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The flaring activity of microquasars is the key to understanding the processes of accretion and generation of jet emission

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Abstract. We present a study of the flaring radio variability of four microquasars during last ten years with RATAN-600. The main aim of researches is a study of the daily light curves at seven frequencies of 1.2–30 GHz and in multi-azimuthal (MA) mode, when for 5h the fluxes are measured every 5–10 minutes at 4.7 and 8.2 GHz. In SS 433 dozens of bright flares were detected over last ten years. The brightest flare (5.5 Jy at 2.3 GHz) in the total history of GRS 1915+105 research occured in August 2023. In 2024 we have detected five giant radio flares in Cyg X-3 during hypersoft-to-hard X-ray states transits. These flares reached fluxes of 13–18 Jy and have similar properties: optically thick phase in the spectra in the beginning of a flare and the exponential fading for 5–30 days. We relate these events with an efficient formation of relativistic jets during the accretion of matter from a normal star. In the Gamma-ray binary LSI+61d303 with regular flares every 26.5 days, we have detected second period of 26.93 days that can be precession period of jets. We find a clear similarity of bright flares in microquasars.

Keywords: X-rays: binaries; radio continuum: stars; radiation mechanisms: non-thermal, synchronton radiation

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1 Introduction

Microquasars – X-ray binary stars with relativistic motions are a rare type of Galactic radio sources. According to the traditional scenario, variable syntrotron radiation is generated gradually as ejected blobs move along the jet, losing energy of electrons in matter from the vicinity of black holes or neutron stars under certain conditions that are not known in detail, but which are obviously related to the accretion process of matter coming from a donor star. This has been confirmed by a lot of examples of the so-called "disk-jet coupling", which manifests itself in the "hysteresis" dependence of the evolution of X-ray radiation in the HID (hardness-intensity-diagram). The radio jets are located on a line in the "soft and bright location" in HID. However, the process of jet ejection formation remains unclear, despite the fact that R. Blandford and colleagues proposed models for the transfer of matter with momentum and energy from the disk to the jet. In any case, radio flares are critical indicator of jet formation processes.

2 Observations

Observations of the sample were conducted with the RATAN-600 radio telescope during 2011–2024 at frequencies of 1.24, 2.3, 4.7, 8.2, 11.2, 21.7 and 30 GHz simultaneously. These receivers are equipped with the modern HEMT amplifiers and can measure fluxes of cosmic sources at the level of 5–30 mJy in the conditions without interference. The flux densities were measured with a typical error of about 3–5 % at 4.7–11.2 GHz and 5–10 % at 1.2, 2.3, 21.7, 30 GHz. Observations of the standard calibrators: 3C 48, 3C 138, 3C 161, 3C 286, NGC 7027, DR 21, from the commonly accepted radio scales (Baars+ 1977 and Ott+ 1994) are included in all astronomical programs. Observations are carried out with the Northern sector and with the Southern sector paired with the Flat mirror of telescope in the mode of transit of sources through fixed antenna beams. Thus we obtain the daily points of measured fluxes at different frequencies. Also we use multi-azimuthal mode, when during ± 2.5 hours from culmination time of sources we can take up to 63 measurements of the fluxes at frequencies 4.7 and 8.2 GHz (each 5–10 minuts), receivers of which are established on the special secondary mirror cabin, capable of change of focus and azimuth of the three-mirror antenna "Southern sector + Flat mirror".

3 Long-term light curves of microquasars

3.1 SS 433

SS 433 is the well-known bright X-ray, optical binary having the precessing jets, visible in X-rays, and on the VLA and VLBI maps. In the Fig. 1 (left) we plotted the total light curves at three frequencies during 13 years. In the Fig. 1 (right) the example of the recent bright flare is shown with exponential fading of the flare. The flares are usually optically thin in the range of 1–21 GHz.

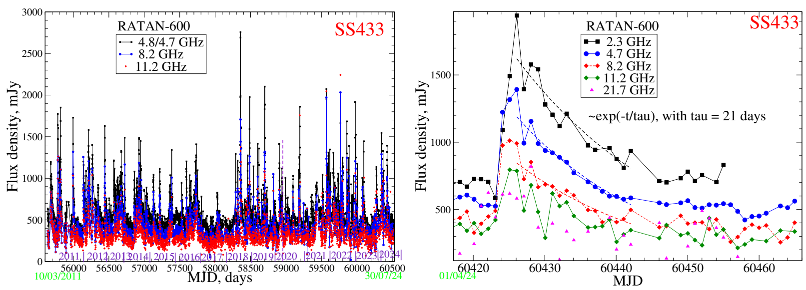

Fig. 1. *Left:* The light curves of the SS 433 at different frequencies in 2011–2024. *Right:* The light curves of the SS 433 at different frequencies in 2024.

3.2 Cyg X-3

Cyg X-3 is the famous flaring source, the X-ray and Gamma-ray binary, consisting of the Wolf–Rayet star and low mass black hole. It contains the relativistic jets that

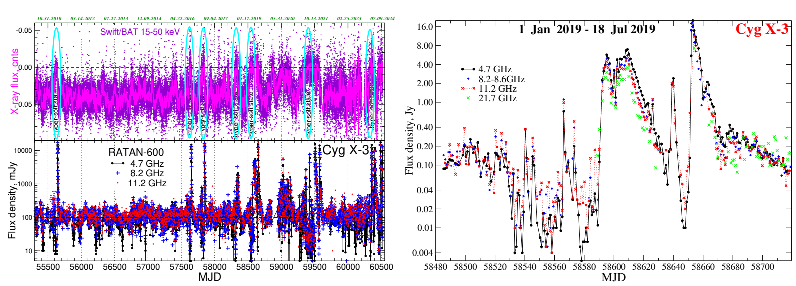

Fig. 2. *Left:* The light curves of the Cyg X-3 measured with RATAN-600 at 4.7, 8.2 and 11.2 GHz and X-ray ones with Swift/BAT at 15–50 keV in 2010–2024. *Right:* The RATAN radio light curves of the Cyg X-3 at 4.7–21.7 GHz in 2019.

were detected with VLBI mapping. These jets are as a rule one-side during the flares, but in a quiet state images could be double-side. Thus radio images are exposed to boosting according to the Doppler effect along the line of sight. In the Fig. 2 (Left) the light curves of the Cyg X-3 are shown for radio range (RATAN) and for X-ray band of the Swift/BAT at 15–50 keV. Obviously the hypersoft-to-hard X-ray states transit, marked by the blue ellipses, coincided with the giant radio flaring events. In the Fig. 2 (right) we show the characteristic light curves of some flaring events together with X-ray (Swift) and gamma-ray (Fermi) light curves. In the Fig. 3 we show the radio flaring light curves and the gamma-ray curves (Fermi 0.1–300 GeV) in 2024. Obviously high energy Gamma-ray emission correlated with radio flares.

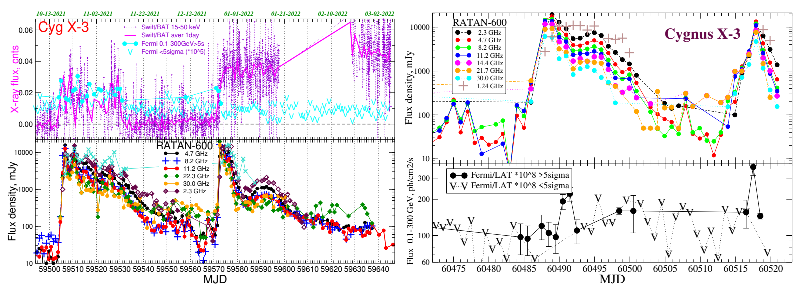

Fig. 3. *Left*: The radio light curves of the Cyg X-3 measured with RATAN-600 at 4.7–21.7 GHz in 2021. *Right*: The same in 2024 together with Fermi data.

3.3 GRS 1915+105

In the giant flare of GRS 1915+105, the peak flux reached 5.5 Jy at 2.3 GHz, which is 3–4 times higher than ever before. We followed up this flare between August 1–9, 2023 at 4.7 GHz and 8.2 GHz in the daily MA-mode observations (Fig. 4), when fluxes were measured every 8.6 minutes within interval of $\pm$ 2.5 hours from the local culmination time. In the synchrotron optically thin radio spectrum, the spectral index changed smoothly from $+0.15$ to -0.95 from August 1 to August 9, and within the interval of MA observations, the spectra (4.7–8.2 GHz) also changed noticeably. In the MA observations fluxes were changed with periods ranging from 30 to 300 minutes. Moreover, in eight MA measurements, QPOs less than 10 % of the average flux were detected on time scales of about 30 minutes at both frequencies. We related the flare activity of GRS 1915+105 with a more efficient formation of relativistic jet emissions during the accretion of matter from a normal star. We find a clear similarity of the flare events in GRS 1915+105 with five giant flares in Cyg X-3 microquasars in 2024.

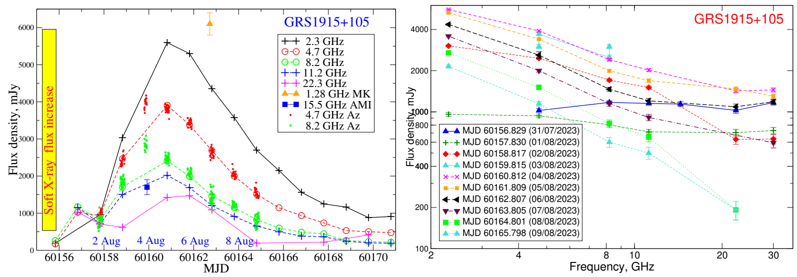

Fig. 4. *Left*:The radio light curves of the giant flare of GRS 1915+105 in 2023. *Right*: Evolution of spectra during this flare.

The brightness of the flares increased linearly with time, and their decay went exponentially ($e^{-t/\tau}$), where the parameter τ slowly changed from 4.3 to 2.7 days with the increase of frequency from 2.3 to 30 GHz. The optically thin spectrum index changed in the range from -0.7 to -0.4. In the second outburst, the exponential law was generally maintained, but the τ at the beginning of the fading was noticeably higher than later.

3.4 LSI+61d303

The X-ray binary LSI+61d303 with detected radio pulsar as a relativistic component lies apart from the main sample of microquasars, although it is the single Galactic radio source showing the clear flaring (orbital) periodicity. The nature of these flares remains the subject of intense debate, and it cannot yet be firmly established that renewable jets are in action. Based on the data we have obtained, we confirm that there are two characteristic periods of 26.49 days (orbital) and 26.93 days in the light curves, which speaks rather in favor of jets. Last one could be the precession period of the expected jets. Thus, the detected super-orbital (SO) period of 1660 days could be explained by usual beating of the close frequencies. Indeed, we can clearly see the modulation of the flares by SO-period in Fig. 5 (Left). The repeated flares in 2022 of LSI+61d303 are well visible in Fig. 5 (Right), where the orbit phase 0.6 are marked by triangles.

4 Discussion

We have studied the variability of the four microquasars during long-term period and found a lot of special properties of the radio emission together with optical and X-ray bands (see for details, Trushkin et al. 2021–2024; Cherepashchuk et al. 2022; Medvedev et al. 2022; Broderick et al. 2021; Egron et al. 2021; Trushkin et al.

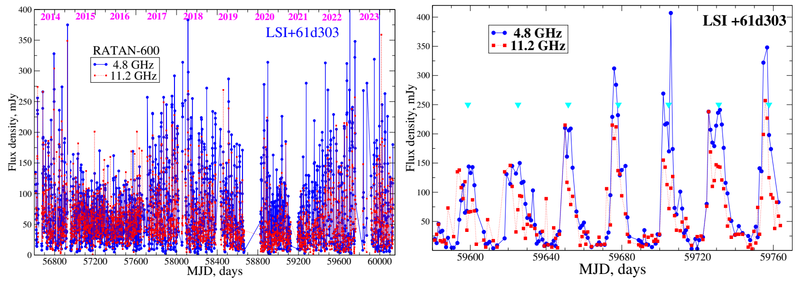

Fig. 5. *Left*: The radio light curves of the LSI+61d303 measured with RATAN-600 at 4.7 and 11.2 GHz during 2013–2023. *Right*: The radio light curves of the LSI+61d303 measured with RATAN-600 at 4.7 and 11.2 GHz during 2022.

2023; Veledina et al. 2023, 2024). Numerous examples of the detected flares from the microquasars give us a list of the main properties of radio emission: the synchrotron spectrum, often having one index from 2 GHz to 200 GHz, optically thick firstly, and optically thin after the maximum, while spectra become steeper; the increase of flux is linear in time; flares fade follows an exponential law; the flares in BH binaries are random in nature, but are definitely related to the X-ray states of them, started after hyper-soft X-ray state. Any model should take into account these properties of flares. Soon, we will discuss the finite jet segment model in application of Cyg X-3 (Marti et al. 1992) and the hollow conical jet emission model for SS 433 (Hjellming & Johnston 1988).

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References

Broderick J., Russell T., Fender R., et al., 2021, MNRAS, 504, p. 1482
Cherepashchuk A., Dodin A., Postnov K., et al., 2022, Astronomy Reports, 66, p. 451
Egron E., Pellizzoni A., Righini S., et al., 2021, Astrophysical Journal, 906, id. 10
Hjellming R. and Johnston K., 1988, Astrophysical Journal, 328, p. 600
Marti J., Paredes J., and Estalella R., 1992, Astronomy and Astrophysics, 258, p. 309
Medvedev P., Khabibullin I., Semena A., et al., 2022, Astronomy Letters, 48, p. 389
Trushkin S., Bursov N., Shevchenko A., et al., 2021–2024, The Astronomer’s Telegram, #14821, #15142, #15671, #15709, #15964, #15974, #16168, #16289, #16581
Trushkin S., Shevchenko A., Bursov N., et al., 2023, Astrophysical Bulletin, 78, p. 225
Veledina A., Muleri F., Dovčiak M., et al., 2023, Astrophysical Journal, 958, p. L16
Veledina A., Muleri F., Poutanen J., et al., 2024, Nature Astronomy, 8, p. 1031