell visible in the radio energies by CGPS (see these Proceedings). The VERJ2019+407 source was detected at 200 GeV by VERITAS [19, 20] correlated with the position of northern part of $\gamma$Cygni SNR shell. In Figure 5 the spectral energy distribution of the $\gamma$-ray emission from $\gamma$Cygni SNR by SHALON ($\triangle$) (1995 - 2015) [18] is presented in comparison with experiment data from EGRET [21, 22] (1995, 1996), AGILE [23] (2010), Fermi LAT [24] (2009 - 2011), VERITAS [19] (2013) (left triangle symbol at 200GeV is flux of VERJ2019+407 source by VERITAS [20] (2009)), MILAGRO [25] (2011) (Fig. 5, right).

Conclusion

Cygnus Region contains the number of powerful sources of radio and X-rays which are supposed as a potential TeV-emitting objects. The results of 20-year observations of the Cyg X-3 at energies 0.8 - 85 TeV, detected by the SHALON telescope in 1995 are presented. A number of high activity period of Cyg X-3 were detected with SHALON during the all period of observation. The significant increases of flux are correlated with flaring activity at lower energy range of X-ray and/or at observations of Fermi LAT. Also, long-term observations of the Cygnus region are revealed the $\gamma$-ray emission from the one of nearby object - $\gamma$Cygni SNR, placed at 2° from Cyg X-3. The results of $\gamma$Cygni SNR observation by SHALON are presented with spectral energy distribution, images and integral spectra at energies 0.8 - 50 TeV. The correlation of TeV $\gamma$-ray emission regions and the shell visible in the radio energies by CGPS is found.

References

[1] Sinitsyna V G and Sinitsyna V Yu 2011 Astron. Lett. 37(9) 621
[2] McCollough M L et al 1999 Astrophys. J. 517 951
[3] Trushkin S A et al 2007 Proc. of IAU Symposium No. 238, 2006 ed V Karas and G Matt p. 463
[4] Samorscki M and Stamm W 2007 Proc. of IAU Symposium No. 238, 2006 ed V Karas and G Matt p. 463
[5] Lloyd-Evans J et al 1983 Nature 305, 784
[6] Sinitsyna V G 1996 Nuovo Cim. 19C, 965
[7] Li T-P and Ma Y-Q 1983 Astrophys. J. 272 317
[8] Sinitsyna V G 2000 AIP 515 205, 293
[9] Sinitsyna V G et al 2005 Int. J. Mod. Phys. A 29 7023
[10] Sinitsyna V G 2006 Rad. Phys. and Chem. 75 880
[11] Sinitsyna V G et al 2009 J. Phys. Soc. Jpn., Suppl. A 78 92
[12] Cordova F A-D 1986 Los Alamos Science Spring 39
[13] Abdo A A et al 2009 Science 326 1512
[14] Matsuoka M et al 2009 PASJ 61 999
[15] Alekšić J et al 2010 Astrophys. J. 721 843
[16] Lozinskaya T A et al 2000 Astron. Lett. 26 77
[17] Uchiyama Y et al 2002 Astrophys. J. 571 866
[18] Sinitsyna V G and Sinitsyna V Y 2013 Bull. of the Lebedev Phys. Inst. 40(5) 113
[19] Aliu E et al 2013 Astrophys. J. 770 93
[20] Weinstein A ArXiv:0912.4492
[21] Thompson D J et al 1995 Astrophys. J. Suppl. 101 259
[22] Esposito J A et al 1986 Los Alamos Science Spring 39
[23] Chen A W et al 2011 Astron.& Astrophys. 525 A33+
[24] Lande J et al 2012 Astrophys. J. 756(1) 5
[25] Abdo A A et al 2011 Astrophys. J. 734 28