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The Giant Flares of the Microquasar Cygnus X-3: X-Rays States and Jets

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Abstract: We report on two giant radio flares of the X-ray binary microquasar Cyg X-3, consisting of a Wolf–Rayet star and probably a black hole. The first flare occurred on 13 September 2016, 2000 days after a previous giant flare in February 2011, as the RATAN-600 radio telescope daily monitoring showed. After 200 days on 1 April 2017, we detected a second giant flare. Both flares are characterized by the increase of the fluxes by almost 2000-times (from 5–10 to 17,000 mJy at 4–11 GHz) during 2–7 days, indicating relativistic bulk motions from the central region of the accretion disk around a black hole. The flaring light curves and spectral evolution of the synchrotron radiation indicate the formation of two relativistic collimated jets from the binaries. Both flares occurred when the source went from hypersoft X-ray states to soft ones, i.e. hard fluxes (Swift/BAT 15–50 keV data) dropped to zero, the soft X-ray fluxes (MAXI 2–10 keV data) staying high, and then later, the binary came back to a hard state. Both similar giant flares indicated the unchanged mechanism of the jets' formation in Cyg X-3, probably in conditions of strong stellar wind and powerful accretion onto a black hole.

Keywords: X-ray binary; black hole; radio emission; relativistic jets

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1. Monitoring Program of Microquasars with the RATAN-600 Telescope

We have carried out the long-term monitoring by almost daily observations of bright microquasars with RATAN-600 radio telescope at 2.3, 4.7, 8.2, 11.2 and 21.7 GHz (and at 1.3 and 30 GHz for flares) during the last seven years (or more than 2000 days) [1–3]. The flux densities were measured simultaneously (exactly within 1–2 min) at all frequencies; thus, the daily radio spectra are available for the analysis of spectral indices. Usually, the errors of flux measurements are less than five percent for fluxes higher than 100 mJy and near 10% for the fainter fluxes.

The X-ray binary Cygnus X-3 is a well-known microquasar composed of a mass-donating Wolf–Rayet WN4-6 star [4] and probably a black hole that is orbited with a period of 4.8 h. The recent estimate of the kinematic distance is 7.4 ± 1.1 kpc [5]. The giant flares have been detected in the GBI two-frequency monitoring program, and [6] have detected that flares occur after the 'quenched state', when radio fluxes decrease to 10–30 mJy at 2–8 GHz. McCollough et al. [7] found that radio fluxes were anti-correlated with the hard (BATSE) X-ray fluxes during the hard state and switched to correlation in the flaring state.

During 2006-2009 Cyg X-3 showed similar dependencies between soft (RXTE ASM), hard (Swift/BAT) X-rays and radio emission ([1,6,8–10]). Gamma-ray emission was detected during the flaring states ([11,12]).

The giant flare ($\sim$ 18 Jy) in the end of March 2011 was detected at 2.3-30 GHz with RATAN-600. Then during almost 2000 days of the 'quiescent state' of the Cyg X-3 we have found that the hard X-ray flux (Swift/BAT, 15-50 keV) and radio flux at 4-11 GHz were strongly anti-correlated (Spearman's correlation coefficient $\rho \leq -0.85$, [13]). The nature of such a clear linear regression could be related to the formation of the compact radio jets, the brightness of which strongly depends on the accretion rate on to a black hole.

2. Results

On 13 September 2016 and 1 April 2017, we detected similar giant flares just after the return from the hypersoft X-ray state to the soft and then to the hard state. The first hypersoft state continued for nearly 20 days and the second one nearly 40 days [13]. The mini-flare and flare in 2016 were studied with European VLBI [14], while only the former was mapped. The flare in 2017 was mapped with EHT [15].

The analysis of the light curves of Cyg X-3, shown in Figure 1, indicated the following points:

1. In both hard states before a flare, the radio spectra were slightly inverted with almost null spectral indices at 4–11 GHz ($S_\nu \propto \nu^\alpha$).
2. During the hypersoft states, the radio spectral indices became strongly positive ($\alpha \sim +1 \div +2.0$) at 4–11 GHz [15].
3. During both ultra-soft states in 2016 and 2017, two mini-flares occurred before 10 and 20 days, respectively. ($\alpha \sim -0.5 \div +0.5$) at 4–11 GHz. The AGILE gamma-ray flare event occurred only in the mini-flare of 2017 [16].
4. The fast rise of both giant flares fit a power-law of time well with almost the same indices: $S_\nu \propto t^4$ at 4–22 GHz. During 1–3 days, the fluxes rose from $\sim$10–$\sim$17,000 mJy.
5. The decays of both giant flares fit an exponential law. However, for first giant flare, the rate of decay were almost the same at all frequencies, for the second flare, the characteristic times decreased with frequency (see below).
6. During the first two days of increase of the fluxes, the spectra of both flares were characterized by an optically-thin power-law synchrotron emission at the higher frequencies and an optically-thick self-absorption synchrotron emission at the lower frequencies.
7. The flaring spectra became steeper: for the flare of 2016, the spectral index changed from zero to -0.6 in the first stage of evolution and then gradually came back to zero.
8. The remarkable multi-frequency spectra created from our RATAN points and IRAM data at 98.5 and 228.7 GHz ([17]) on 6 and 7 April 2017 were well fit with a power law with the same spectral indices -0.37 (Figure 2). Furthermore, we used the SMA measured flux point at 220 GHz ([18]) and found that the single power law spectrum on 13 April 2017 had a spectral index -0.7.

Thus, such behavior could be explained as a single blob in the jet, far enough from the core of the X-ray binary such that absorption was not important.

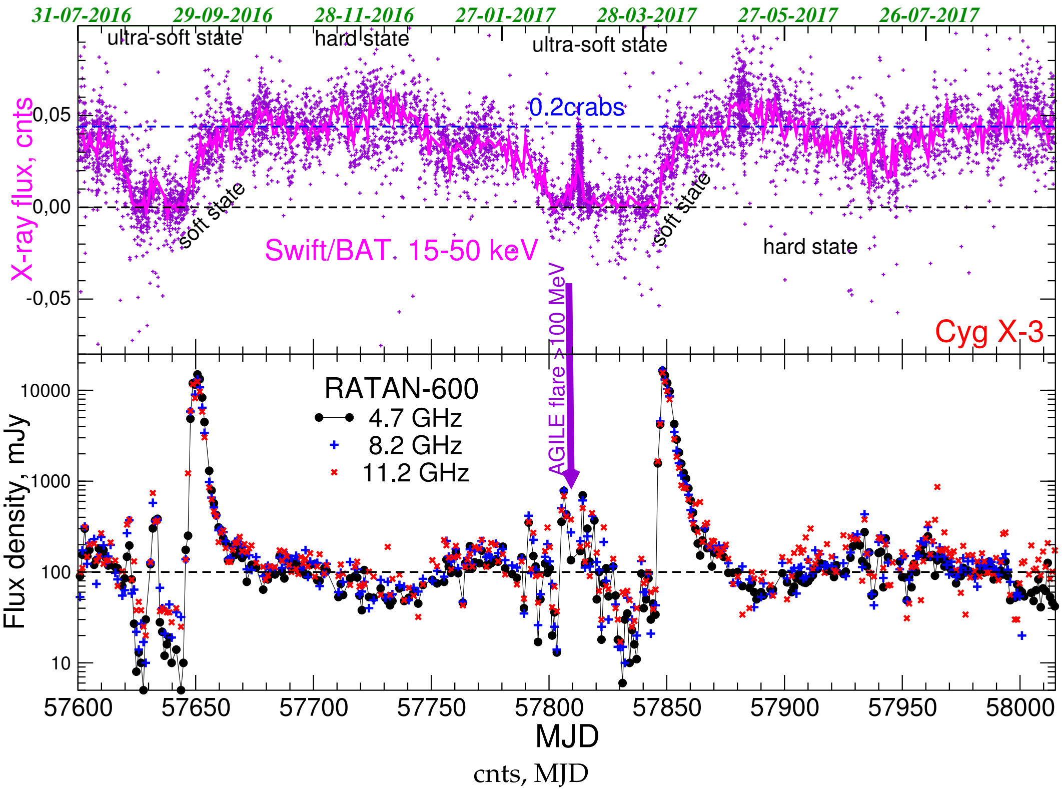

Figure 1. The light curves at 4–11 GHz with RATAN-600 (**bottom**) and at 15–50 keV with Swift/BAT (**top**) of Cyg X-3 during 2016–2017. The characteristic X-ray states are marked on the top plot. The detected AGILE flare (>100 MeV) preceded the giant flare on 1 April 2017.

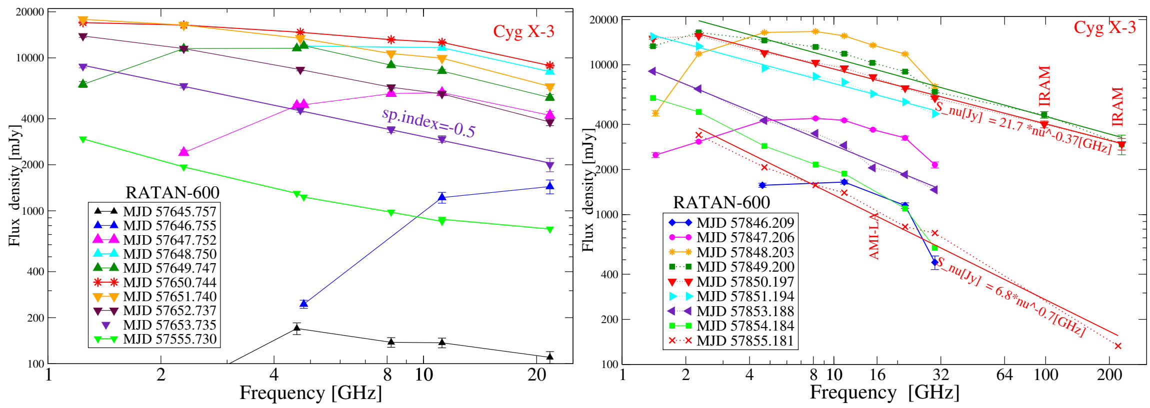

Figure 2. The radio spectra of the first flare (**left**) in September 2016 and the second one in April 2017 (**right**). There are clear transitions from the optically-thick mode to the optically-thin one in both flares.

3. Discussion

The accretion disk-jet coupling in X-ray binaries has been discussed during the last 10–15 years, especially in the frame of the Hardness-Intensity Diagram (HID) studies [19]. Based on the first developed HID of the microquasar Cyg X-3, [20] have detected the 'jet-line' of the powerful ejections only after a so-called 'hypersoft' state, when hard X-ray fluxes fell down to the detection level; meanwhile, the soft X-ray emissions remained at a high level. The work in [2] successfully applied a computer routine to model the radio flaring activity (in July 2006) of Cyg X-3, based on the model created by [21], and found the following main parameters: magnetic field ($\sim$0.05 Gs), thermal electron densities (3×10^5) cm^{-3} and the bulk speed of jets ($\sim$0.5 c). The spectral evolution of the giant flare is described by a single (during 3–4 days) ejection of the relativistic electrons, which moved with high velocity ($\sim$0.5 c) away from the binary and expanded as a conical structure. During the first days, the ejection jets are probably optically thick due to synchrotron self-absorption or thermal electrons mixed with relativistic ones. It is interesting that just at the beginning of the new flare in September 2016, the MAXI soft X-ray (2–20 keV) fluxes decreased from 0.35 Crabs down to 0.1 Crabs returning Cyg X-3 to a hard state.

During these two periods of activity, we undertook multi-wavelength observation campaigns with observations in the radio (RATAN-600, AMI-LA , Metsahovi), sub-millimeter (SMA, EHT), X-ray (Swift/XRT, MAXI), hard X-ray (Swift/BAT, NuSTAR) and gamma-ray (AGILE, Fermi, VERITAS) spectra. At the peak of the major radio flare in April 2017, observations were made with VERITAS (TeV), NuSTAR (hard X-ray) and the Event Horizon Telescope (sub-millimeter). These measurements of the flares with different telescopes will be presented in [15]).

Here, we notice that the γ-ray activity began even before the entrance of Cyg X-3 into the hypersoft state. The maximal Fermi-LAT fluxes were reached during the mini-flare in March 2017 and then at the beginning of the giant flare in April 2017 [22]. The Fermi-LAT, Swift/BAT and RATAN 4.7-GHz light curves are shown in Figure 3.

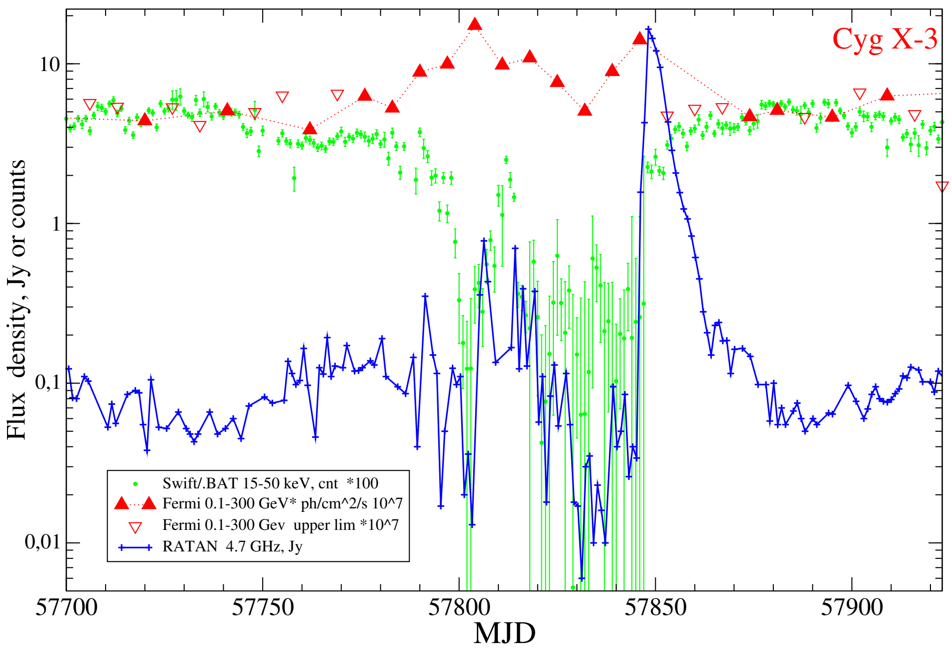

Figure 3. The light curves during the flare in April 2017 with data from Swift/BAT (15–50 keV) and the Fermi Gamma-ray Space Telescope, LAT (0.1–300 GeV).

We have plotted the light curves of both flares to follow the characteristics of their decays over time. We have fit the decreases of fluxes at different frequencies by the exponential law: $S_\nu = S_{\max} \exp\left[-\frac{(t-t_{\max})}{t_{\mathrm{decay}}}\right]$, where $t_{\max}$ is the time of the maximal flux $S_{\max}$. The flare in 2016 decayed with almost the same $t_{\mathrm{decay}} = 1.7$–2 days, but the decay of the flare in 2017 varied with respect to the frequency, and the characteristic times changed almost linearly from $t_{\mathrm{decay}} = 3.5$ days at 2.3 GHz to $t_{\mathrm{decay}} = 2$ days at 21.7 GHz.

The decay usually fits a power-law of time. Indeed, such a law is more natural for the evolution of the synchrotron blobs in jets. The synchrotron emission evolutions of two relativistic jets are determined by their conical geometry and an adiabatic expansion of the blobs, which are composed of relativistic electrons embedded in magnetic fields, moving away from the core hollow jets [21,23].

The giant flares in September 2001 and March 2011 decayed as the power-law with amazingly similar indices ~ -4.

Generally, some of the latest giant flares (2001, 2010, 2011, 2016 and 2017) were amazingly similar with respect to their main parameters: the maximal fluxes, the spectral indices of optically-thin regime ($-0.4 — -0.7$), the rates and e-folding times (1.5–3.5 d). The flares in september 2001 and 2016 had two highs (Figure 4). Often, the increases of the flares followed a power-law with index $\sim$+4.

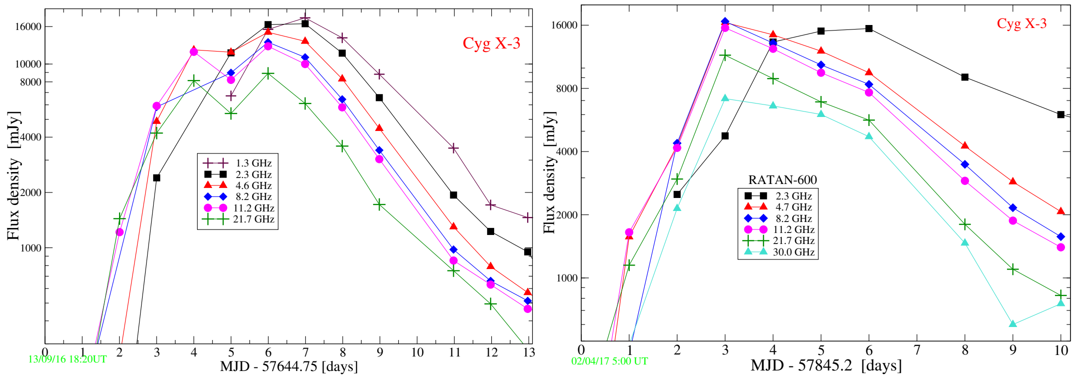

Figure 4. Evolution of the first giant flare (**left**), counted from its start on 13 September 2016, and the second one (**right**), counted from its start on 1 April 2017.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BATSE	Burst and Transient Source Experiment aboard Compton Gamma Ray Observatory
GBI	Green Bank Interferometer, NRAO, USA
LAT	Large Area Telescope on-board Fermi observatory, NASA, USA
MAXI	The Monitor of All-sky X-ray Image aboard the International Space Station
NuStar	Nuclear Spectroscopic Telescope Array
RATAN-600	Radio Astronomical Telescope Academy of Science SAO RAS
RXTE ASM	Rossi X-ray Timing Explorer All Sky monitor
SAO RAS	Special Astrophysical observatory RAS
SMA	Submillimeter Array, Smithsonian Institution and the Academia Sinica
Swift/BAT	Burst Alert Telescope aboard Swift observatory, NASA, USA

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