RADIO EMISSION OF THE GALACTIC X-RAYS BINARIES WITH RELATIVISTIC JETS

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Abstract

Variable non-thermal radio emission from Galactic X-ray binaries is a trace of relativistic jets, created near accretion disks. The spectral characteristics of a lot of radio flares in the X-ray binaries with jets (RJXB) is discussed in this report. We carried out several long daily monitoring programs with the RATAN-600 radio telescope of the sources: SS433, Cyg X-3, LSI +61°303, GRS 1915+10 and some others. We also reviewed some data from the GBI monitoring program at two frequencies and hard X-ray BATSE (20-100 keV) and soft X-ray RTXE (2-12 keV) ASM data.

We confirmed that flaring radio emission of Cyg X-3 correlated with hard and anti-correlated with soft X-ray emission during the strong flare (> 3 Jy) in May 1997. During two orbital periods we investigated radio light curves of the remarkable X-binary LSI +61°303. Two flaring events near a phase 0.6 of the 26.5-day orbital period have been detected for first time at four frequencies simultaneously.

Powerful flaring events of SS433 were detected at six frequencies in May 1996 and in May 1999. The decay of the flare is exactly fitted by an exponential law and the rate of the decay τ depends upon frequency as τ ∝ ν⁻⁰.⁴ in the first flare and does not depend upon frequency in the second flare, and is equal to τ = 6 ± 1 days at frequencies from 0.96 to 21.7 GHz in the last flare in May 1999.

Many flaring RJXB show two, exponential and power, laws of flare decay. Moreover, these different laws could be present in one or several flares and commonly flare decays are faster at a higher frequency. The decay law seems to change because of geometric form of the conical hollow jets. The synchrotron and inverse Compton losses could explain general frequency dependences in flare evolution. In conclusion we summarized the general radio properties of RJXB.

X-rays binaries with jets

The Galactic plane bright X-ray sources are close binaries, in which a neutron star (NS) or black hole (BH) traps matter from a companion, forming an accretion disk. Amongst ∼ 250 X-ray binaries only ∼ 30 are detected as radio sources (Sν > 1 mJy). Many (or all!!) such bright sources resolved into the relativistic jets with detectable proper motion of bright blobs. This sample of 10-15 such X-ray binaries with jets (RJXB) is extremely interesting for understanding of the astrophysical relativistic jets phenomenon.

In this paper I discuss mainly spectral and temporal properties of the RJXB radio emission. I would like to address the reader to some remarkable reviews, devoted to properties of RJXB:
Figure 1: The flux density variations of GRO J1655−40 during power flare in August 1994 at five frequencies and the MOST data at 843 MHz.

Fender et al. (1997), Mirabel and Rodriguez (1998), Fender (2000a,b,c), papers from two workshops “Relativistic Jets from Galactic Sources” (1997, Jodrell Bank; 1999, Paris).

Just after the discovery the superluminal sources in 1994, ten Galactic radio-emitting X-ray binaries were unified into a sample of RJXB showing relativistic jets. In such close binaries the accretion disks are created by flowing of material from a normal star, filling its Roche lobe, to a compact one. The rate of accretion of material in such binaries could change sporadically or periodically, in accordance with orbital or precession periods. Then two opposite directed relativistic jets from poles of the accretion disk around a compact object are created because of a high accretion rate. Powerful variable radio emission of RJXB seems to form in relativistic moving matter of jets, and could be a trace of the jets formation in the Galactic sources. The causes and details of relativistic electrons generation are unclear, but the accumulated data confirm the strong shocks formation, spreading within the jets. The circumstellar envelope and strong stellar wind, forming a hot corona must be added in convincing models.

The monitoring is continued by Rossi XTE satellite as All Sky Monitoring (ASM) program during the last 150 weeks. In radio band Ryle’s interferometer at 15 GHz and Green Bank interferometer (GBI) at 2.25 and 8.3 GHz carried out monitoring of RJXB during some years. RATAN-600 could obtain complementary daily radio spectra in a wide frequency range.

The RATAN-600 radio monitoring of RJXB

In last years we carried out the monitoring program of radio variability of RJXB: GRO J1655−40, LSI +61°303, GRS 1915+10, SS433, Cyg X-1, Cyg X-3, and CI Cam. In 1995–1999 long-time observational sets of RJXB the dynamical radio spectra at 1–31 cm wavelength range were detected. We found consistent patterns in spectral variability of RJXB. Some light curves of the RATAN monitoring of the RJXB are in Bursov & Trushkin (1995), Trushkin (1998) and Trushkin & Bursov (1999). The last paper is from the “Odessa” part of GMIC’99.
GRO J1655-40

The dynamically resolved black hole GRO J1655−40 is a second (after GRS 1915+105) superluminal X-ray transient discovered by BATSE in July 1994, with 0.9c jets detected by VLBI and the VLA. This is bright emission lines variable optical object showing an orbital modulation of 2.6 days.

We observed GRO J1655−40 only during the decay of most powerful flare in August 1994. Fig.1 shows the light curves at five frequencies and the beginning of the flare from MOST data at 843 MHz. The straight lines are fits by a exponential law of the flare decay. The rates of flux decreasing are similar at different frequencies, but the power law spectra are steeper from 12th to 22th days from the flare beginning as seen in Fig.2.

The RATAN data indicate that GRS J1655−40 could be in a weak nonthermal radio shell diameter of $6'$ or $5.6 \ d/d_{HI}$ pc (if distance $d_{HI} = 3−6$ kpc) with the spectrum $S_\nu [\text{Jy}] = 0.27\nu^{-0.5}$ GHz. Such a shell does not seem to be a supernova remnant because it is much weaker than a typical Galactic SNR with such a surface brightness and diameter.

LSI 61° 303

The Be star/X-ray source LSI 61° 303 was discovered as the variable source GT0236+61 in the patrol Galactic plane survey by Gregory and Taylor (1983). In Fig.3 are shown the light curves of LSI 61° 303 at five frequencies and the GBI data at 2.25 GHz. The x-axis is modified Julian days. We marked the orbital period phases 0.6, during which usually the radio flares (or flux maxima) occur again.

Generally the light curves are well correlation, while the latter maxima of flares come at the lower frequencies. The delay at 2.3 GHz is equal to 1−2 days from the maximum of flux at 11.2 GHz. Daily radio spectra changed quickly day by day and were flat at the beginning of the flare rise, as a consequence of the delay, and then became usual optically-thin synchrotron spectra. Both results could be explained in a model of relativistic jets, moving away from a compact object in the radio-absorbing dense thermal envelope formed by a stellar wind of the binary.
The light curves of LSI 61° 303 in X-ray band 2–12 keV, from RXTE satellite (quick-look data in RXTE ASM program; Levine et al., 1996) show that soft X-ray emission was lower than the detection level during the radio flux maxima, equal to $\sim 5$ mCrab, and just in period the radio flux minimum (MJD 51000 ± 3) reached a prominent value of 20 mCrab (0.0362 mJy).

During the observational set we detected variable radio emission from the recently discovered X-ray binary CI Cam (XTE J0421+560) at 3.9 GHz. Its nonthermal radio emission was firstly detected at a level of 0.5–1 Jy at the end of March 1998, just during a powerful X-ray flare. After three months the radio flux decreased to $\approx 50$ mJy and the source showed small daily flux fluctuations to 20–30% around the mean value.

**GRS 1915+105**

Mirabel et al. (1994) detected apparent superluminal motions in first Galactic source GRS 1915+105, X-ray and radio transient mapping of which with VLA has revealed to possess relativistic jets with true resolved velocity of 0.92c.

We detected GRS 1915+105 with RATAN-600 observations at 3-4 frequencies simultaneously. Thus we plotted daily spectra, which are often inverse with a positive spectral index of $+0.4 - +0.9$ during “quiet” periods. In Fig.4 radio light curves of GRS 1915+105 are shown at 2.25 and 8.3 GHz (JD = 2450900.5 is 00UT 28 March 1998). We used a semi-log plot in order to show the laws of flares decay. Unfortunately it is difficult to say which law is present really. The first and second powerful flares are best fitted by power and exponential laws, respectively while a last law is better fit in general. The spectral index changed from $-0.4$ to $-1.0$ for the first flare in Fig.4 and, in contrast, for second one from $-0.2$ to $+0.5$.

Possible association GRS 1915+105 with SNR G45.7−0.4 is unclear. The X-ray binary is located at the south-west boundary of SNR. The defined size of this SNR (22') is very indefinite and G45.7−0.4 could be wider in X-ray binary direction, as seen from the NVSS map at 1.4 GHz. The distances to SNR and GRS 1915+105 are comparable: $d(\Sigma - D)$=9-10 kpc, and $d$(GRS)=10-12.5 kpc.
Figure 4: The flux density variations of GRS 1915+105 during seventy days of 1995 from GBI data at 2.25 GHz and 8.3 GHz.

Cyg X-3

Since 1972, when Gregory detected a powerful variable radio source, associated with the X-ray binary Cyg X-3, it is regular monitored at radio frequencies. Trushkin (1998) described in details some interesting flaring events during the 80-days monitoring set in summer of 1997. It is coincided with collaborating multi-band monitoring program. Analysis of the light curves in X-ray and radio range (McCollough et al., 1998a,b) confirmed a high correlation of the hard X-ray flux (20–100 keV) and flaring radio flux, and a anticorrelation with soft X-ray emission (2–12 keV) during powerful flaring activity. These light curves are shown by Trushkin & Bursov (1999). For the powerful flare dates of the correlation coefficients are found: $\rho$ (RXTE – 11 GHz) = $-0.64 \pm 0.04$, $\rho$ (BATSE – 11 GHz) = $0.54 \pm 0.04$. Then for the post-flare period the picture is changed: $\rho$ (RXTE – 3.9 GHz) = $+0.69 \pm 0.01$ or $\rho$ (RXTE – 11 GHz) = $+0.66 \pm 0.02$. In general the soft and hard X-ray emission show the anticorrelation in total active period: $\rho$ (2-10 keV – 20-100 keV) = $-0.64 \pm 0.01$, that also confirms before discovered dependence, that a hardness of the X-ray emission anti-correlates with its brightness in a flare.

Probably a flaring variability is a direct evidence of jets formation and their expanding in thermal shell around Cyg X-3 (Trushkin, 1998). On other hand during the deep minimum of the radio flux (below 10 mJy) the formation of the jets are ceased temporarily, in 1–2 weeks. And we see only weak radio emission with flat spectrum from envelope.

The variability of Cyg X-1, the well-known black hole candidate, was studied at 3.9 GHz during the same set. Non-thermal radio emission weakly fluctuated in a range from 10 to 30 mJy. We could not find any significant radio flux modulation with orbital period 5.6 days, recently detected at high frequencies (Pooley et al., 1999). The orbital modulation of the soft X-ray emission was in detail investigated using two-year monitoring program data with RTXE (Wen et al., 1999).

In the 40-day set of observations in December 1998 – January 1999 flux variability of the Cyg X-3 is monitored during very low soft X-ray flux ($\sim 80$ mCrab in range 2-12 keV). Then optically thick radio emission has positive spectral index ($\sim +0.3$) in the range 2.3–11.2 GHz. A flux changed from 40 to 160 mJy at the frequencies.
The X-ray binary and luminous star SS 433 is a persistent bright radio source, detected first in 4C survey. Its active periods are characterized by powerful flares with the flux increasing two-ten times during 1-2 days (e.g. Bursov & Trushkin, 1995). SS433 was resolved into radio blobs on scales from 0.005" to 3", the radio structure location followed a kinematic model, constructed from “moving” emission lines, originated in two opposite directing precessing jets.

Here we can discuss only some characteristics of the powerful flares of SS433 in the last years.

In Fig.5 the radio light curves of the SS433 flares, derived with the continuum radiometric complex of the RATAN-600 radio telescope are given. The usual quiet spectrum, defined in the date range of MJD50210–50215 was subtracted.

In Fig.6 plots of the first flare decays of SS433 are given on different log/semi-log scales with two different fits for comparison. In the figures there are no a distinguished difference of the fits, but the exponential law gives other important and reliable dependence – a power law frequency dependence of a decay rate. In Fig.6 (left) this dependence is shown. The fitting gives \( \tau(\text{days})=14.3\nu^{-0.4}\). It allowed me to argue that the flare decay follows the exponential law. In Fig.6 (right) the best power law fitting of the second flare in May 1996 is shown.
indicating that these dependences are steeper with increasing frequency, from -0.5 to -1.0 at 0.96 and 11.2 GHz, respectively.

In the 60-day set of observations in April 23 – June 23 1999 the strong flare of SS433 was detected during relative low soft X-ray emission state – 20 mCrab in the range 2–12 keV. The data of GBI monitoring of SS433 show that its X-ray and radio activity increase in last year. That is determined by common increasing quiet level in 1.5 times at all frequencies with constant spectral index ($\sim −0.6$) and increasing the frequency of powerful X-ray and radio flares. (see Trushkin & Bursov, 1999).

In Fig. 5(right) radio light curves of the SS433 flares detected in May 1999. We subtracted the “minimum quiet state” that is determined far long ago and being coincident to fluxes in the beginning of June 1999: $S_ν[Jy] = 1.15 ν^{−0.60}_{\text{GHz}}$. Daily radio spectra during the set indicated a negative spectral index. The flare spectrum became steeper during its decay.

A delay of flaring maxima increase with decreasing of the frequency, and is particularly traceable at 0.96 GHz. Decline of the flare (May 10–28) is exactly fitted by exponential law at all frequencies, that is reliable during twenty days at different frequencies. In contrast with the first flare in May 1996 there are no any detectable dependence of rate of decreasing $\tau$ ($S_ν \sim S_o \exp(−t/τ)$) upon frequency. This rate of decay seems to be similar $τ = 6 ± 1$ days at six frequencies.

If a light curve in the beginning of a flare are characterized by a high absorption in a thermal circumstellar envelope, then a spectrum of $S_o$ does indeed indicate the initially injected distribution of the relativistic electrons. In Fig. 8 dependence $S_o$ on frequency is exactly followed to a power law with spectral index equal to $−0.8$ that is usual for non-thermal cosmic sources, like quasars or radio galaxies, indicating acceleration of relativistic electrons on strong shocks in jets.

In Fig. 9 shifts of maximum fluxes dependence, $ΔT$ on frequency are given. It is exactly followed to a power law with spectral index equal to $−0.64$ that is usual for non-thermal cosmic sources, like quasars or radio galaxies, indicating acceleration of relativistic electrons on strong shocks in jets. It is commonly for SS433 that $ΔT(ν)$ is exactly followed to a power law with spectral index being in range from $−0.8$ to $−0.4$. 

Figure 7: Left: Decay rates ($τ$) of the first SS433 flare in May 1996. defined for exponential fitting of the decay via frequency. Right: Power law fittings of the second flare decay in May 1996.
The common property of RJXB is anticorrelation a radio flaring radio flux and a level of soft X-ray emission in comparison of these data. Usually X-ray flares coincided with quiet periods in radio light curves and, vice versa, rare and powerful radio flares coincided with periods of low X-ray emission, probably formed in far regions around SS433. The variable hard X-ray emission, originated from inverse Compton scattering of stellar photons off relativistic electrons responsible for the radio flux could strongly increase during flaring events.

Conclusions

Below we summarize some general radio emission parameters in RJXB:

- Sources Cyg X-3, Cir X-1, CI Cam (XTE 0421+560), 1E1740.7−2942, GRS 1758−258, GX339–4, LSI+61°303 and SS433, are radio jet X-ray binaries. Probably jets play a key role in formation of powerful non-thermal radio emission. The correlation of hard X-ray and radio emission seems to be a common feature of RJXB.

- All RJXB are strongly variable X-ray and IR sources. The Cir X-1 show the neutron star and GRO J1655−40 is a dynamically resolved system with a black hole. Other binaries are only probable NS or BH.

- VLBI observations of RJXB show multi-component structure on a scale 0.001 − 5″. High velocities, 0.1 − 0.92c, are detected from the proper motion of blobs in resolved sources, often showing a apparent superluminal expansion. The relativistic electrons and magnetic fields reserved a large portion of the total power of flare.

- The synchrotron spectra $S_\nu = S_\nu \nu^\alpha$ of RJXB are variable with flares up to 1000 times comparing with quiescent state. Also high linear polarization was detected in SS433, Cyg X-3 during the flares. The processes of thermal absorption in a dense envelope are used for explanation of the frequency-dependent delays of flare maxima.

- The basic model of the synchrotron emission evolution is an adiabatic expansion of the blobs moving away from binaries, which contain the relativistic electrons and magnetic fields (Shklovski, 1960, van der Laan, 1966; then Marti et al., 1992). A conical geometry of jets and
Figure 9: Shifts $\Delta T$ of maximum fluxes at different frequencies from the beginning of the SS433 flare of May 10–20 1999 via frequency. It well enough fitted by a power law with index of $-0.64$.

Considerations of the radiative losses, synchrotron radiation and inverse Compton scattering (ICS) are a modification the basic model to satisfy the spectral and temporal dependences during the flare evolution. ICS in the hot corona around a binary could be responsible for correlation of hard X-ray and radio emission.

- Monitoring of radio variability shows that the decay of flaring flux after the maximum follows: a power law $S_\nu = S_\circ t^{-2p}$, as the Shklovski-van der Laan model predicts and an exponential law $S_\nu = S_\circ e^{-t/\tau}$, the cause of which is a geometric structure of jets. Here often (but not always) $\tau \sim \nu^\beta$, where $\beta$ ranged from $-0.8$ to $-0.4$, thus a flare decays faster at the higher frequency. Maybe there are two different types of flare in RJXB with or without delays and different laws of decay: “flare of core” and “brightening zone” in SS433.

- Quasi-periodical oscillations are detected at X-ray or radio light curves with characteristic frequencies: 0.01-1000 Hz in the black hole candidate RJXB.

- Non-thermal radio halos are produced by precessing jets. Good examples are SS433 and Cir X-1, probably GRS J1655–40 could be in a weak radio shell, and GRS 1915+10 seems to be associated with SNR.

- Similar (magnetic, hydrodynamic, relativistic) models of jet confinement are applied for the Galactic and extragalactic jets despite their different spatial scales.

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