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The history of long-term studies of Galactic X-ray binaries with jet emissions with RATAN-600

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The first "Cold" survey of the CMB anisotropy has been carried out for almost 100 days in 1980 with the Northern Sector of RATAN-600, by the decision of Yu.N. Parijskij at the declination of the most famous Galactic object SS 433. Interestingly then this very variable sources was stable at cantimeter wavelengths. Since 1980 we conduct regular observations of the SS433 and later of new discovered Galactic stellar radio sources, collectively called microquasars. Indeed the radio emission and SS 433 and the first the Galactic 'superluminal' source GRS 1915+105 strongly resembles many well-known extragalactic sources associated with active galactic nuclei (AGNs). Already in the 1980s, VLA mapping of SS433 showed 'jet-like' morphology of its radio emission. Also from VLBI mapping it became clear that the famous flaring radio source Cyg X-3, which contains either a black hole (BH) or a neutron star (NS) in the binary with a massive Wolf-Rayet star, has an elongated radio emission shape at small angular scales, again similar to quasars. Now our long-term intensive studies of SS 433 allow us to assert that *all* the flaring events have been detected over the past ten years, and the bright flares themselves are unambiguously associated with the features of jet activity, well studied using optical spectroscopy of the object. In GRS 1915+105, we found a lot of relatively bright flaries associated with dramatic changes in the X-ray state, which was monitored in the ASM programs on the instruments of RXTE, SWIFT and MAXI. We studied on the properties of the giant Cyg X-3 flares detected on a long (weeks) and short (hours) time scale. For the last task see paper by Shevchenko et al. in this issue. Origin of the super-orbital 4.6-year period of the microquasar LSI+61d303 is probably associated with beats of the jets precession (26.95d) and the orbital (26.5d) motion of a pulsar. In general, the monitoring of microquasars with RATAN-600 is the highly productive program due to the features of the telescope and the sensitive multi-frequency measurements. Unknown properties of jets-disk coupling in X-ray binaries were detected, bringing clearance in common physics of cosmic relativistic jets.

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1. Introduction

The variable synchrotron radio emission is a good tracer of active processes in relativistic jets in the Galactic X-ray binaries (XRB) – microquasars [1]. We continued the multi-frequency monitoring of SS433, Cyg X-1, LS5039, Cyg X-3, GRS1915+105, LSI+61d303 and some transient X-ray binaries, as V4641 Sgr, V404 Cyg, MAXI J1820+070 and others (see [2],[3]).

The elongated, jet-like structure was confirmed in most bright microquasars, proving the similarity of physical processes in them and in ANGs, primarily the process of accretion onto supermassive BH in AGNs and onto BH of stellar masses, during which powerful radio jets are formed [1]. However, it should be noted that in microquasars, both BH and NS can be a relativistic object, which is shown by several obvious examples: Cyg X-1, LS 5039, GRS 1915+105, V404 Cyg undoubtedly contain BH, but Cir X-1 and LSI+61d303 contain radio pulsars. Of course, in AGNs an accretion always goes onto supermassive BHs with different spin parameters, that seems to be important for effectivity of jets radio emission [4].

The monitoring programs were carried out with the North sector RATAN-600 radio telescope on radio continuum radiometers in the band 1.3 – 30 GHz. Usually we have daily observed three-four microquasars at 3-4 frequencies (2.3, 4.7, 8.2 and 11.2 GHz), and we can use also 1.3 and 30 GHz radiometers for strong flares with the relatively lower sensitivities. The details of the observations are given in [5]. The additional sets of the bright microquasars and observations of LSI+61d303 were carried out with other antenna: the South Sector and the Flat mirror of RATAN-600. Thus we have intensively measured daily spectra of microquasars during last 10-12 years. Always we have observed secondary calibrators (3C286, J1347+12, J1850-0101 and NGC7027) for accurate calibration of the measured flux densities at different frequencies. Usually we have lost less 5 % of the observations from the weather conditions or from the different RFI. The errors of the flux density measurements are usually less 3-5 % at 4-11 GHz for fluxes higher 100 mJy.

Radio emission of microquasars have been monitored especially intensively, when these objects are included in the key whole-sky monitoring (ASM) programs at all space observatories or X-ray and Gamma-ray satellites. In the last 10-12 years, we have also striven to monitor microquasars in fact, in a daily mode. The measured light curves are extremely important for the comparison analysis with data in other bands, and a flaring radio emission itself is the best indicator of activity in the microquasar. And, indeed, our announcements about activity often caused to begin of the ToO alert programs on many telescopes around the world: Integral, SMA, LOFAR, EHT, etc [2], [6]-[13]. Now our data are used by researchers of cosmic neutrinos and very high energy Gamma emission. In the report, we present the main observational results of new data obtained in recent years.

2. SS433 – the first relativistic star

The famous microquasar, bright emissive star SS433 with jets bulk motion about 0.26c shows intensive super-Eddington rate of accretion and the continuous massive ejections [14]. Many monitoring sets (e.g., with GBI [15], RATAN (see [2] and references there) were began in 1970-80th.

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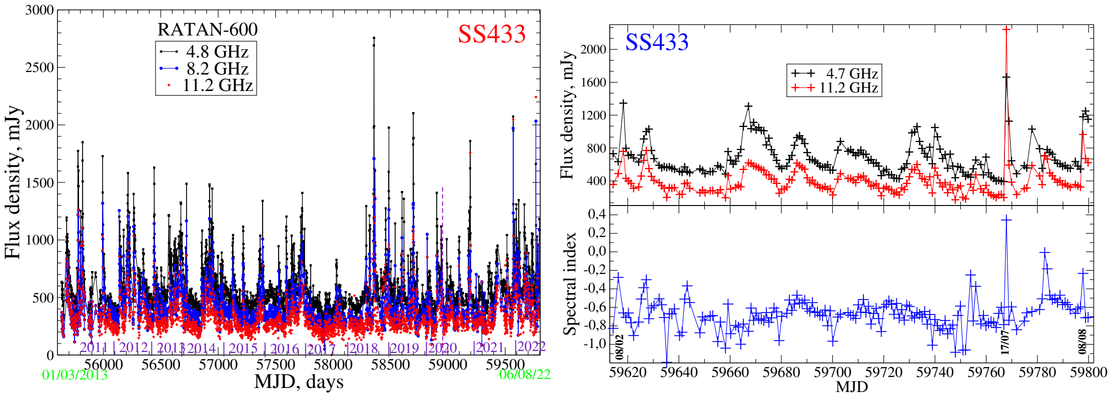

Figure 1: The RATAN light curves of SS433 during 2011-2022 (*left*) and during the first half of the year with the two-point spectral index (*right*).

In Fig.1(left) the light curves of SS433 during near last 4000 days are shown. The total number of flux measurements exceeds 5000 from 2005. A lot of bright flares have been detected and studied [16]. In Fig.1(right) the light curves at 4.7 and 11.2 GHz and the two-frequency spectral index in 2022 are presented. We see increased activity as a lot of radio flares. So the last ones (on MJD 59767.891 and 59797.809) its fluxes increased in 3-4 times by 5-11 GHz in one day. It is worth to notice that the some flares were initially optically thick ($\alpha \geq -0.3$), while others do not stand out in any way on the plot of the spectral index, remaining optically thin. The mean spectral index of the power-law fit for the dates of MJD 59660-59740 is equal -0.68 ± 0.1. We did not find any correlation between the active (flaring) periods and the orbital or precessional phases for the total data.

In order to estimate influence of the orbital modulation we cut all data at 4.7 GHz higher 600 mJy, so the level can be consider as a flaring state level. The result series consists of 1800 points. We used the Lomb-Scargle periodogram to search for characteristic periods in the data. We detected three significant harmonics with the periods: 6.05, 6.1 and 6.59 days, which are probably connected with nutation and half-orbit periods. Thus we confirm the former detection for the shorter sets [17]. Obviously that even quiet fluxes are from the constant jets in SS433, probably are a summa of many discrete blobs (plasmons). It is interesting to compare the radio and optical emission during the active states. We have found that the bulk velocity of jets notably increased during bright flares [18]. The photomertic and spectroscopic data during very bright flare in December 2018 was discussed in [19] and recently in [20].

3. GRS1915+105 – the first microquasar

After detection of the superluminal motion of the radio blobs in the VLBA maps in the GRANAT source GRS1915+105 it has been by right obtained the "Galactic quasar" or microquasar [1]. Indeed it is very active binary with BH and a F star on a orbit (3.8d). Bright radio flares (up to 1.5 Jy) were detected in the GBI monitoring program in 1990th and by us in 2000th [21]. We have detected a clear connection between X-ray flaring activity and a formation of the radio jets, manifesting as radio flares in the light curves [7]. But from 2019 (>MJD 58500) the source has

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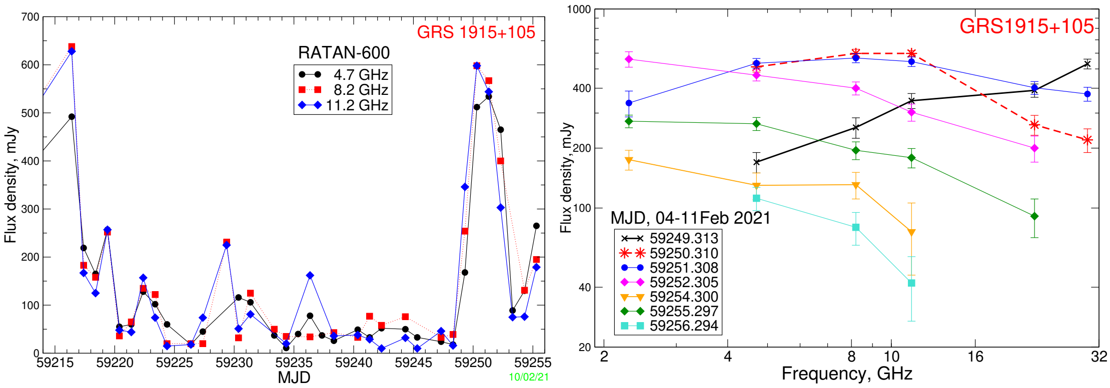

Figure 2: (*Left*): Light curves of GRS 1915+105 at 4.8, 8.2 and 11.2 GHz during 2020-2022. (*Right*): Radio spectra in the February 2021 event.

switched to a soft X-ray state and was very quiet with rare flares. The last one occurred in February 2021. In Fig.2(left) the light curves in 2021 are shown. In Fig.2(right) the daily spectra in the bright flare in February 2021 are shown. They are characterized by optically thin synchrotron emission after a day in the beginning, when the source shows the optically thick spectrum. Thus we can propose evolution of the jets from compact size to extended size at least in one dimension during a flare.

4. Cyg X-3 – the giant flares

Cyg X-3 is the famous radio-emissive X-ray binary including probably BH and a massive Wolf-Rayet star on the orbit (4.8h). A lot of VLBI maps detected the one-side jet-like structure (see for ex.[22]). Indeed in early years [23] and now a lot of the giant (very bright) flares have been detected just after the dramatic changes of the X-ray state – from a high/hard one to a hyper-soft state [24]. It is interesting that Cyg X-3 did not show bright flares during 2012-2016. Such a transit from a quiescence state to a flaring state well illustrated by HID – 'hardness-intensity diagram', firstly constructed in [25]. Such HID is the key evolutional dependence of the X-ray emission of the microquasars [4][26], when Cyg X-3 must pass the 'hyper-soft' X-ray state, in order the powerful radio jets form and we see the gaint flares in the light curves [27]. So two most recent giant flares in October and December 2021 reached 15 and 20 Jy at 11 GHz in maximum for 1-2 days just after a such transit from the null hard X-ray flux at 15-50 keV (Swift/BAT) and again appearance of the notable and the hard X-ray flux and the gamma-ray flux at 0.1-300 GeV (Fermi/LAT). In Fig.3(left) in the bottom panel the radio light curves and in the top panel fluxes at 15-50 keV (Swift/BAT) and Fermi/LAT 0.1-300 GeV during 2021-2022 are shown. Between two giant flares the X-ray state came back in a 'hyper-soft' one.

In Fig.3(right) the multi-frequency spectra during ten days in December 2021 are shown. The early phase of the giant flares is characterized by the optically thick mode in two first days and by the optically thin one in the rest days. Then the spectral index at high frequencies varied gradually from −0.2 to −0.8 and −0.4 to −0.8 for the flare in October and December respectively. Such a behavior is a typical for evolution of the conical jets [27] and we have detected such a evolution of spectra in the many giant flares [28].

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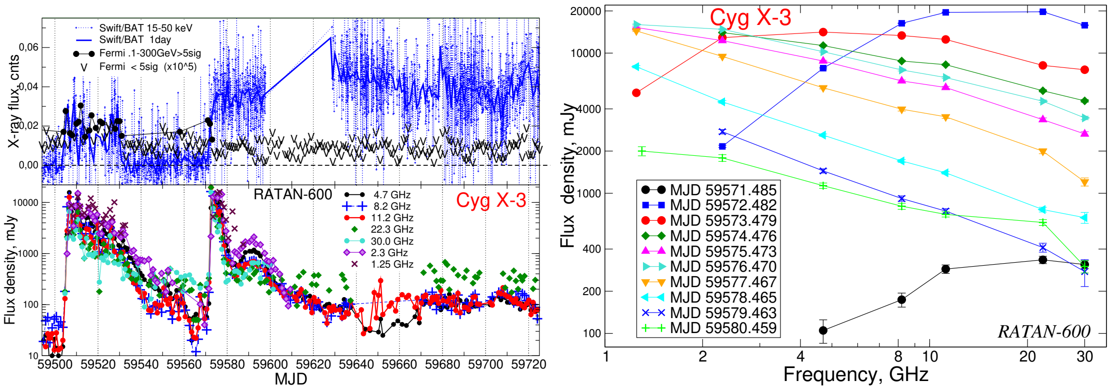

Figure 3: (*Left*): Radio, X-ray, and Gamma-ray light curves of Cyg X-3 during 2021-2022. (*Right*): Radio spectra of the giant flare in December 2021.

5. LSI+61d303 – the first periodical flaring X-ray binary

X-ray binary LSI+61d303 is the luminous Be star, the single periodically flaring radio source GT0236+61, bright gamma-ray source, as recently detected, a transitional radio pulsar with transient period about 269 ms [29]. Indeed the radio properties are very contradictory for the time being. But now in the first time we met a binary with NS, changing two states: an ejector along its orbit and an propeller close to orbit periastron. In radio maps LSI+61d303 seem to have a comet-like structure [30] or shows as a precessing 'jet-like' structure [31]. The strange and no having clear explanation 4.6-year super-orbital modulation were detected by Gregory from the GBI-data of two-frequency monitoring [32]. In Fig.4(left) the light curves during 2013-2022 are shown. The 4.6-year modulation of the maximal flux is well seen. In Fig.4(right) The Lomb-Scargle periodogram of the light curves at 4.7 and 11.2 GHz during MJD 56600–59757, excluding an unclear periodicity of radio flares within MJD 56960–57730. We have detected two clear harmonics with periods 26.47d and 26.93d. For comparison the found periods in GBI data from [33] are shown by the pointed vertical lines. The beat of our harmonics (26.47d and 26.97d) formally give the super-orbital period $\approx$ 1500 days, while it is clear that this value is very dependent from the difference of the found harmonics.

We started the almost daily monitoring of LSI+61d303 with RATAN-600 in 2013 and up to now we have measured the light curves at 4.7 and 11.2 GHz, received the data about almost 120 orbits. In Fig.4(left) the light curves during 2021-2022 are shown. In Fig.4(right) the average for phases of last 20 orbits light curves and the evolution of the spectral index are shown. The spectral index of the power-law fit of the radio emission evolved according to an usual behavior of the synchrotron-emissive blobs in jets, moving away from the binary: from inverse (positive Sp.I.) to steep spectra (negative Sp.I.), and back to flat one.

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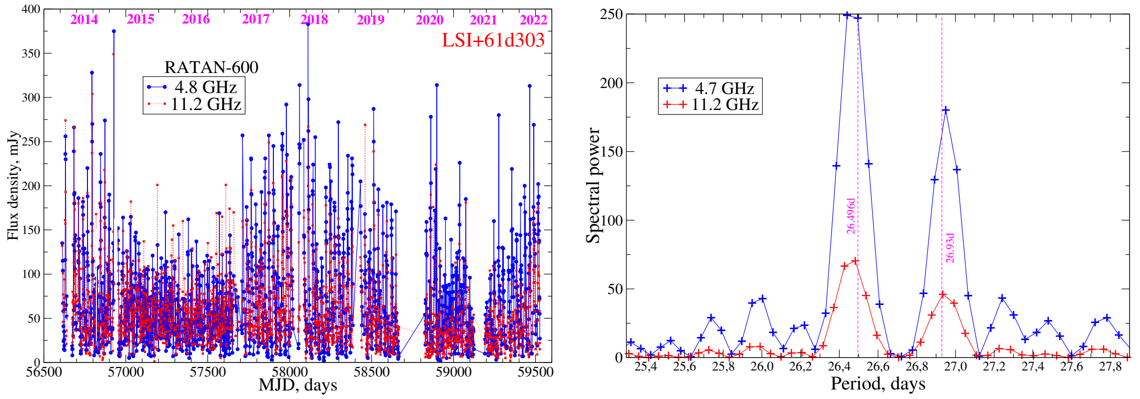

Figure 4: (*Left*): The RATAN light curves of LSI+61d303 during the 120 orbits in 2013-2022, (*Right*): the Lomb-Scargle periodogram of the light curves during MJD 56600–59757.

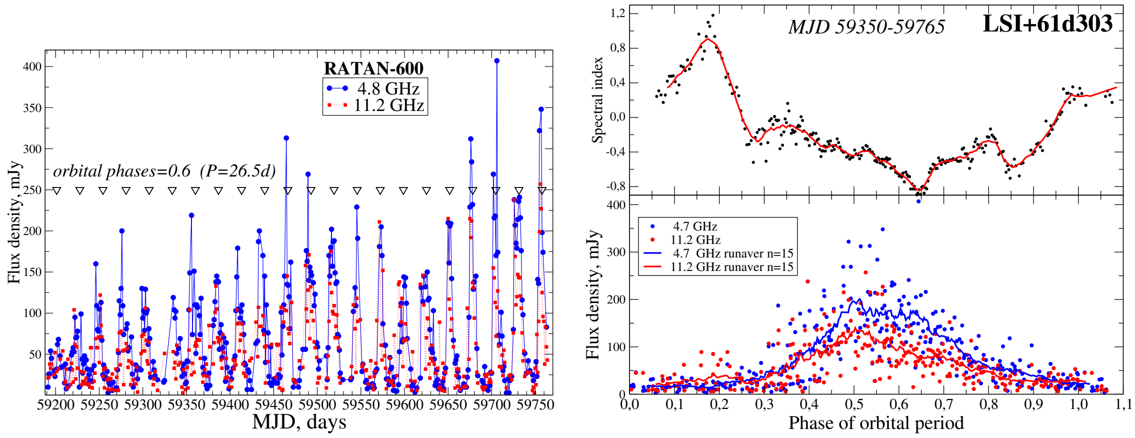

Figure 5: (*Left*): The RATAN light curves of LSI+61d303 during the last 22 orbits in 2021-2022, (*Right*): averaging for an orbit phase light profile of the flare with distribution of the spectral index.

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