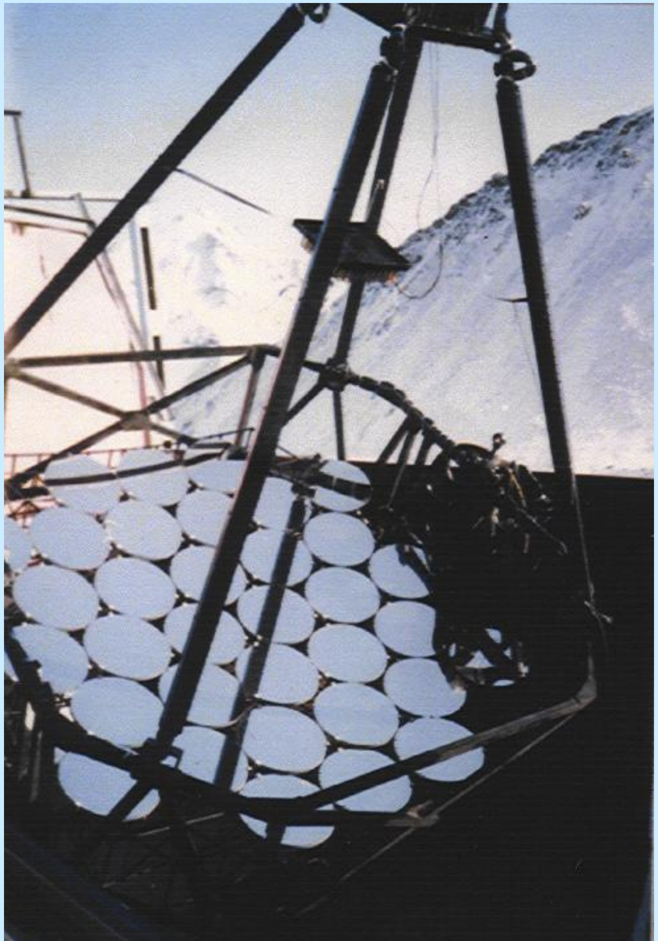


Long-term studies of the Cygnus Region and its objects

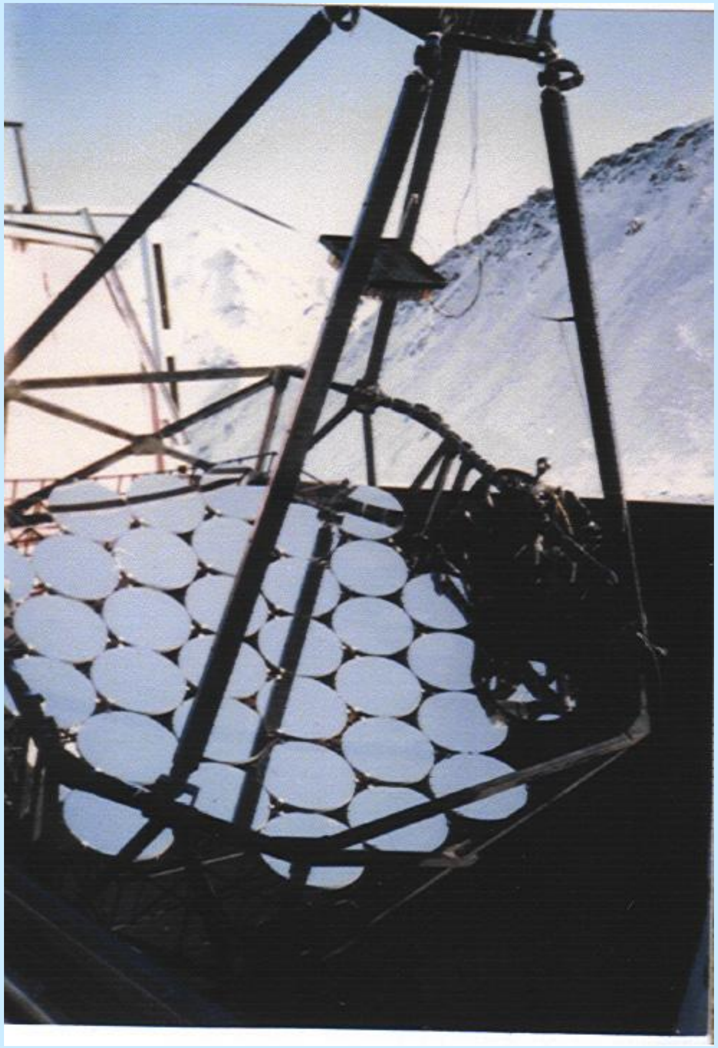
V.G. SINITSYNA and V.Y. SINITSYNA

P. N. Lebedev Physical Institute,
Leninsky prospect 53, Moscow, 119991 Russia


SHALON 2
SHALON 1

HIGH MOUNTAINOUS OBSERVATORY SHALON ALATOO

SHALON mirror Cherenkov telescope created at Lebedev Physical Institute and stated in 1991 - 1992



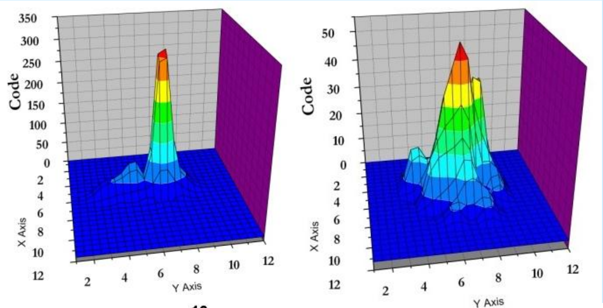
- Total area of spherical mirror — 11.2 m^2
- Radius of mirror curvature — 8.5 m
- The angle range of telescope turn:
  - azimuth — 0^o-360^o
  - zenith — 0^o-110^o
- The accurace of telescopic axis pointing — $\leq 0.1^o$
- The photomultiplier tube camera (12x12) — 144 elements
- Field of view > 8^o
- Weigth 6 ton
- altazimuth mounting

It is essential that our telescope has a large matrix with full angle >8^o that allows us to perform observations of the supposed astronomical source (ON data) and background from extensive air showers (EAS) induced by cosmic ray (OFF data) simultaneously. Thus, the OFF data are collecting for exactly the same atmospheric thickness, transparency and other experimental conditions as the ON data.

HIGH MOUNTAINOUS OBSERVATORY SHALON ALATOO

SHALON mirror Cherenkov telescope created at Lebedev Physical Institute and stated in 1991 - 1992

- Total area of spherical mirror — 11.2 m^2
- Radius of mirror curvature — 8.5 m
- The angle range of telescope turn:
  - azimuth — 0^o-360^o
  - zenith — 0^o-110^o
- The accuracy of telescopic axis pointing — $\leq 0.1^o$
- The photomultiplier tube camera (12x12) — 144 elements
- Field of view > 8^o
- Weigth 6 ton
- parallactic mount



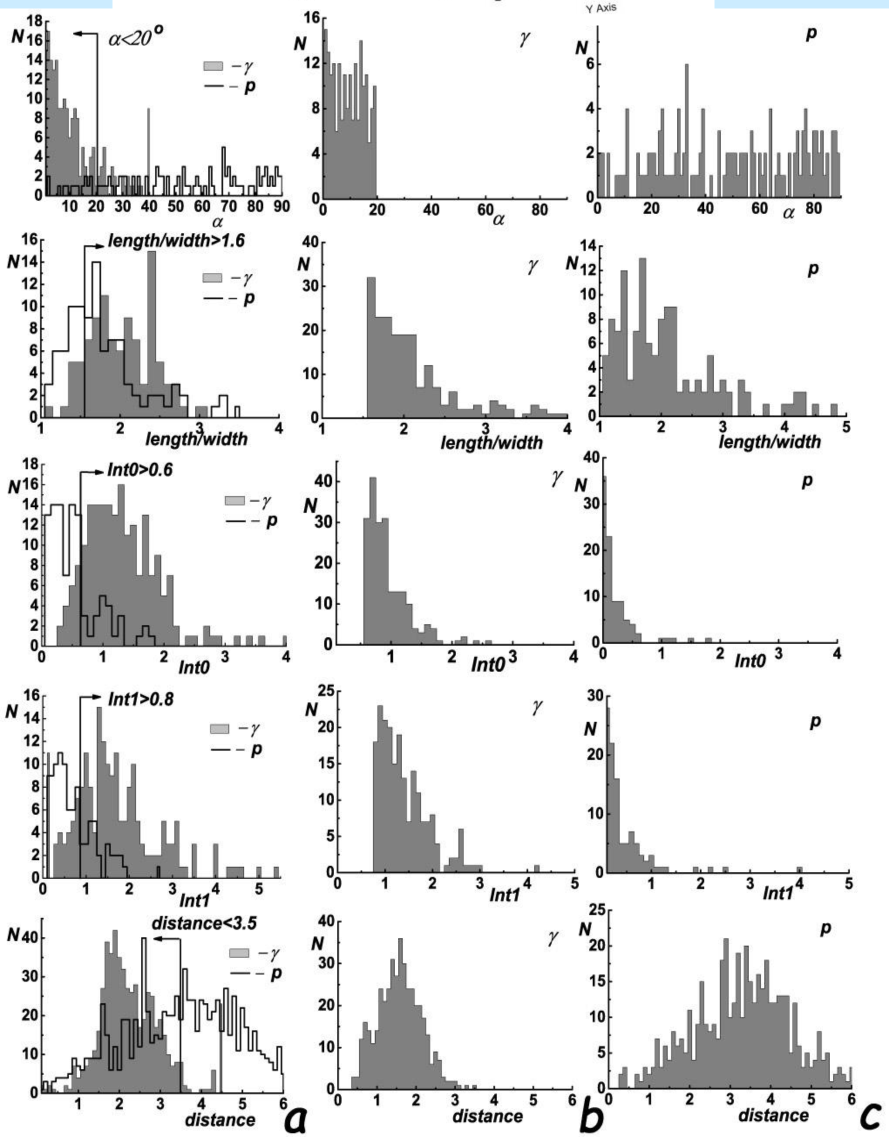
Criteria

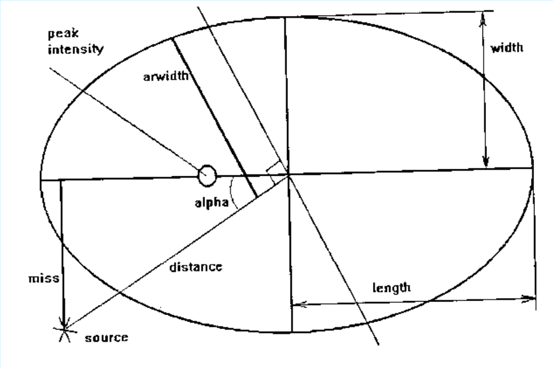
The selection of gamma-initiated showers from the background of proton showers is performed by applying the following criteria:

1) **$\alpha < 20^o$; 72% rejection**
2) **length/width > 1.6**; **49% rejection**
3) the ratio **INT0** of Cherenkov light intensity in pixel with maximum pulse amplitude to the light intensity in the eight surrounding pixels exceeds **> 0.6**; **92% rejection**
4) the ratio **INT1** of Cherenkov light intensity in pixel with maximum pulse amplitude to the light intensity in the in all the pixels except for the nine in the center of the matrix is exceeds **> 0.8**; **88% rejection**
5) **distance** is less than **3.5** pixels. **50% rejection**

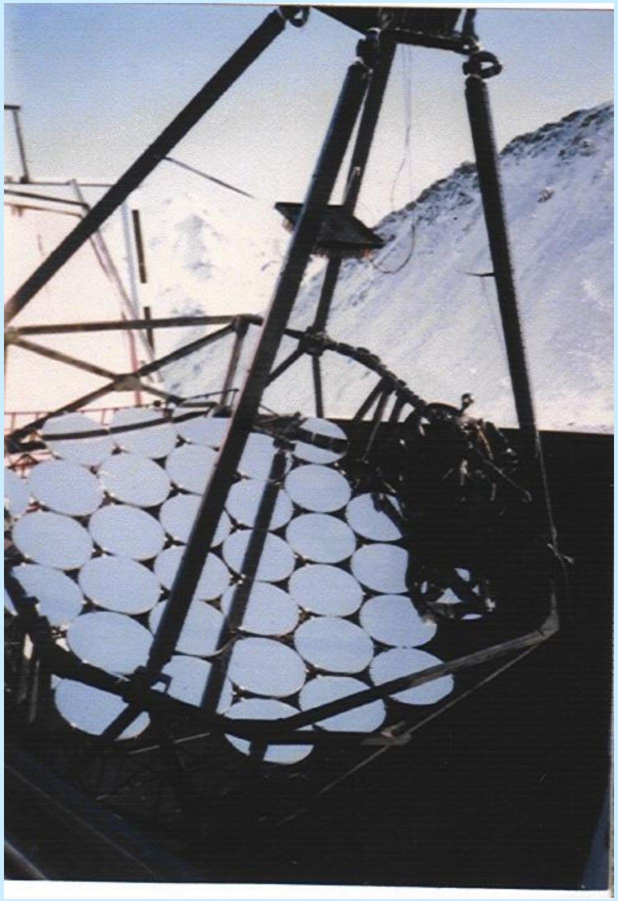
It is essential that our telescope has a large matrix with full angle $>8^o$ that allows us to perform observations of the supposed astronomical source (ON data) and background from extensive air showers (EAS) induced by cosmic ray (OFF data) simultaneously.

Using these criteria the background is rejected with 99.92% efficiency, whereas gamma's rejection is no more than 35% (that is taking into account) and the amount of background gamma-like events is less than 10%.





TeV GAMMA-RAY EMISSION from GALACTIC SOURCES

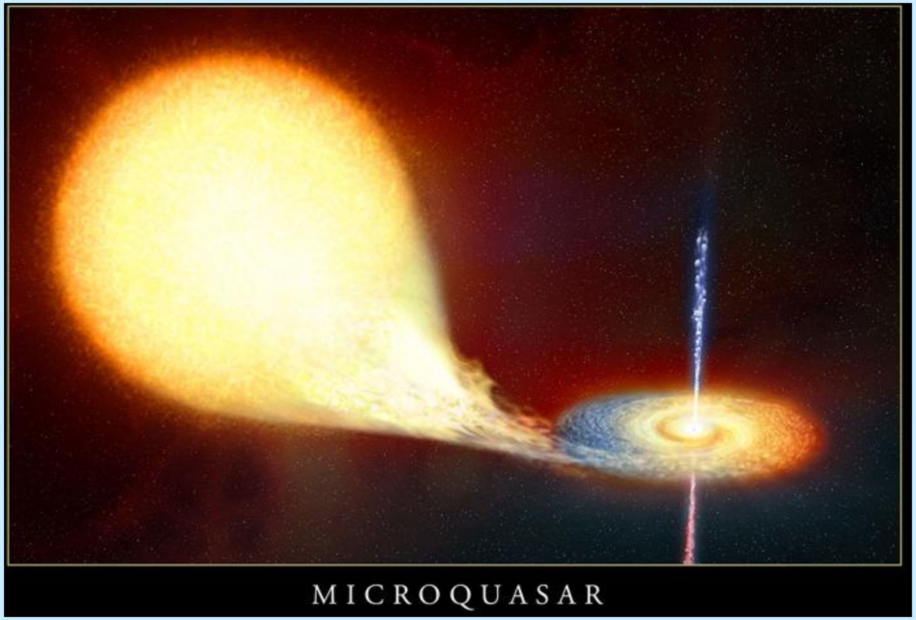


The gamma – astronomical researches are carrying out with SHALON since 1992. During the period 1992–2015 SHALON has been used for observations of metagalactic sources: Mkn 421, Mkn 501, Mkn 180, NGC 1275, SN2006gy, 3c454.3, 1739+522 and galactic sources: Crab Nebula, Cyg X-3, Tycho's SNR, Cas A, Geminga, 2129+47XR etc.

SHALON catalogue of galactic gamma -quantum sources

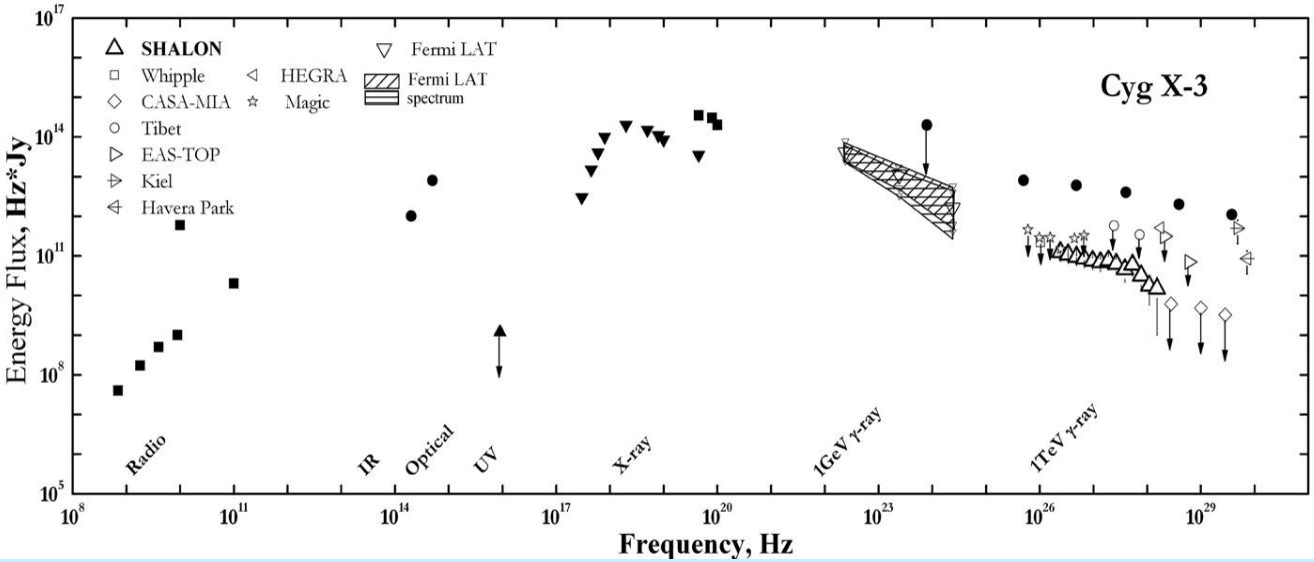
Source	Observable flux, $cm^{-2}s^{-1}$	Distance, kpc
Crab Nebula	$(2.12\pm0.12)\times10^{-12}$	2.0
Geminga	$(0.48\pm0.07)\times10^{-12}$	0.25
3c 58 (SN1181)	$(0.56\pm0.15)\times10^{-12}$	2.6 – 3.2
Tycho’s SNR	$(0.52\pm0.04)\times10^{-12}$	3.1 – 3.5
Cas A	$(0.64\pm0.10)\times10^{-12}$	3.1
IC 443	$(1.69\pm0.58)\times10^{-12}$	1.5
γCygni SNR	$(1.27\pm0.11)\times10^{-12}$	1.5
Cygnus X-3	$(0.68\pm0.04)\times10^{-12}$	10
2129+47XR	$(0.19\pm0.06)\times10^{-12}$	6.0
Her X-1	$(0.45\pm0.18)\times10^{-12}$	6.6
PSR1953+29	$(0.21\pm0.09)\times10^{-12}$	3.5 – 5.0
M57	$(0.30\pm0.17)\times10^{-12}$	0.7

Cygnus X-3

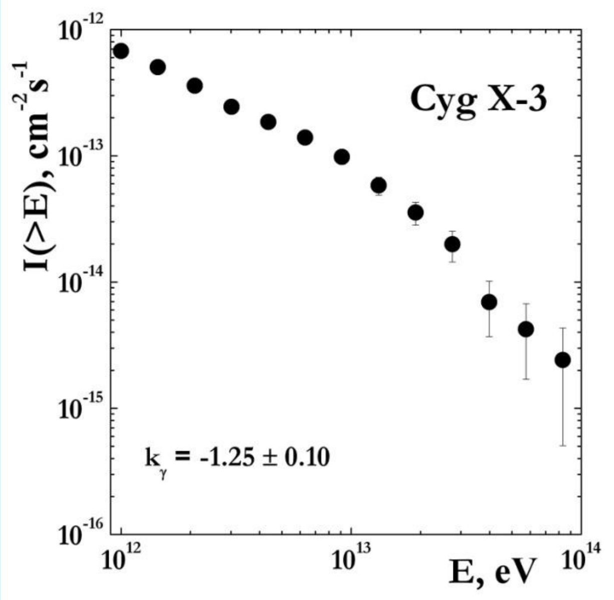


Cyg X-3 is peculiar X-ray binary system discovered about 50 years ago. The system has been observed throughout wide range of the electromagnetic spectrum. It is one of the brightest Galactic X-ray sources, displaying high and low states and rapid variability in X-rays. It is also the strongest radio source among X-ray binaries and shows both huge radio outbursts and relativistic jets. The radioactivity is closely linked with the X-ray emission and the different X-ray states. Based on the detections of ultra high energy gamma-rays, Cygnus X-3 has been proposed to be one of the most powerful sources of charged cosmic ray particles in the Galaxy.

The spectral energy distribution of Cyg X-3. Black points are the archival data from Cordova, (1986). The high level points in radio and X-ray bands correspond to radio-frequency activity and increased x-ray activity of the source. TeV range is represented with integral spectrum by SHALON (open triangles) in comparison with other experiments: TIBET, HEGRA, EAS-TOP, Whipple, CASA-MIA, Kiel, Havera Park



Cygnus X-3

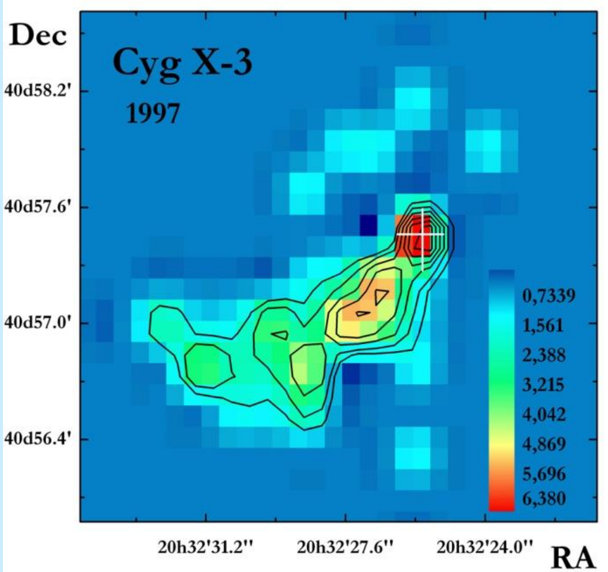


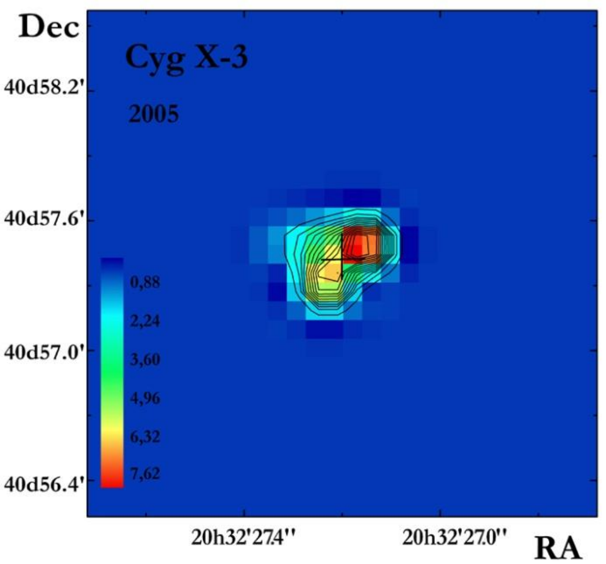
Cyg X-3 has been regularly observed since a 1995 with SHALON telescope during the 283.6 hours in total. All observations were made with the standard procedure of SHALON experiment during moonless nights with zenith angles from 4 to 35 degree. The gamma-ray source associated with the Cyg X-3 was detected above 800 GeV with a statistical significance of **35.3σ** Li&Ma with a γ-ray flux above 800 GeV :

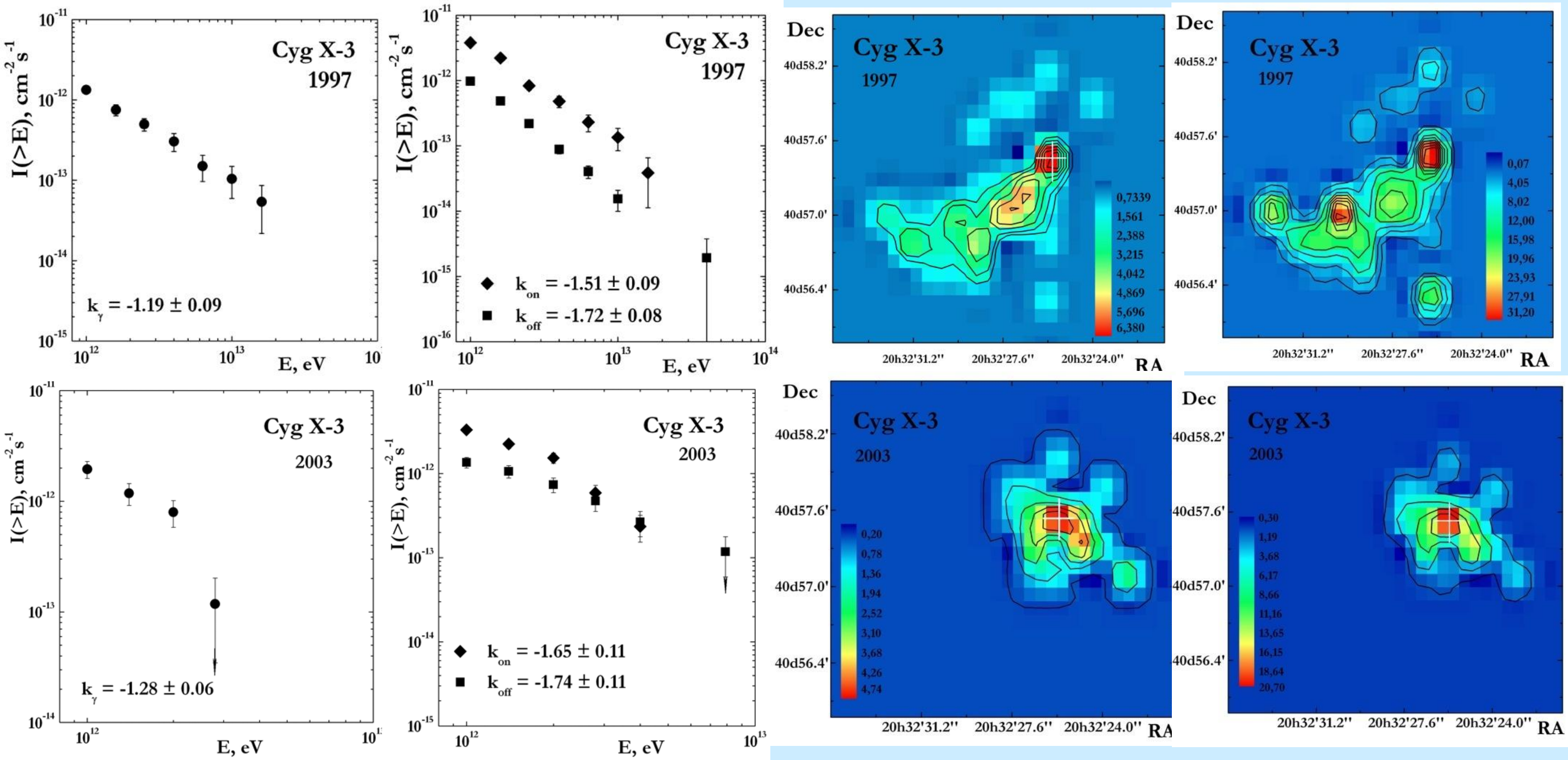
$$F(E_O>0{,}8\ \mathrm{TeV})=(6.8\pm0.5)\bullet10^{-13}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

The energy spectrum of Cyg X-3 at 800 GeV - 85 TeV can be approximated by the power law $F(>E_O) \propto E^{k\gamma}$, with k_γ=-1.25± 0.10. This flux, measured for the first time, is several times less than the upper limits established in the earlier observations.

For example, the images of Cyg X-3 in silent period at 2005 and flaring period of 1997y are shown in comparison. There are no features revealed at flaring periods found at 2005y. The last two significant increase of very high energy gamma-quantum flux have detected in May 2009 and October 2011, which is correlated with flaring activity at lower energy range of X-ray and/or at observations of Fermi LAT. Earlier, in 1997, 2003 and 2006 a comparable increase of the flux over the average value was also observed







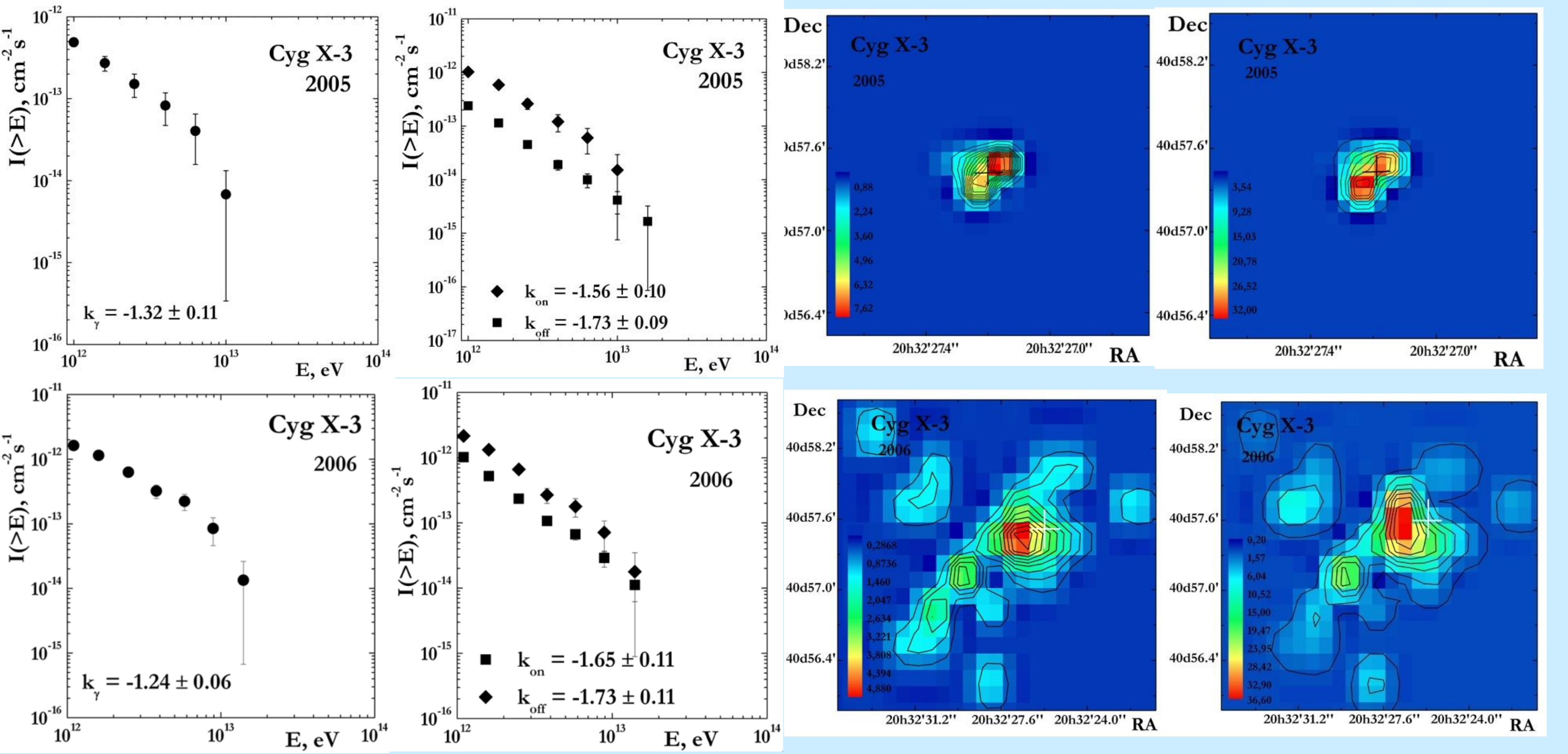
The gamma-ray flux detected by SHALON in 2003 was estimated as

$(1.79\pm0.33)\times10^{-12}cm^{-2}s^{-1}$ with the indices of integral spectra are

k_γ=-1.28± 0.06, k_{ON}=-1.65 ± 0.11 and k_{OFF}=-1.74 ± 0.11.

Earlier, in 1997, a comparable increase of the flux over the average value was also observed and estimated to be **$(1.2\pm0.5)\times10^{-12}cm^{-2}s^{-1}$** with the indices of integral spectra are

k_γ=-1.19± 0.09, k_{ON}=-1.51±0.09 and k_{OFF}=-1.72 ± 0.08.



The binary Cyg X-3 came to new period of flaring activity at radio- and X-ray energies in 2006. In May and July 2006 the significant increase of Cyg X-3 flux have detected with SHALON at TeV energy with flux values $\mathbf{(4.12\pm1.01)\times10^{-12}cm^{-2}s^{-1}}$ and $\mathbf{(1.62\pm0.75)\times10^{-12}cm^{-2}s^{-1}}$ respectively. The gamma-ray flux in the June $\mathbf{(0.46\pm0.18)\times10^{-12}cm^{-2}s^{-1}}$.

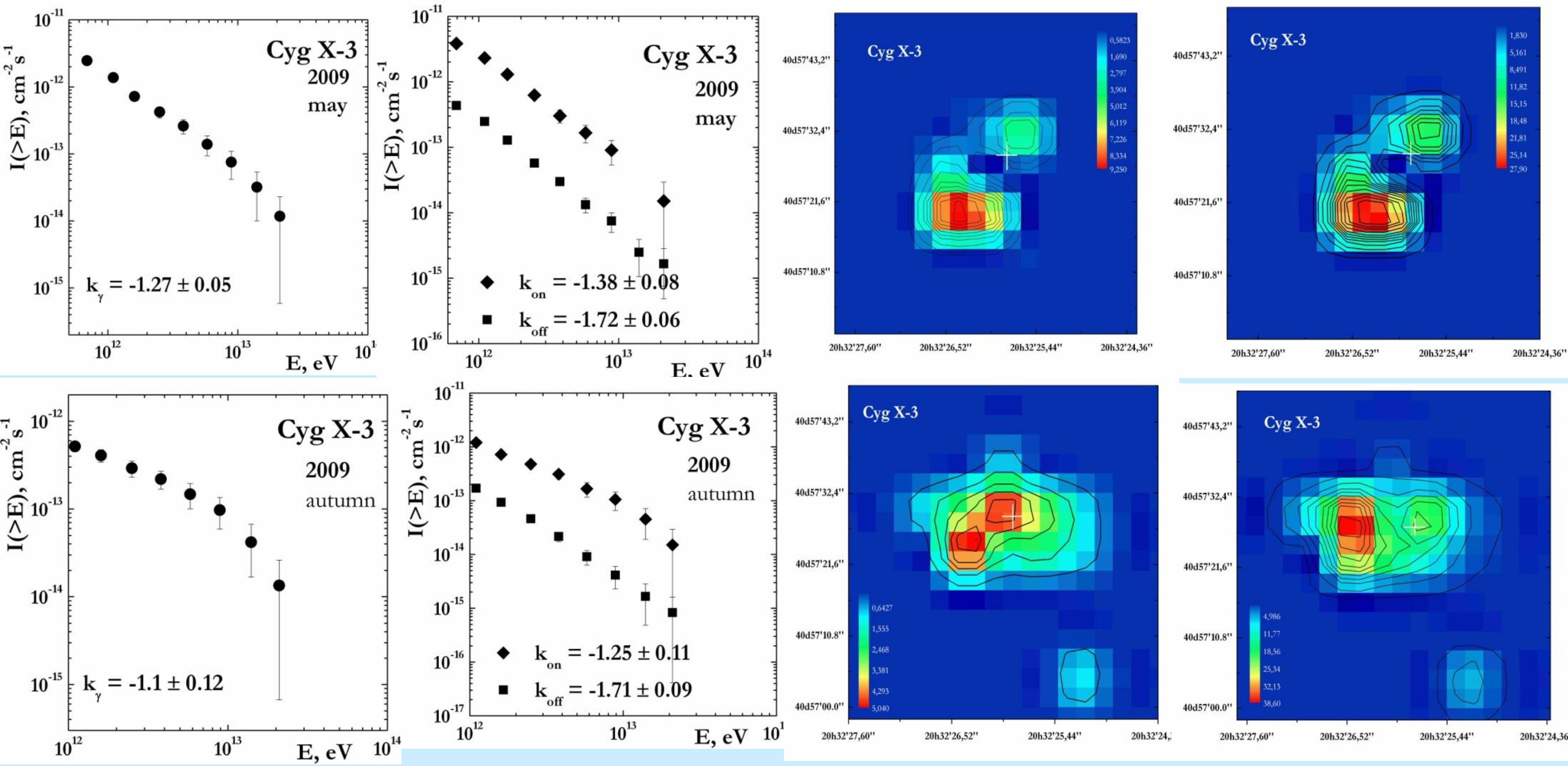
The average gamma-ray flux detected by SHALON in the flaring period from May to July 2006 was estimated as $\mathbf{(1.47\pm0.24)\times10^{-12}cm^{-2}s^{-1}}$ with the indices of integral spectra are $k_\gamma=-1.24 \pm 0.06$, $k_{ON}=-1.65 \pm 0.11$ and $k_{OFF}=-1.73 \pm 0.11$.

This intensity increase was also observed by Crimea Observatory and the integral flux was estimated as $\mathbf{F(E_O > 1TeV) \sim(3 \div 5) \times10^{-12}cm^{-2}s^{-1}}$.

In the 2005 Cyg X-3 was in the quiet period in TeV energies.

The average gamma-quantum flux from Cygnus X-3 for energies more than 0.8 TeV is estimated as $\mathbf{(0.54\pm0.07)\times10^{-12}cm^{-2}s^{-1}}$ with the indices of integral spectra are $k_\gamma=-1.32 \pm 0.11$, $k_{ON}=-1.56 \pm 0.10$ and $k_{OFF}=-1.74 \pm 0.09$

The images of Cyg X-3 in silent period at 2005 have no revealed the features found at flaring periods.

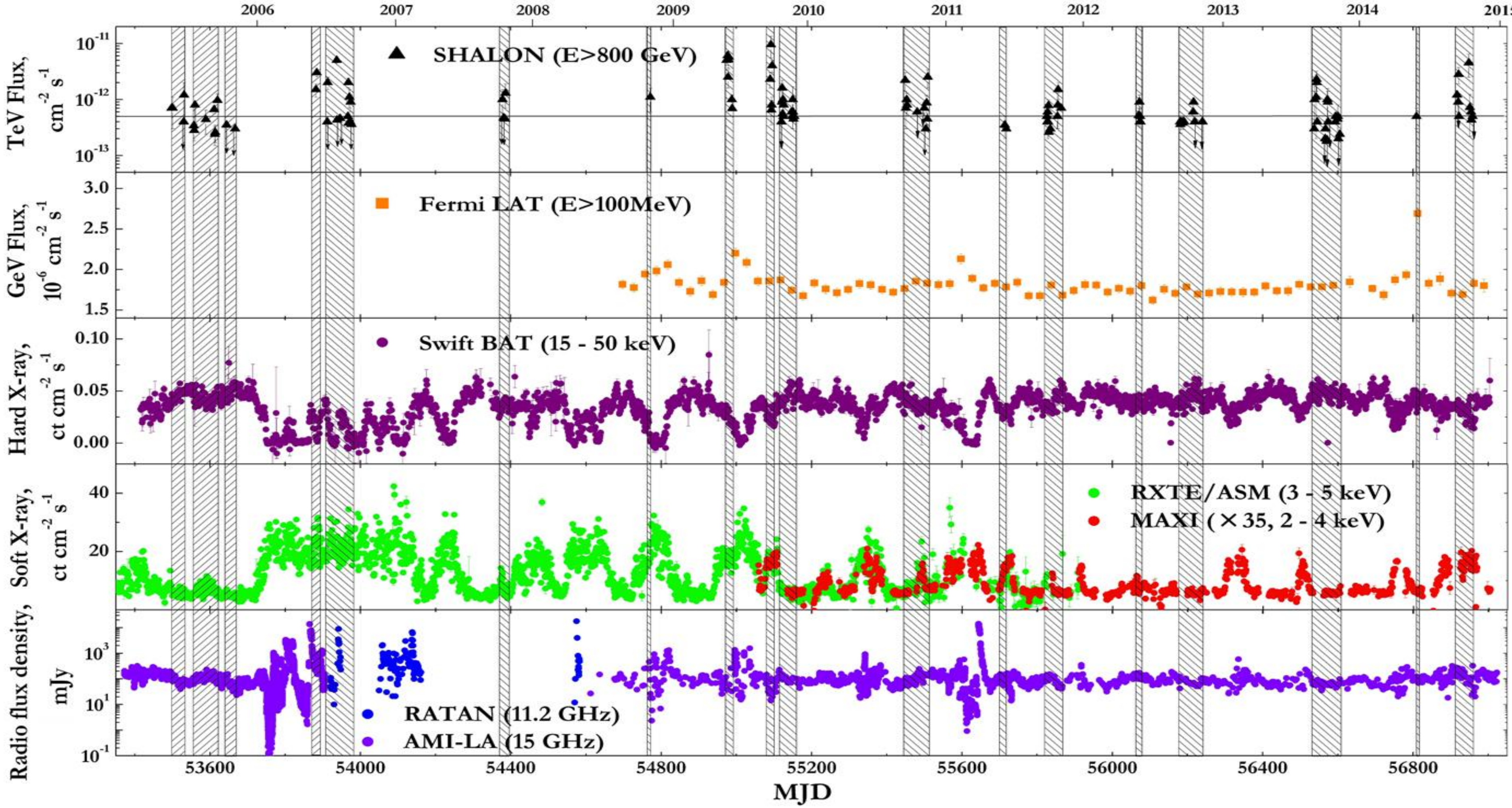


The last significant increase of very high energy gamma-quantum flux have detected in May 2009: **(2.78±0.24)×10^{-12}cm^{-2}s^{-1}** with the indices of integral spectra are $k\gamma$=-1.27 ± 0.05, k_{ON}=-1.38 ± 0.08 и k_{OFF}=-1.72 ± 0.06.

The increase is correlated with flaring activity at lower energy range of X-ray and at observations of Fermi LAT with average flaring flux of F = (190±40)×10^{-8}ph cm^{-2}s^{-1} above 100MeV. The average spectrum between 100MeV and 3GeV is well described by a power law with photon index 1.8±0.2.

In the automn of 2009 Cyg X-3 comes again in the quiet period in TeV energies. The average gamma-quantum flux from Cygnus X-3 for energies more than 0.8 TeV is estimated as **(0.46±0.07)×10^{-12}cm^{-2}s^{-1}** with the indices of integral spectra are $k\gamma$=-1.10 ± 0.12, k_{ON}=-1.25 ± 0.11 and k_{OFF}=-1.71 ± 0.09

Confirmation of the variability of very high-energy gamma-radiation from Cygnus X-3 by the future observations would be important for understanding the nature of this astrophysical object.

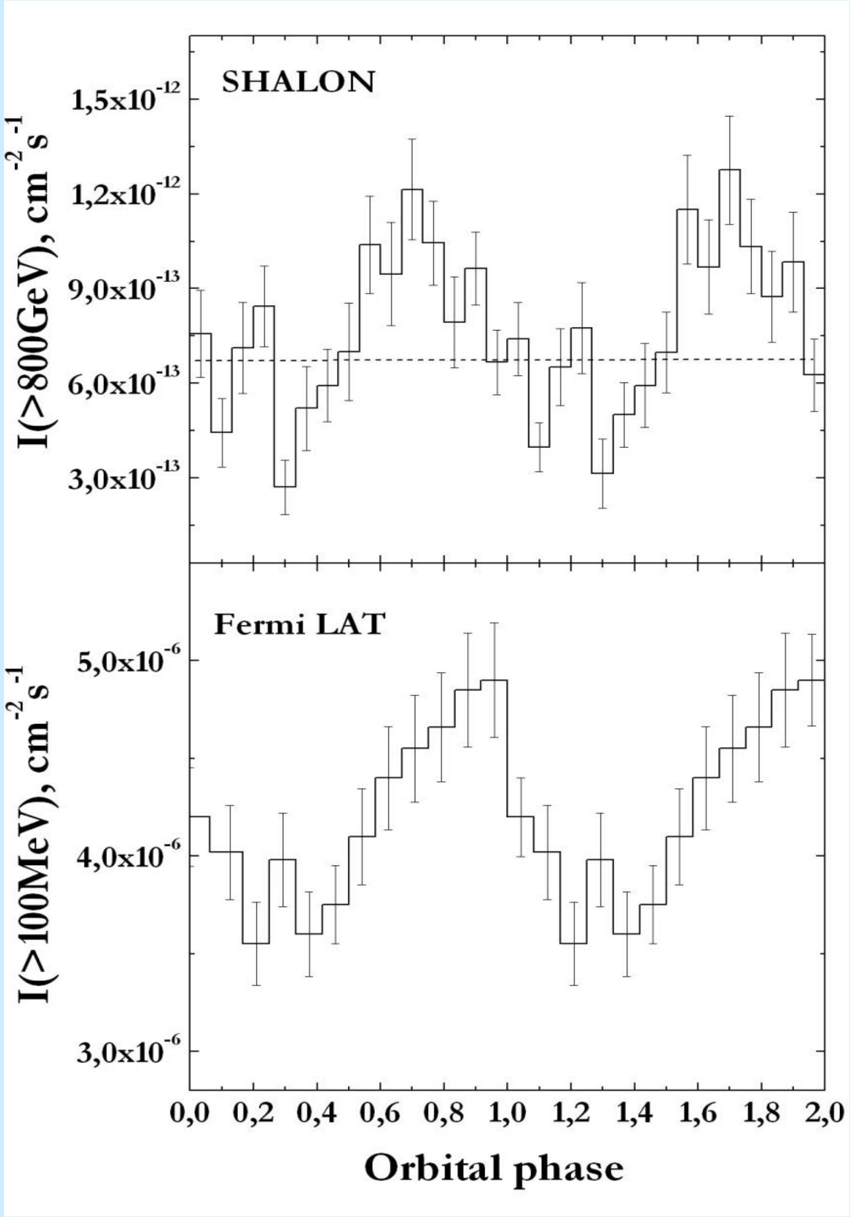


During the period of observations of Cyg X-3 with SHALON 8 significant flux increases were detected at energies above 0.8 TeV. To reveal possible correlation of periods of activity in the TeV energy range with the fairings at the low energies the light curves of Swift/BAT (15 - 50keV),35 RXTE/ASM (3 - 5 keV), MAXI (2 – 4 keV) the fluxes at radio-ranges from RATAN, RT/AMI, MeV-GeVfluxes from Fermi LAT and TeV fluxes from SHALON observations were analyzed.

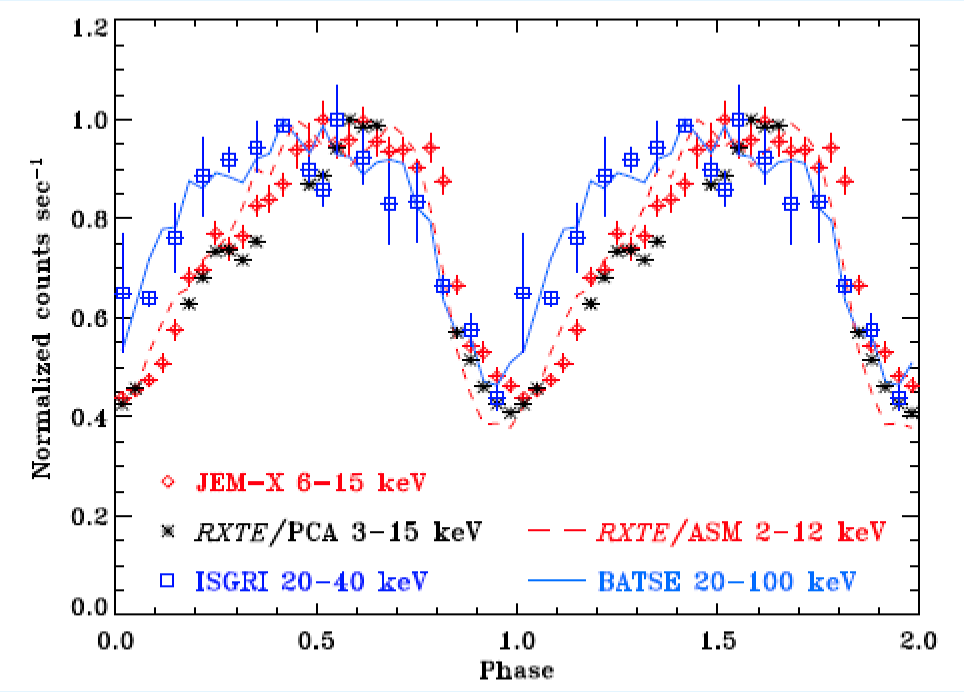
The significant anticorrelation of the fluxes at TeV and hard X-rays and the correlation of very high energy flux and soft X-ray were found. It is note, that TeV flaring activities occur close (within the 4 – 5 days) to strong radio flares. Probably, it is linked with the powerful ejection from the regions 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 very high energy γ-ray fluxes is traced since 1996.

Cygnus X-3

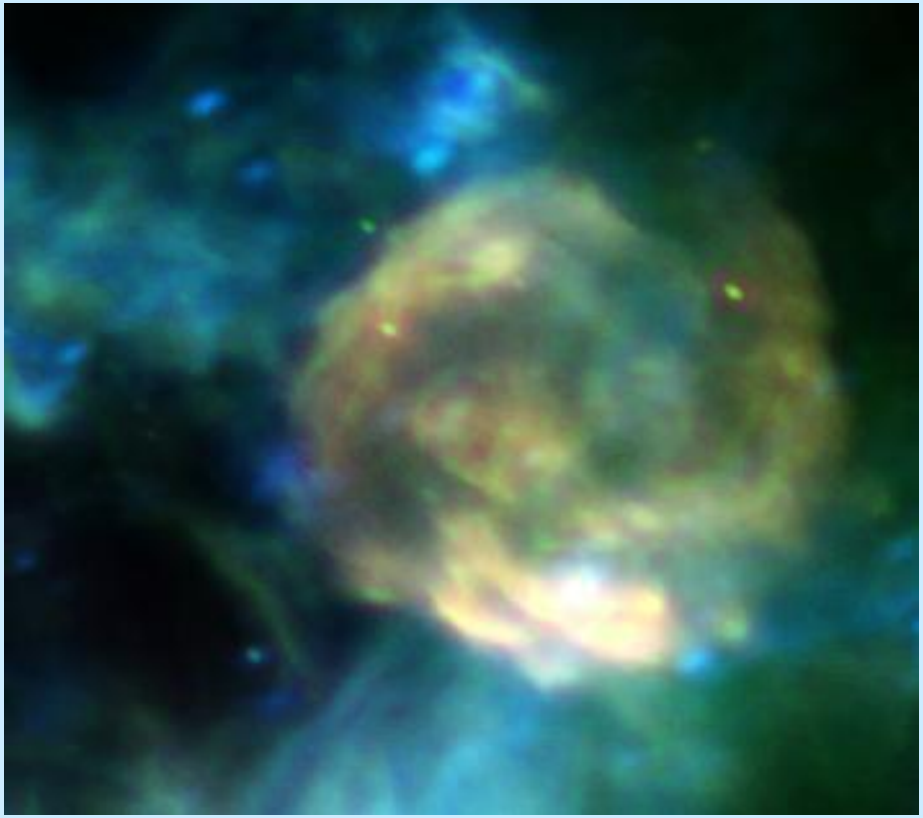
SHALON light curve of Cyg X-3 folded on the orbital period; The dashed line shows the level of averaged integral TeV γ -ray flux



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. We compared the 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 (2 – 12keV), 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 sifted on about 0.15 in phase and its shape have the local maxima. But, phase of SHALON maximum flux is close the phase of minimum of X-ray count rate, shifted by 0.3 in phase.



γ Cygni SNR

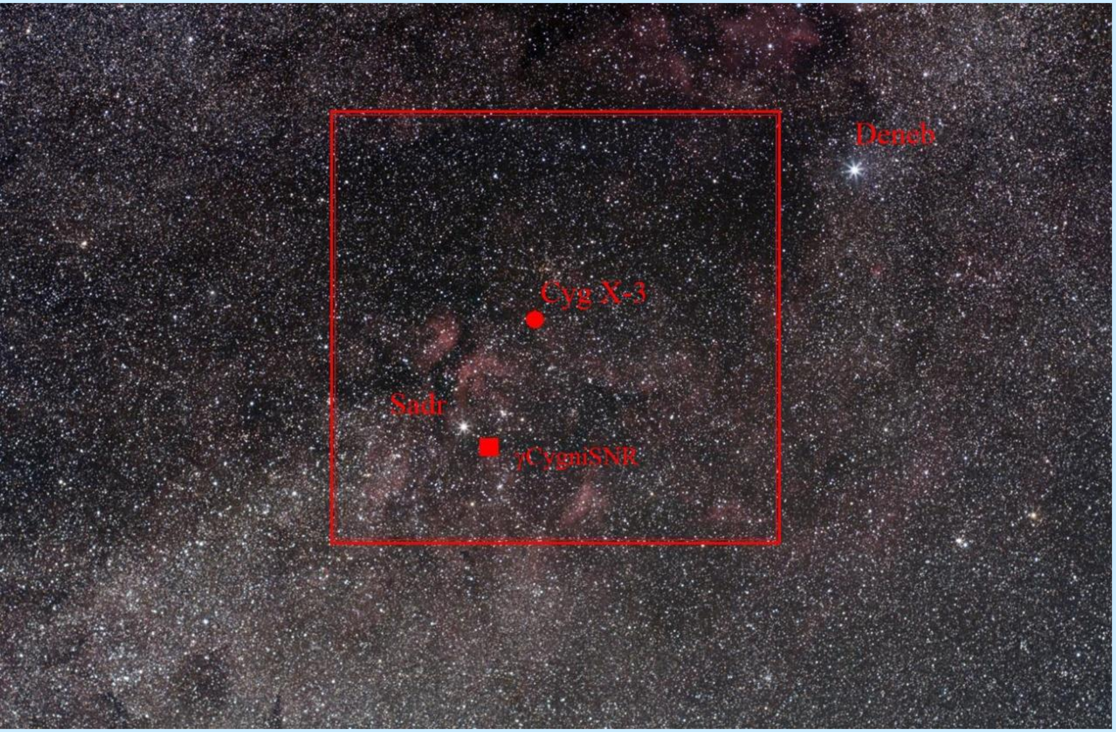


The radio astronomy image of γCygni SNR, from the Canadian Galactic Plane Survey (CGPS)

γCygni SNR (G78.2+2.1) is a shell-type supernova remnant at a distance of ~ 1 – 2 kpc and with the observed diameter of ~1^{o}. The shell-like features are known in radio- and X-ray energy regions. γCygni SNR is older then Cas A and Tycho's SNR, its age is estimated as ~ 5000 – 7000 yr. and its supposed to be and 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.

Cygnus Region contains a number of sources of radio and X-ray emission which also supposed to be a GeV-TeV gamma-ray emitters, some of them were detected at high energies with Fermi LAT (2009 - 2013) and earlier with EGRET (1995, 1996) and also at very high energies with Milagro (2011); Whipple (1998) and HEGRA (1996).

γ Cygni SNR



During the observations of Cyg X-3 the SHALON field of view contains γCygni SNR as it located in Cygnus Region at ~2^o SW from Cyg X-3. So due to the large telescopic field of view (~8^o) the observations of Cyg X-3 is naturally followed by the observations (tracing) of γCygni SNR.

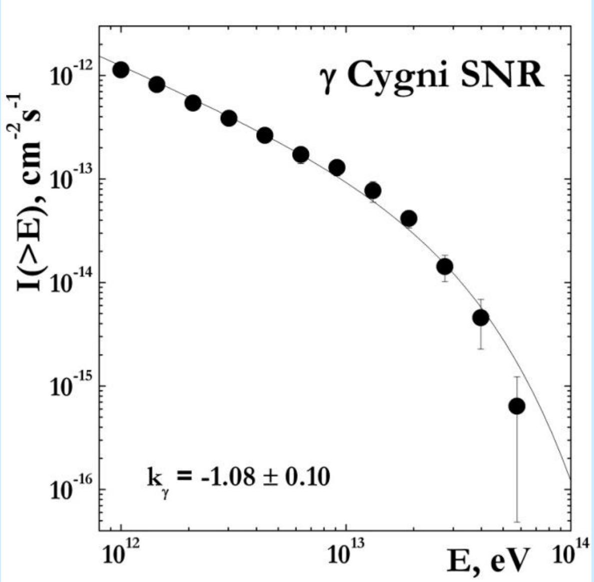
SHALON telescope field of view during the observation of Cyg X-3

γCygni SNR as a source accompanying to Cyg X-3 is systematically studied with SHALON telescope since 1995y. γCygni SNR was observed with SHALON telescope during the period from 1995 till now for a total of 240 hours. The γ-ray source associated with the γCygni SNR was detected above 800 GeV with average gamma-ray flux above 0.8 TeV:

$$\mathbf{I_{\gamma \mathit{Cygni\ SNR}}(>0{,}8TeV) = (1{,}27 \pm 0{,}11) \bullet 10^{-12}\ cm^{-2}s^{-1}}$$

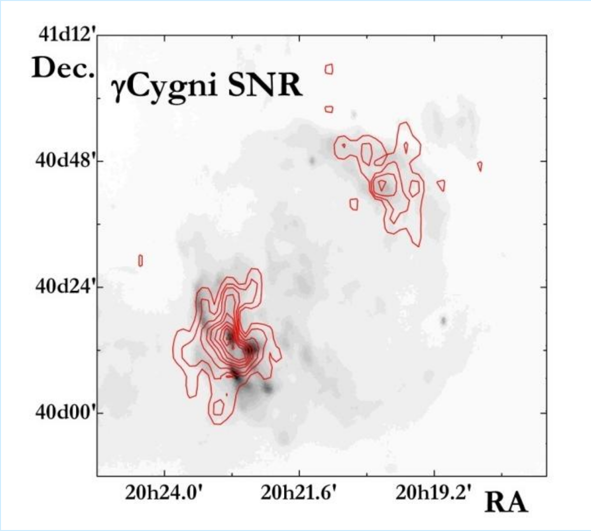
[V.G. Sinitsyna, V.Y. Sinitsyna, 2013, Bull. of the Lebedev Physics Institute, v. 40(5), pp. 113 – 118]

γ Cygni SNR

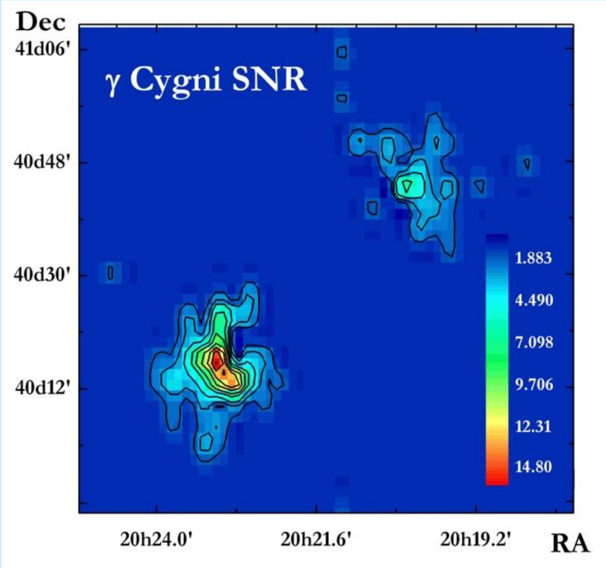


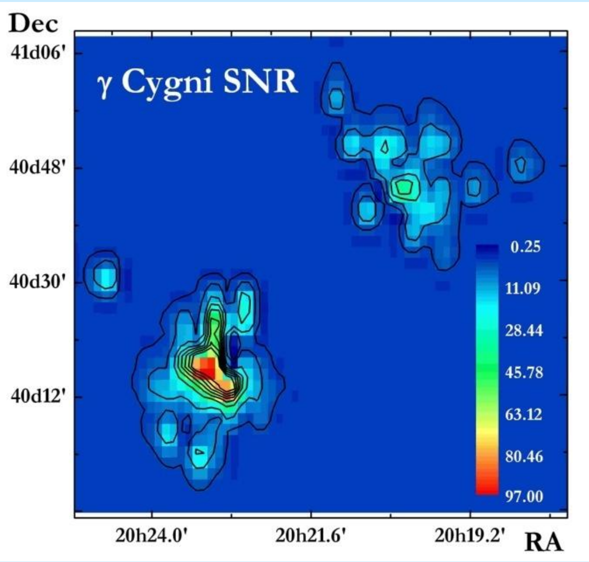
The γ-ray integral spectrum by SHALON at energies 0.8 – 28 TeV is compatible with a power law: $I(>E_\gamma) \propto E_\gamma^{-1{,}08 \pm 0{,}10}$

γCygni SNR observations were made during moonless nights with zenith angles from 5 to 35 degree. The γ-ray source associated with the γCygni SNR was detected above 800 GeV with a statistical significance of **14σ** *Li&Ma*. The signal significance for this SNR is less then one for the source with similar flux and spectrum index obtained in the same observation hours because of less collection field of view relative to the standard procedure of SHALON experiment. The corrections for the effective field of view were made to calculate source flux and energy spectrum. Taking into account the proximity to a nearby source (Cyg X-3), we made the observation data procession first associated with Cyg X-3 and then with γCygni SNR. We found that 2.4% of showers are common for the both sources. After the detailed analysis of arrival direction of these showers and angular distance less than 1% of Cyg X-3 showers were recognized to be SNR showers. This didn't change the average flux of Cyg X-3.



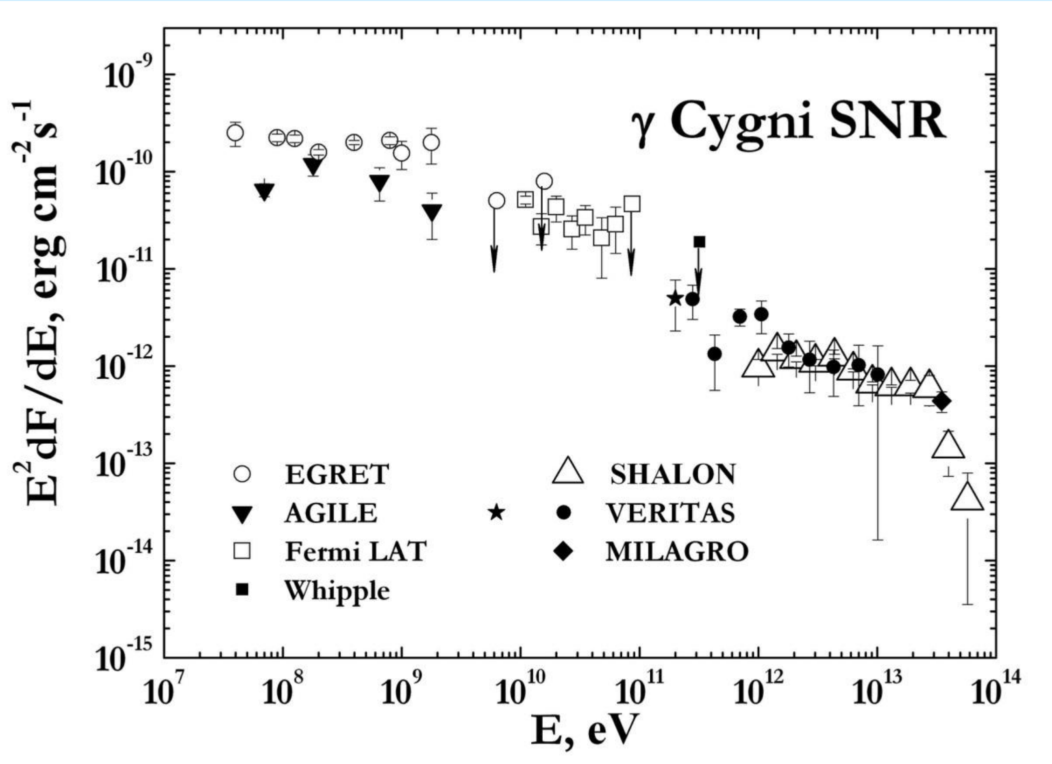
Radio image of γCygni SNR (CGPS); The contour lines show the TeV-image by SHALON





The images of γCygni SNR by SHALON

γCygni SNR



The spectral energy distribution of the *gamma*-ray emission from γCygni SNR by SHALON (Δ) in comparison with other experiment data EGRET, AGILE, Fermi LAT, Whipple, VERITAS, MILAGRO.

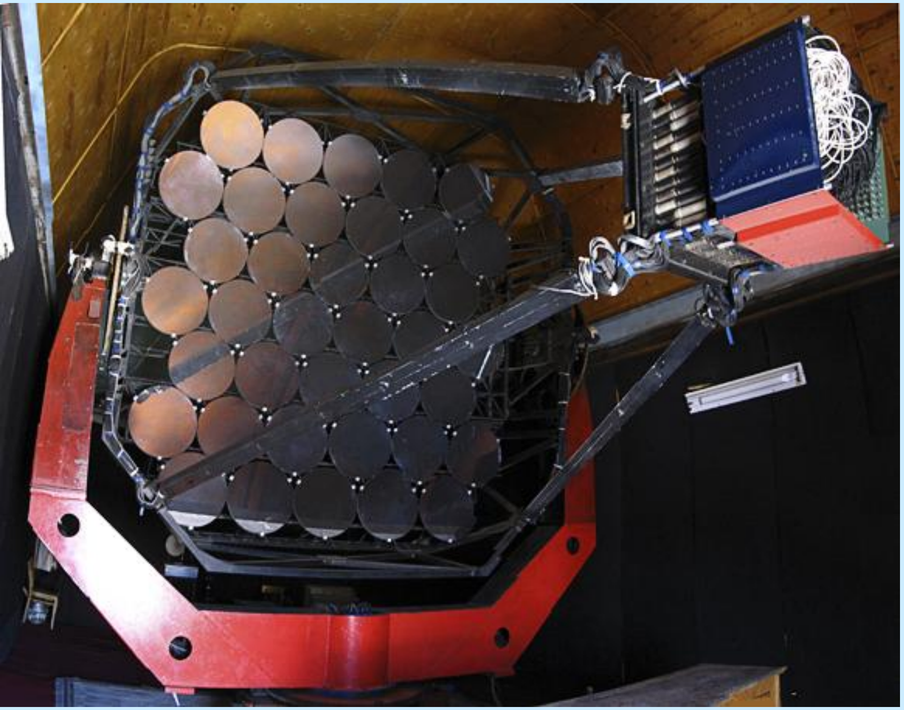
The nearby γCygni SNR source VERJ2019+407 was detected at 200GeV by VERITAS (see ★ at spectrum). γCygni SNR has been detected at 35 TeV by MILAGRO (2011). This SNR has been recently detected by VERITAS (2013) as a source of TeV γ-rays. The spectral energy distribution of the γ-ray emission from γCygni SNR by SHALON is presented in comparison with experiment data from Fermi LAT (2009 - 2011), EGRET (1995, 1996), AGILE (2010), VERITAS (2013), MILAGRO (2011).

The energy spectrum of γ-rays in the observed energy region from 800GeV to 50 TeV is well described by the power law with exponential cutoff:

$$\mathbf{I(>E_\gamma/TeV)=(1{,}12\pm0.11)\times(E_\gamma/(1TeV))^{-0{,}93\pm0{,}09}\exp(-E_\gamma/20TeV)}$$

[V.G. Sinitsyna, V.Y. Sinitsyna, 2013, Bull. of the Lebedev Physics Institute, v. 40(5), pp. 113 – 118]

Very-High Energy Gamma-ray emission form γCygni SNR and Cyg X-3



We present the results of observations of Cygnus region centered on Cyg X-3. The results of nineteen-year observations of the Cyg X-3 at energies 800 GeV – 85 TeV, detected by the SHALON telescope in 1995 are presented with spectral energy distribution, images and integral spectra. 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 1995y. The last two significant increase of very high energy γ-ray flux have detected in May 2009 and October 2011, which is correlated with flaring activity at lower energy range of X-ray and/or at observations of Fermi LAT. Also, we present the results of long-term observations of the Cygnus region around Cyg X-3 which are revealed the γ-ray emission from the one of nearby object - γCygni SNR, placed at ~2^{o} from Cyg X-3. The results of γCygni SNR observation by SHALON are presented with spectral energy distribution, images and integral spectra at energies 800 GeV – 50 TeV.