Cygnus X-3 at very high energies

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Abstract.

Cyg X-3 is a well-known binary system which also belongs to a microquasar-type objects. It is actively studied through the wide range of electromagnetic spectrum including ultrahigh energies. Here, we present the results of more than 20-year-long studies of Cyg X-3 in the range of 800 GeV-100 TeV with the SHALON telescope. The detected TeV $\gamma\text{-ray}$ source was identified with Cyg X-s based on the detection of the γ -ray flux modulation at the orbital period of this binary system of 4.8 hours. Detected modulation of TeV γ -ray emission with orbit together with the high luminosity of the companion star of Cyg X-3 and the close orbit leads to an efficient generation of the part of γ -ray emission in the inverse Compton scattering. The correlation of TeV flux increases with the flaring activity of Cyg X-3 at X-ray and radio ranges is found which could be associated with powerful mass ejections from the central regions around the black hole.

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1. Introduction

Relativistic objects in the Galaxy at very high energies have been searched for in the SHALON experiment from the very beginning of its operation [1, 2, 3, 4, 5, 6]. 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 (see [7] and references within). 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 m^2 focusing Cherenkov light of an air shower onto the detector camera which consists of 144 FEU-85 photomultiplier tubes assembled into a square array mounted at the mirror focus. The detector has the largest field of view $> 8^{\circ}$ among similar instruments. It allows monitoring of the background from charged cosmic-ray particles and atmospheric transparency simultaneously with γ -ray source observations. As a result, 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 [7]. The accuracy of the determination of the coordinates of the γ -ray shower source in SHALON experiment is $\sim 0.07^{\circ}$, and it is improved by a factor of 10 after additional processing (see [8, 9]) using deconvolution algorithm [10]. 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 2.1×10^{-13} cm⁻² s⁻¹. In the energy range from 1 - 50 TeV the minimum detectable flux falls to the value of 6×10^{-14} cm⁻² s⁻¹ [7, 11]. 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.

The long-term studies of Cyg X-3 binary system with SHALON telescope was started at the 1995 year and has been intensively studied since then. This observations revealed a new Galactic source of γ -ray emission at energies E > 800 GeV associated with Cyg X-3 [4, 5, 6].

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Figure 1. from left to right: Differential spectrum of Cyg X-3 from the SHALON data compared with data [18, 19]; The SHALON light curve (grey area) of Cyg X-3 folded with the orbital period of 4.8 h compared with other data (see text). The fluxes are normalized to the respective maxima; The differential γ -ray spectra for Cyg X-3 at very high energies in different intervals of orbital modulation. The lines represent the fit to each spectrum.

2. Cyg X-3 characteristics at very high energies

Gamma-ray emission from Cyg X-3 was detected by the SHALON telescope at energies above 800 GeV at a 34.1 σ level [12] for the 312 hours of observation. The mean integral flux at energies above 800 GeV for Cyg X-3 is $(6.8 \pm 0.4) \times 10^{-13}$ cm⁻² s⁻¹. The differential spectrum of Cyg X-3 was obtained by SHALON in the energy range 800 GeV - 100 TeV and is fitted with $dF/dE = (6.6 \pm 0.5) \times 10^{-13} \times E^{-2.04\pm0.09} \times exp(-E/(72 \pm 8)\text{TeV}) \text{ cm}^{-2} \text{ sec}^{-1} \text{ TeV}^{-1}$ with $\chi^2/DoF = 1.35$ (with DoF = 10). (see Fig. 1, \blacktriangle).

To identify the detected γ -ray source with Cyg X-3 we performed an addition analysis to search for the 4.8-hour orbital period, which is a clear signature of Cyg X-3. The light curve for the source detected by SHALON was folded and includes events that passed the selection criteria and that were used to construct its spectrum (Fig. 1, left). We used the parabolic ephemerides of Cyg X-3 from [13, 14] with an orbital period of 0.1996843 day, an epoch of the minimum X-ray flux JD 2454857,193 [14] and the time derivative of the period is 6.48×10^{-10} [15, 16, 17]. As a result, we found that the derived γ -ray light curve at energies > 800 GeV has a pseudo-sinusoidal shape with a rise followed by a decay, and a period of 4.79143 h characteristic for the orbital motion of the binary system Cyg X-3 (Fig. 1 and [6] for details). Also, it was found [6], that the folded light curves (Fig. 1) in the energy ranges of 800 GeV - 100 TeV (grev area), 100 MeV - 100 GeV (Fermi LAT [20], red line), 20 - 100 keV (BATSE, blue line) and 2 - 12 keV (ASM, points) have a similar shape. In contrast to the X-ray light curves, ones at high and very high energies (see [6]) have an additional local maximum in the region of the global minimum (phases ~ 0.3 and ~ 0.2 for the Fermi LAT [20] and SHALON experiments, respectively). In addition, there is a phase shift of the minimum in the light curves at different energies. Additionally, differential spectra for three intervals of orbital phase as an inferior conjunction, additional maximum and superior conjunction were extracted (see Fig. 1 middle and right and [6]).

Over the entire period of SHALON observations, the periods of a high intensity and flares in Cyg X- 3 at energies > 800 GeV were found to have occurred at a certain relationship between the radio and X-ray activities [6]. An increase of the very high energy gamma-ray flux during a high activity in soft X-rays and a low activity in hard X-rays within 6 - 8 days before its radio flares was observed. The Spearman correlation coefficient of the high γ -ray fluxes of > 1.5×10^{-12} cm⁻² s⁻¹ at > 800 GeV with the radio emission from the RT/AMI data (from 1995) during flares with a flux density > 300 mJy was calculated as a function of the time shift dT. The maximum value of $r_s = 0.87$ and is achieved with $dT = 7 \pm 2$ days. A correlation between the very high energy γ -ray flux and the soft X-ray flux (RXTE/ASM from 1996 and MAXI from 2012) is traced over the entire period of SHALON observations with Spearman

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Figure 2. Differential spectra of the γ -ray emission from Cyg X-3 during the flux increases and decrease in 2009. Images of Cyg X-3 at energies > 0.8 TeV during its flux increase in May 2009, increase in September 2009 and flux decrease in October-November 2009.

correlation coefficient $r_s = 0.8 \pm 0.1$. While there is an anticorrelation of TeV γ -ray flux with the hard X-ray flux (Swift BAT from 2005) at the level of $r_s = 0.75 \pm 0.15$.

Also, the changes of TeV γ -ray spectra and emission regions were traced over the high and low periods of activity of Cyg X-3. Thus, in the periods of a high activity before minor and major radio flares at very high energies > 800 GeV, the emission from the source is characterized by a hard power-law spectrum with an index $\Gamma_{diff} \sim -2.1$ (see Fig. 2); it is detected from a ~ 10'' - 20'' region around Cyg X-3 with the presence of jets. In quiescence the emission originates from a ~ 40'' region and its spectrum is described by a softer power law with an index $\Gamma_{diff} \sim -2.5$ (see for details [6]).

For example, in Fig. 2 the changes in the emission characteristics of Cyg X-3 in 2009 were traced from the flare (Fig. 2, filled circles) occurred in the period of high soft X-ray and low hard X-ray fluxes 8 days before the major radio flare. A flux increase at energies > 100 MeV from the Fermi LAT data was also observed. In this case, the emission detected at very high energies originates from a ~ 15" region, the presence of a jet in the northeastern part is possible (Fig. 2, may). Then, in September a rise in TeV γ -ray intensity was observed (Fig. 2, filled squares) at the period of low radio flux densities, during the decrease to ~ 10 mJy, and during the decrease of the soft X-ray fluxes, and during the rise of intensity in the hard X-ray band. The very high energy emission region is ~ 20" in size. The succeeding decrease of the intensity of very high hard X-ray fluxes, a low state in soft X-rays and quiescent radio fluxes were observed in this period. The intensity range in the images in Fig 2 is presented on the same scale and the grey scale is in units of the excess above the minimum detectable signal.

3. On the origin of TeV emission from Cyg X-3

The generation of very high energy γ -rays requires the presence of particles accelerated to energies higher than TeV and a target containing photons and/or matter of sufficient density. Presently, both leptonic and hadronic origins of the primary particles responsible for the very high energy γ -ray emission in these objects are considered.

Detected modulation of TeV gamma-ray emission with orbit together with the high luminosity of the companion star of Cyg X-3 [21] and the close orbit [6, 20] leads to an efficient generation of the part of gamma-ray emission through the inverse Compton scattering in this object. The correlation of activity at TeV energies with the flares of Cyg X-3 at radio band and delay observed between the flares in these energies could be associated with powerful mass ejections from the central regions around the black hole. The different type variability of very high-energy gamma emission and correlation of radiation activity in the wide energy range can provide essential information on the mechanism of particle production up to the very high energies.

4. References

- Nikolsky S I & Sinitsyna V G 1989 Proc. of Int. Workshop of VHE Gamma-ray Astronomy, Ed. A. A. Stepanian, p. 11
- [2] Nikolsky S I & Sinitsyna V G 2004 Phys. At. Nucl. 67, 1900
- [3] Sinitsyna V G 1996 Nuovo Cim. 19C 965
- [4] Sinitsyna V G 1998 Proc. of the 16th ECRS Ed. by J. Medina (Univ. de Alcala, Spain) p. 383
- [5] Sinitsyna V G & Sinitsyna V Y 2016 J. Phys.: Conf. Ser. 718 052040
- [6] Sinitsyna V G & Sinitsyna V Yu, 2018 Astron. Lett. 44(3) 162
- [7] Sinitsyna V.G., Sinitsyna V.Yu. et al., 2019, Nucl. Instrum. Methods Phys. Res. A, (in press)
- [8] Sinitsyna V G and Sinitsyna V Yu 2014 Astron. Lett. 40(2-3) 91
- [9] Sinitsyna V G et al. 2018, Adv. Space Res., 62(10), 2845-2858.
- [10] Goncharskii A V, Cherepashchuk A M, Yagola A G, 1985 Ill-Posed Problems in Astrophysics (Nauka, Fizmatlit, Moscow, 1985)
- [11] Sinitsyna V G 1997 Proc. of the Workshop, Towards a Major Atmospheric Cherenkov Detector V, p 136
- [12] Li T-P, & Ma Y-Q 1983 Astrophys. J. 272 317-324
- [13] Kitamoto S. et al. 1995 Astron. Soc. Jpn. 47 233
- [14] van Kerkwijk M H et al. 1996 A&A **314** 521
- [15] van der Klis M & Bonnet-Bidaud J M 1989 $A \mathscr{C} A$ 214 203
- [16] Manzo G. et al. 1978 A&A **70** 317
- [17] Singh N S et al., 2002 A&A **392** 161
- [18] Archambault S et al. 2013 Astrophys. J. 779 150
- [19] Aleksić J et al., 2010 Astrophys. J. 721 843
- [20] Abdo A A et al. 2009 Science **326** 1512
- [21] Zdziarski A A et al., 2012 MNRAS 421 2956