Bull. Astr. Soc. India (2001) **29**, 271–276

# Multiwavelength studies of galactic black-hole candidates

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**Abstract.** One of the Galactic Black-hole Candidates GRS 1915+105 has shown spectacular variability on various time scales in X-ray, Infrared (IR) and Radio wavelengths and has been extensively studied in multiwavelengths during last few years. This X-ray transient source has earned the name "microquasar" as it is known to emit superluminal relativistic radio jets. Since microquasars are much smaller, closer and show faster variability than the extragalactic systems (quasars and other active galactic nuclei (AGNs), they are supposed to be potential "laboratories" for the study of black hole accretion relativistic jet systems. We summarise here some of the exciting multiwavelength studies of this source and discuss the progress made in understanding the accretion disk - jet connection.

*Key words* : accretion, black hole binaries, x-rays, radio, jets

## 1. Introduction

Two Galactic X-ray transient sources GRS 1915+105 and GRO J1655-40 are known to produce relativistic radio jets (Mirabel & Rodriguez 1994; Tingay et al. 1995). These stellar-mass black hole sources are known as microquasars as they possess all the three basic ingredients of quasars: a black hole, an accretion disk heated by viscous dissipation, and collimated radio jets. In black hole binaries accreting at Eddington limit, the characteristic black body temperature of inner accretion disk is $\propto M^{-1/4}$ where M is the mass of the black hole in solar masses (Rees 1984). Therefore, while accretion disks in AGNs have strong emission in the optical and UV, the microquasars with stellar-mass black holes are usually first identified in X-rays. The particles emitted at relativistic speeds can travel up to distances of a few light years only in microquasars instead of several million light years in giant radio galaxies, as length and time scales of the flow around black holes are $\propto$ M (Sams et al. 1996). Since microquasars are much smaller, closer and show faster variability than the extragalactic systems, they are potential "laboratories" for the study of black hole accretion/relativistic jet systems.

At present, there are about 200 known Galactic X-ray binaries (van Paradijs 1995). About 10% of these are radio-loud. Nine of these sources have shown evidence of relativistic jets of synchrotron emission. Among the few stellar-mass black hole binaries, only three X-ray transient sources GRS 1915+105, GRO J1655-40 and XTE J1748-288 are identified as sporadic sources of superluminal radio jets where apparent expansion speed of the radio blobs exceeds the speed of light (Mirabel & Rodriguez 94; Tingay et al. 1995; Hjellming et al. 1998). The X-ray transient GRS 1915+105 has been most active out of all the three superluminal sources in our Galaxy. This source is ~ 12 kpc from the Sun on the opposite side of the galactic plane (Chatty et al. 1996). The precise nature of the binary has been elusive as source can not be studied in optical due to the large extinction by dust.

## 2. Results and discussion

GRS 1915+105 has shown spectacular variability since its discovery in 1992 (Castro-Tirado et al. 1994). The X-ray and radio light curves are shown in top and bottom panels respectively of Figure 1 for about three years 1997-99. The Indian X-ray Astronomy Experiment (IXAE) pointed observations are marked by thick line in the top panel (Agrawal et al. 1996; Yadav et al. 1999; Naik et al. 2001). Time in years is marked in the bottom panel. The X-ray intensity was found to vary on a variety of time scales and the light curve showed a complicated pattern of dips and rapid transitions between high and low intensity (Greiner et al. 1996; Belloni et al. 1997). Yadav et al. (1999) have made a detailed study of various types of X-ray bursts seen in GRS 1915+105 from IXAE observations during 1997 June - August. It is suggested that the peculiar bursts are characteristic of the fast change of state of the source as a result of appearance/disappearance of an advective/halo disk. When an advective/halo disk appears the source goes to the low-hard state, and when it disappears the source reverts back to the high-soft state. Recently, Belloni et al. (2000) have classified a large sample of 163 RXTE/PCA observations in 12 separate classes on the basis of their X-ray light curves and the color-color diagrams (CDs). They have concluded that all the variations shown by the source in X-rays are due to the transition among three basic states: a low-hard state, a high-soft state and a low-soft state. The latter is special to this source.

GRS 1915+105 has also shown remarkable variability in radio as shown in Figure 1 (bottom panel). Eikenberry et al. (2000) have classified the IR and radio emission from GRS 1915+105 into three classes: (A) the relativistic events producing bright superluminal radio jets of ~ 1 Jy with decay times of several days (Mirabel & Rodriguez 1994; Fender et al. 1999), (B) the "baby jets" associated with ~ 100–200 mJy IR and radio flares of about half an hour duration and decay times of several minutes (Eikenberry et al. 1998; Mirabel et al. 1998), and (C) faint IR flares with peak amplitude of ~ 0.5 mJy and duration of 8-10 minutes (Eikenberry et al. 2000). The baby jets and relativistic jets which are extensively studied, are marked by "B" and "R" respectively in Figure 1 (bottom panel) along with their time of occurring.

Harmon et al. (1997) have shown a long-term correlation between hard X-ray flux and jet activity in GRS 1915+105. Simultaneous multiwavelength observations during last four years have substantially improved our understanding of disk-jet connection. The $\beta$ class X-ray activity of Belloni et al. (2000) classification is described as the most complex, and is always accompanied by IR/radio flares. The presence of a "spike" in the X-ray light curve, which separates the dips with hard and soft spectra, clearly distinguishes this class from others. Eikenberry et al. (1998) have compared X-ray and IR profiles during 1997 August 14 simultaneous observations and

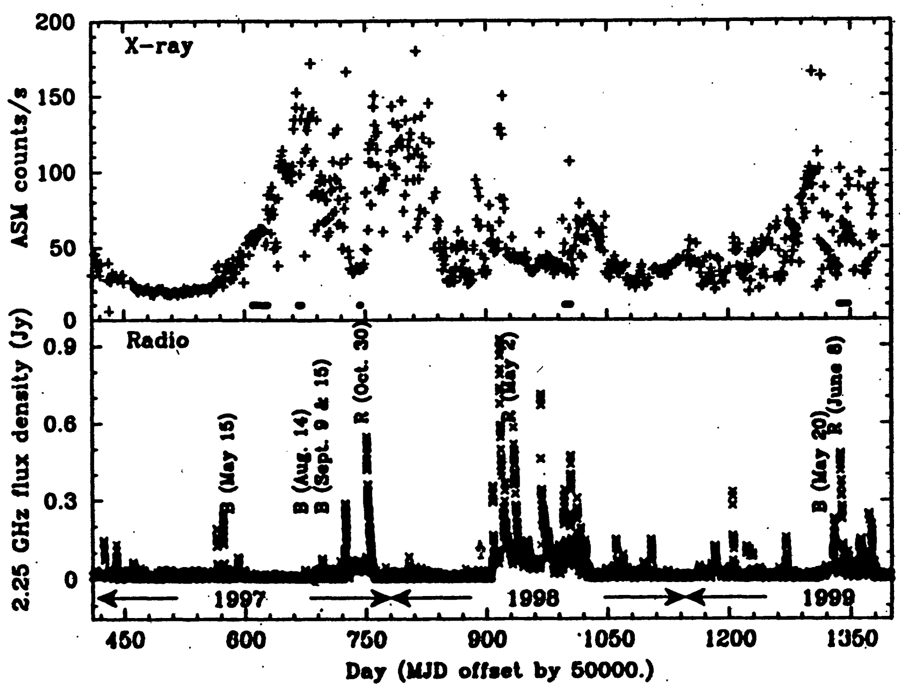


**Figure 1.** X-ray light curve (1.3 – 12.3 keV) of GRS 1915+105 (one day average) obtained with the RXTE/ASM during 1997-99 (~ 3 years) is shown in the top panel. The times of IXAE observations are indicated by thick line. The radio flux at 2.25 GHz from the NFS-NRAO-NASA GBI is shown in the bottom panel for same duration. The positions of extensively studied baby jets and relativistic jets are marked by "B" and "R" respectively alongwith their time of occurring.

have found that the "spikes" in the $\beta$ class coincide with the beginning of IR flares. The IR intensity reaches its peak flux shortly after the X-ray peak. The IR flares have decaying phases very similar in their smoothness and time scale to the rising phases. On the other hand, the X-ray flux begins the fast oscillations after reaching their peak level. During another simultaneous observation of $\beta$ class in IR and radio on 1997 September 9, Mirabel et al. (1998) confirmed the role of the "spike" in initiating IR flares and have found that the radio flares follow the IR flares with a time delay consistent with broad band synchrotron emission. The profiles of IR and radio flares are quite similar.

Recently, Yadav (2001) has presented evidence of a direct accretion disk – jet connection in the Galactic microquasar GRS 1915+105 based on their analysis of RXTE/PCA data of $\beta$ class X-ray activity spanning over a year and have provided an explanation for these most complex light curves observed to date in the Galactic microquasar GRS 1915+105. It is suggested that the "spike" which separates the dips with hard and soft spectra marks the beginning of the burst phase, when the luminosity of the soft X-rays increases by a large factor (~ 10). This produces a major ejection episode of the synchrotron - emitting plasma termed as baby jets with the half-hour spacing widely reported in the literature. Subsequent short but frequent soft dips produce overlapping faint flares which result in an enhanced level of quasi-steady emission.

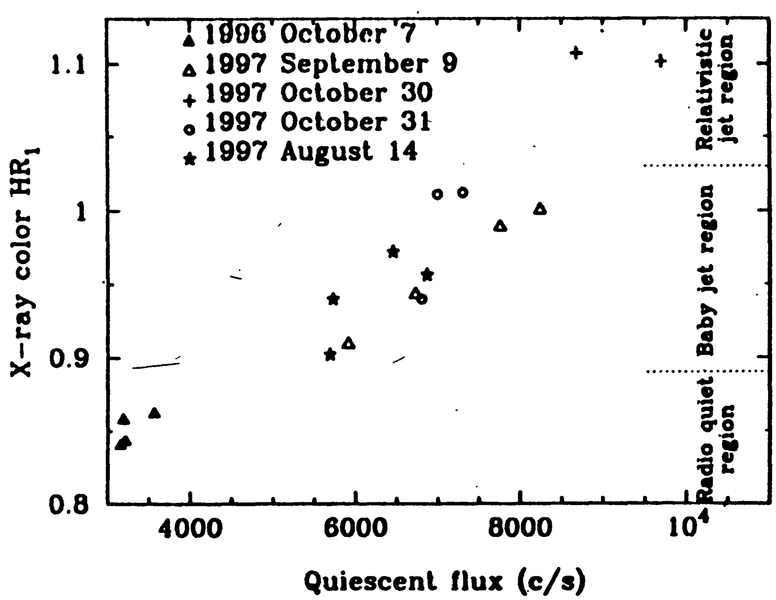


**Figure 2.** The average X-ray color $HR_1$ during the quiescent phase (low-hard state) is plotted as a function of average quiescent flux. The $HR_1$ is defined as the ratio of the flux in the 5 – 13 keV band to flux in the 2 – 5 keV band. Regions of radio quiet, baby jets and relativistic radio jets are marked in the figure.

It is shown that the classes $\beta$ and $\lambda$ of Belloni et al. (2000) actually belong to the same class (Yadav 2001). The average X-ray color $HR_1$ during the quiescent phase (low-hard state) is plotted for these two classes observed over a year in Figure 2 as a function of average 2–13 keV quiescent flux. The $HR_1$ is defined as the ratio of the flux in the 5–13 keV band to flux in the 2–5 keV band. It is found that the radio emission increases as the hardness ratio increases during the low-hard state. The regions of radio quiet, baby jets and relativistic radio jets are marked in Figure 2. It may be noted that the baby jets may also be observed close to the source during a relativistic jet (Fender et al. 1999). Both baby and relativistic radio jets are observed during only two classes $\beta$ and $\theta$ out of twelve classes of Belloni et al. (2000). The sequence of regions in Figure 2 may be valid for both the classes, however the boundaries of the regions may shift in case of $\theta$ class X-ray activity. The spectral analysis suggests that the soft X-ray luminosity (5 – 15 keV) increases over a factor of ten during the high-soft state while the hard X-ray luminosity (20–100 keV) reduced to half than that during the low-hard state when source is undergoing rapid transitions (Rao et al. 2000). The ratio of luminosity during the high-soft state and the low-soft state is ~ 2 in both the soft and hard X-ray bands. The $\Gamma$ becomes steeper, and the inner accretion disk radius decreases during the low-soft state as compared to the high-soft state suggesting a portion of the inner disk and the halo are blown away/disappears during the soft dips (Yadav 2001). The missing energy and mass in X-rays is broadly in agreement with the required energy and the mass outflow rate estimated from radio data. In Figure 3 we show the radio flux at 2.25 GHz from the NSF-NRAO-NASA Green Bank Interferometer for 1997 October 30-31 (data for ~ 48 hours) on the y-axis (left). The X-ray average color $HR_1$ during the quiescent phase is plotted on the y-axis (right) during the same time (data for ~ 24 hours). Clearly, results shown in Figure 4 suggest a correlation between the radio and X-ray data.

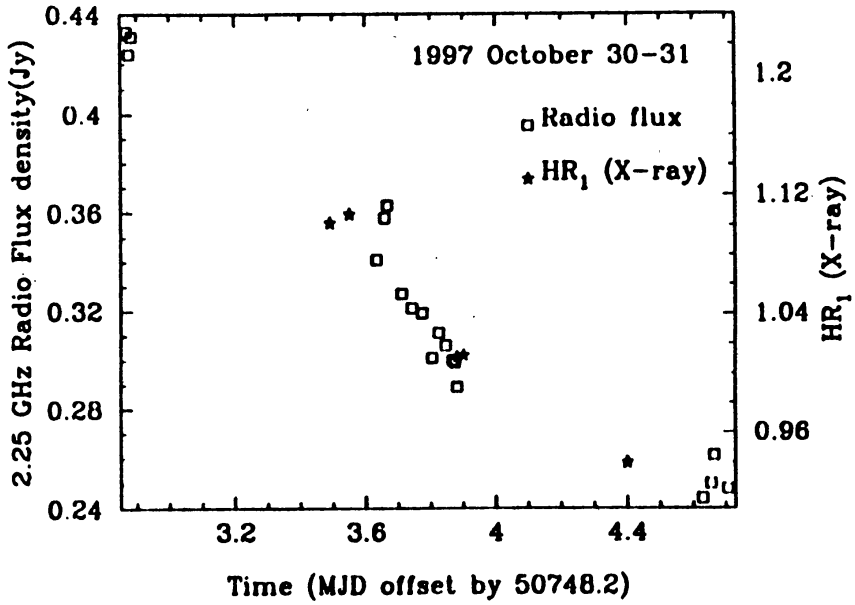


**Figure 3.** The radio flux at 2.25 GHz is plotted for 1997 October 30-31 (data for ~ 48 hours) on the y-axis (left). The X-ray average color $HR_1$ during the quiescent phase (low-hard state) is plotted on the y-axis (right) during the same time (data for ~ 24 hours).

The radio emission during baby jets is consistent with synchrotron emission from an adiabatically expanding small cloud (within a distance of few tens of AU of the inner accretion disk) with a flat radio spectrum. The dominant decay mechanism is adiabatic expansion losses. For a pure adiabatic expansion and a flat radio spectrum, a unit peak radio luminosity will decay to a value of ~ 0.44 in 15 minutes time (Yadav 2001) which is in good agreement with the observations (Eikenberry et al. 1998, Mirabel et al. 1998; Pooley & Fender 1997). The radio emission during the relativistic jets is consistent with synchrotron emission from a extended radio cloud with ballistic motion on the scale of 300-5000 AU and steepening of the spectrum with time ($\alpha$ changes from 0.5 to 1.0 in a few days). Atoyan & Aharonian (1999) have shown that a single population of relativistic particles accelerated at the time of ejection cannot explain the radio emission from the relativistic jets and it requires continuous replenishment of energetic particles with energy dependent losses. Recently, Kaiser et al. (2000) have developed an internal shock model for the origin of relativistic radio jets in microquasars assuming quasi-continuous jet ejection. Recent results of Yadav (2001) support the relativistic jet model with quasi-continuous mass ejection and strong variations in the jet speeds required for the formation of strong internal shocks to continuously accelerate the particles.

## 3. Conclusion

We have presented the variability characteristics of microquasar GRS 1915+105 in multiwavelengths: X-ray, IR and radio and have described how simultaneous observations have changed our understanding of jets and the accretion disk-jet connection which can be used to gain a general understanding of relativistic jets elsewhere in the universe.

Author thanks RXTE and NSF-NRAO-NASA Green Bank Interferometer teams for making their data publicly available.

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