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The Intraday multi-frequency radio observations of the microquasar Cygnus X-3

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The results of the intraday multi-frequency monitoring of Cygnus X-3 during four flares in 2019-2021 are presented. Study of the radio spectra evolution at different time scales is the key for understanding the formation of jets during the accretion of the matter from a Wolf-Rayet star to a black hole or a neutron star. We carried out long-term almost daily observations of bright microquasars at frequencies 1.2-30 GHz during last years (see Trushkin et al in this value). Since August 2016, Cygnus X-3 has entered a new active phase (as a rule, characterized by the hyper-soft X-ray state). We detected the giant flares in 2016, 2017, 2019, 2020 and 2021. The first time the intraday observations of the last flares (2019-2021) were carried out with the southern sector of the antenna with a flat mirror, when 31 measurements at 1-3 frequencies around a local culmination time were made with time steps of about ten minutes. We have detected a clear evolution of the spectra during the 5.5 hours of the sets. We detected the very beginning of the flare on 18 June 2019 and found the linear growth of the fluxes, starting almost sumultaniously on MJD 58651.5. These new data could be used for the modeling of synchrotron radiation in relativistic jets.

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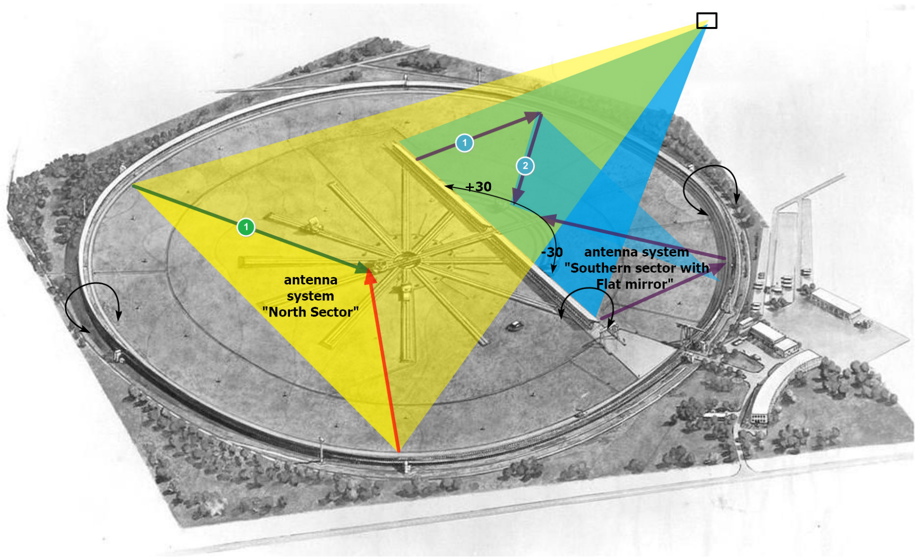

Figure 1: Sketch of the "North sector" and "South sector with Flat mirror" RATAN-600 antenna systems.

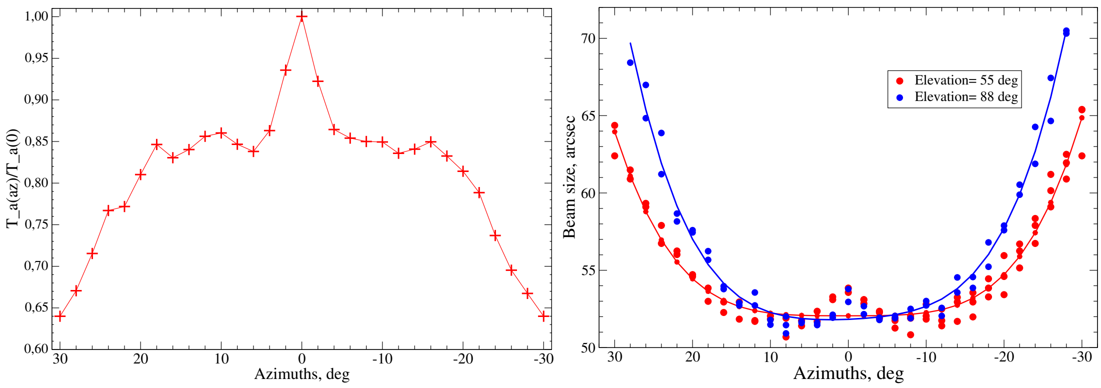

Figure 2: The RATAN-600 antenna system "South sector with Flat mirror" parameters: *left* – normalized T_a of calibration sources and *right* – beam sizes in arcsec for two elevations.

1. Introduction

Galactic X-ray binary Cygnus X-3 is the brightest microquasar that shows the relativistic jet ejections, appearing in the VLBI maps. Cygnus X-3 consists of a massive Wolf-Rayet star and a compact object (a black hole or a neutron star). The orbital period of the compact lasts about 4.8 hours and an intense stellar wind could be a main reason for the uniqueness of this binary. Probably the most unusual microquasar Cyg X-3 shows giant radio flares, when its fluxes rise up to 1000 times from a pre-flare state, associated with so-called hyper-soft X-ray state, characterized by the high soft X-ray fluxes and a very low hard, in fact null X-ray fluxes. The giant flares occur after long or short 'quenched states', when radio fluxes decreases to 5-20 mJy at 4-11 GHz [1]. Recently the importance of the intraday measurements has been emphasized in [2],[3], because they allow to define the internal structure and the physical parameters of the jets.

2. Observations

For the intraday multi-azimuthal observations we used three radiometers with 4.7, 8.6 and 16 GHz for the flux densities measurements. In June 2019 we used one 4.7 GHz-radiometer from the three-beam complex of four-channel sensitive radiometers.

We used a three-mirror antenna system "South sector with Flat mirror" and the third mirror, moving on circle rails, with receivers in focus (see Fig.1). Such antenna allows to follow a cosmic source, by changing the azimuth of the southern sector (±30°), the elevation of the flat mirror and at last the azimuth of the third mirror (±30°). For discrete antenna configurations (with step 2°) we can carry out 31 measurements every 10 minutes during some hours, depending on the declination of a source. The main parameters of the antenna (effective area and beam size) were measured with a sample of calibration sources and are shown in Fig.2.

We have used standard tools and methods for daily monitoring of Cygnus X-3 with RATAN-600 radio telescope with receivers based on the total power radiometer mode [4]. Low-noise transistor (HEMT) amplifiers were installed on all of the radiometers. Although interference sometimes prevented realization of the maximum sensitivity of the radiometers, daily observations of the reference sources indicate that the errors in the flux density measurements did not exceed < 5% at 2.25, 4.7, 8.2 and 11.2 GHz and < 10% at 22.3 and 30 GHz.

3. Results

The flux density calibration was performed using the observations of NGC1275 (0319+41) and NGC7027 (2107+42) for the multi-azimuthal mode. For 0319+41 we measured the current values of flux densities 25.1, 33.6, 29.1 Jy at 4.7, 8.6, and 16.2 GHz respectively in 2019.

We accepted the fluxes of NGC 7027 according the new flux measurements from [5].

The standard FADPS processing system of the RATAN-600 telescope was used for data analysis for the procedure of Gauss-analysis in drift scans [6].

3.1 Flaring activity of Cygnus X-3 from April to June 2019

From April to June 2019, the regime of multi-azimuth measurements was applied for the first time on the antenna system "South sector with Flat mirror", when 31 measurements of Cygnus X-3 flux densities at frequencies 4.7, 8.6, 15 GHz were carried out daily during 5.5 hours. Thus for the first time with RATAN-600 fast (~10 minutes) variability was detected in the period of the giant radio flares of Cygnus X-3 (see Fig.3). This period consisted of two independent flaring events in April-May and in June 2019, when we detected the giant radio flares (in peaks – nearly 7 Jy and 20 Jy at 4.7 GHz) [7],[8].

Importantly the first time with RATAN-600 radio telescope we measured the beginning stage (the first day) of the June flare with intraday multi-azimuthal observations. The June flare evolution has been fit well by a simple linear dependence $S_\nu \propto A \times \Delta t$, where $\delta t = t - t_0$ is a time period from the beginning of the ejection. For three frequencies 4.7, 8.6 and 16 GHz we obtained three start moments MJD 58561.75, 58561.60 and 58561.50 respectively.

The spectral index (4.7-8.6 GHz) changed from +1.6 to +0.7, while spectral index (8.6-16.0 GHz) was around null (see Fig.4). It can be concluded that the spectral index reflects a transition

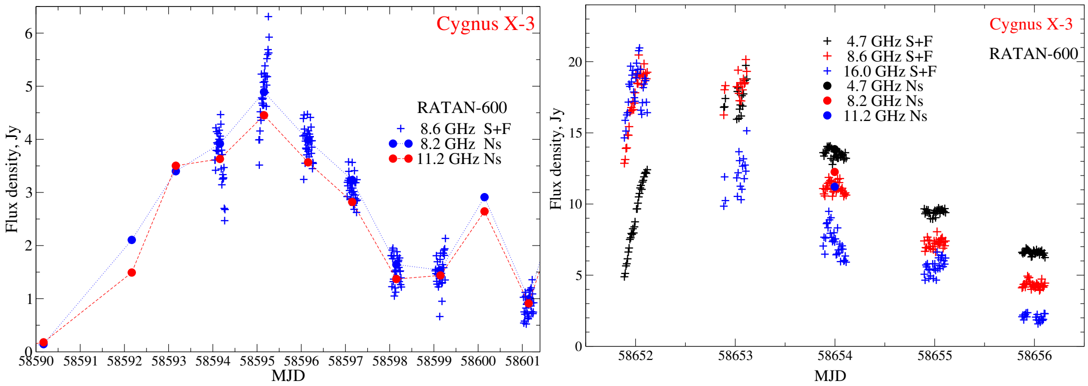

Figure 3: The RATAN-600 measurements with S+F in April 2019 *left* – and *right* in June 2019 with daily flux points from measurements with the northern sector of the antenna.

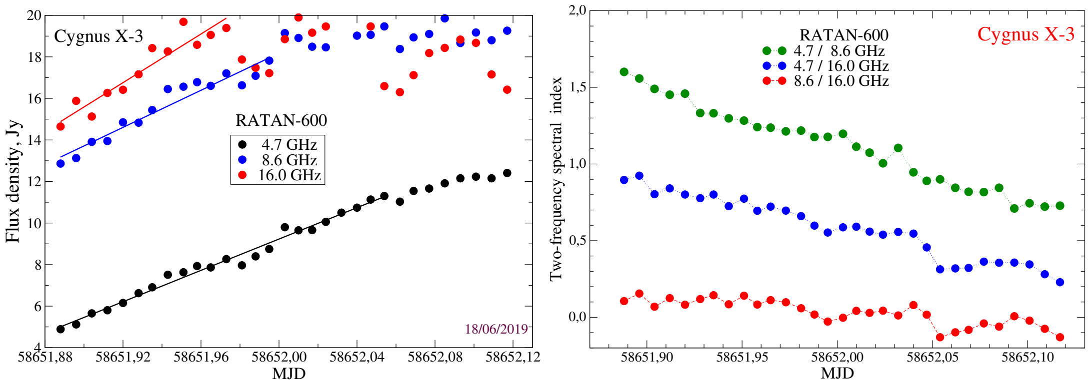

Figure 4: The RATAN-600 measurements with S+F in 18 June 2019 *left* – light curves with linear fitting ($S_\nu \propto t$) and *right* – two-frequency spectral indices.

from the optically thick state to the optically thin one, when the maximum brightness has passed. In general, the picture corresponds very well to the idea that either synchrotron self-absorption or absorption from thermal electrons mixed with the relativistic ones works first. A value close to $\alpha = 2$ indicates that either self absorption or a thermal absorption mechanism dominate on a background of the adiabatic energetic losses (or even inverse Compton loses) of relativistic electrons.

On 16 January (MJD 58864) we detected flux density of about 5 mJy at 4.7 GHz then during the next 12 days radio fluxes were very low, as well as during a hyper-soft state. The first short and faint event happened on MJD 58876, when fluxes grew to 100 mJy at 4.7 GHz. The second bright event of about 1 Jy was detected on MJD 58881.3 and the spectrum was optically thick. At last, we detected the third event - a giant flare - on MJD 58887.3. See also in [9].

3.2 Flaring activity of Cygnus X-3 in December 2021

In 2021 during the multi-frequency monitoring we detected the giant flare at 1.2-30 GHz from the microquasar Cygnus X-3 on 31 August 2021. This flare was probably characterized by a single ejection event and was over relatively soon after two weeks. As in most of the giant flares, this flare is associated with the significant gamma-ray event, detected by Fermi/BAT at 0.1-300 GeV on MJD 59425.0, almost a day before the maximal flux at 4.7 GHz on MJD 59425.88.

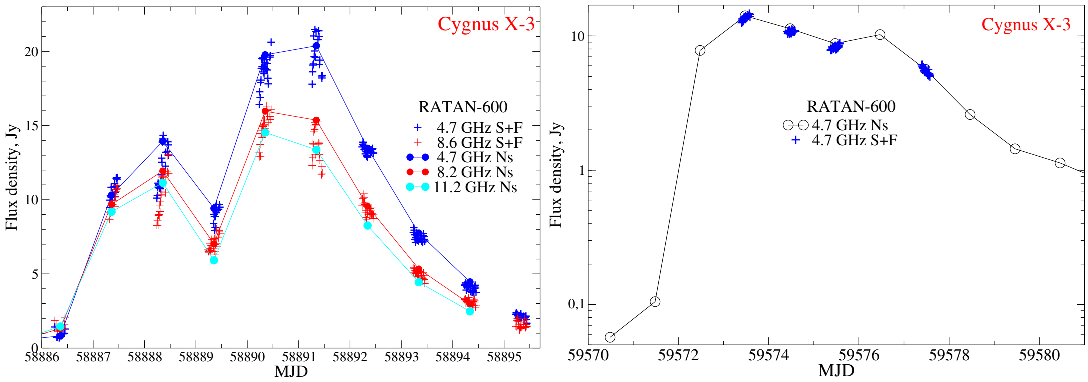

Figure 5: *left* The RATAN-600 measurements with S+F in February 2020 and *right* in December 2021 with daily flux points from measurements in December 2021 with the northern sector of the antenna.

The active X-ray state continued according to the Swift/BAT data at 15-50 keV, and on 18 October 2021 (MJD 59505) we detected a very unusual long giant flare with the maximum flux of about 16 Jy at 4.7 GHz. This flare was comprised of some consistent ejection events and was over after 45 days, on MJD 59550. Also the October flare was accompanied by the gamma-ray activity, detected by the Fermi observatory, and continued to MJD 59531.

On 24 December 2021 (MJD 59572.48) we detected a new giant flare with fluxes: 2.0, 7.7, 16.1, 19.1, 18.8 and 12.7 Jy at 2.3, 4.7, 8.2, 11.2, 22.3 and 30 GHz respectively. Again from the synchrotron theory such spectrum is determined by optically thick (spectral index $\alpha = +1.6$) and optically thin ($\alpha = 0$) modes of the forming jets. The Cygnus X-3 flare evolved to a fully optically thin one with $\alpha = -0.55$. We have carried out only four sets of multi-azimuthal observations, but have not detected strong intraday variations at 4.7 GHz (see Fig.5).

4. Summary

The radio flares are a good indicator of the process of jet emission formation. The beginning of a flare, the stage of fast growth is especially interesting, because we can understand how synchrotron emitting electrons are generated. In the giant flare on 18 June 2019 we reliably showed that the flaring fluxes at 4.7, 8.6 and 16 GHz increased linearly from the MJD 58651.5 with little time delay 0.1-0.15 MJD between frequencies. The fast evolution of optically thick radio emission imposes restrictions on the geometry of the jets. Indeed, after the beginning of a flare the bulk blobs within jets must expand as a rule in three dimensions, according to the primary model by van der Laan [10]. But in a conical geometry of jets such expansion could be exponential [11], some kind of thin shells of shocks in jets can give a two-dimension expansion and so on. The spectral indices indicated optically thick emission, probably related to an internal thermal absorption or to a self-synchrotron absorption [2].

Smoothed intraday variability of the radio fluxes was detected at the stage of flaring decays. The values of the measured fluxes in the multi-azimuth mode are in good agreement with the fluxes measured with the northern sector of antenna. We have not detected any evidence of the orbital modulation (4.8h) in intraday measurements, at least in flaring states, while our sets lasted just about

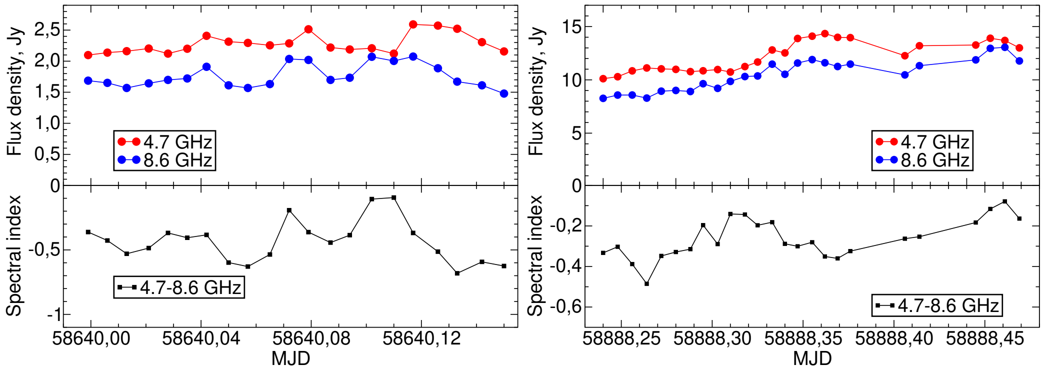

Figure 6: *Left* Light curves in April 2019 during moderated flare (top panel). In the bottom panel the spectral index variation are shown. *Right* Light curves in February 2020 during the second increase of the flare (top panel). In the bottom panel the spectral index variation is shown.

five hours. Possibly such modulation should be searched for during quite states or in the sequences of small flares [12].

We detected the case of short faint flares during a set on 06 April 2019. This flaring event was relatively short and also associated with a detected gamma-ray event (Fermi/BAT). In Fig. 6 (left) we show the two-frequency light curves and the variation of spectral index around MJD 58640. Obviously, there we met with the optically thin flare, related to the gamma-ray event (Fermi/BAT). In Fig 6 (right) we show the two-frequency light curves and the variation of spectral index around MJD 58888 on 09 February 2020. The increase of optically thin flare is characterized by the change of spectral index from -0.5 to -0.1.

Daily multi-frequency monitoring of microquasars and now intraday measurements during periods of active states of the binary system Cyg X-3 allows us to better understand the jet-disk coupling in all microquasars. In the models of synchrotron radiation we can estimate sizes and brightness temperature of the emission regions.

Acknowledgments

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