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PECULIAR X-RAY DIPS IN THE SUPERLUMINAL SOURCE GRS 1915+105 OBSERVED IN THE SOFT STATE

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ABSTRACT

This paper reports the detection of a series of X-ray dips in the superluminal black hole source GRS 1915+105 during 1999 June 6−17 from observations carried out with the Pointed Proportional Counters of the Indian X-ray Astronomy Experiment on board the Indian satellite IRS−P3. The observations made in the soft state after the source had made a transition from a low-hard state to a high-soft state, reveal large number of x-ray dips each lasting for about 100- 150 seconds on most of the days. Quasi periodic oscillation (QPOs) with characteristics similar to those of the 0.5−10 Hz QPOs, seen during the low-hard state of the source, were detected in the non-dip portions of the data. The QPOs are, however, not present during the onset or in the dip-period data. During the dips the energy spectrum is soft and the variability is low compared to the non-dip periods. These features re-appear as the dip gradually recovers. Coincident with the occurrence of a large number of X-ray dips, a huge radio flare of strength 0.48 Jy (at 2.25 GHz) was found from the NRAO archival data. It is suggested that the X-ray dips represent mass ejection due to the evacuation of matter from an accretion disk around the black hole and that a super-position of a large number of such dip events leads to production of huge radio jet in GRS 1915+105.

INTRODUCTION

The enigmatic X-ray source GRS 1915+105 discovered in 1992 shows superluminal motion and other radio characteristics similar to those of quasars and hence has been termed as a ‘micro-quasar’. Its variability and spectral features resemble those of black hole binaries. It exhibits strong variability over a wide range of time scales in the X-ray, infrared and radio bands. Its X-ray emission is characterized both by chaotic variability as well as narrow quasi-periodic oscillations (QPOs) at centroid frequency in the range of 0.001 − 10 Hz. The QPOs were discovered in the X-ray emission with the Indian X-ray Astronomy Experiment (IXAE) (Agrawal et al. 1996) and the RXTE (Morgan and Remillard 1996). It is found that the intensity dependent narrow QPOs are a characteristic feature of the hard state and they are absent in the soft state which corresponds to the very high state similar to those of other black hole sources. A strong correlation is also detected between the QPO centroid frequency and spectral and timing parameters like the one found in Galactic black hole candidates in the intermediate state. From the RXTE data there is evidence that the 0.5 − 10 Hz QPOs are correlated with the temperature of the accretion disk (Muno, Morgan and Remillard 1999). Based on extensive X-ray studies the behavior of the source can be classified in two distinct states: the spectrally hard state, dominated by a power-law component when the QPOs are present and the soft state, dominated by thermal emission when the QPOs are absent.

Quasi periodic bursts with period of about 45 s were detected with the IXAE in 1997 June − August. The slow rise and fast decay of the bursts was interpreted as evidence for disappearance of matter into the event horizon of the black hole (Paul et al (1998). Yadav et al. (1999) made a systematic analysis of different types of bursts with recurrence time of about 20 − 150 s. They suggested that the irregular long-duration

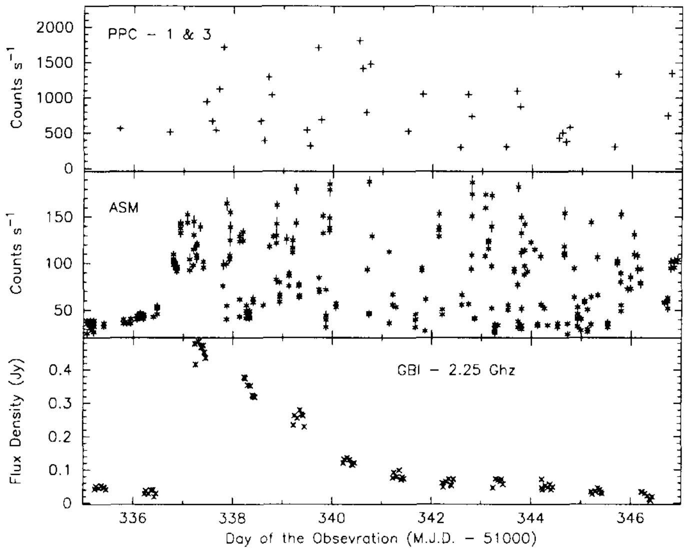

Fig. 1. The X-ray light curve for GRS 1915+105 with the PPCs (averaged over each orbit) in the energy range 2–18 keV, with RXTE ASM in the range 1.3–12.2 keV and radio flux at 2.25 GHz with NSF-NRAO-NASA Green Bank Interferometer, during the observation of the source by the PPCs in IXAE in 1999 June.

bursts (recurrence time $\sim$ 120 s) during which the spectrum becomes harder as the burst progresses and becomes hardest at the end of the decay, are characteristic of the change of state of the source. These irregular bursts were also quasi-simultaneously observed by Belloni et al. (1997a) who interpreted them as repeated filling and evacuation of inner accretion disc.

Simultaneous X-ray and infrared observations of the source established a close link between the non-thermal infrared emission and the X-ray emission from the accretion disk (Eikenberry et al. 1998). Similar episodes of X-ray and radio flares were detected by Feroci et al. (1999) using the BeppoSAX satellite. Simultaneous multi-wavelength observations establish the disk-jet connection in GRS 1915+105. These observations, however, pertain to jet emission which can be termed as "baby-jets" from consideration of energy (Eikenberry et al. 1998). On the other hand, the accretion disk phenomena giving rise to superluminal jets are not very clearly established. Though there is some indication of association between radio and X-ray emission based on low time resolution observations (RXTE ASM and GBI), detailed quantitative association between the two is not very conclusive.

In this paper we report the detection of multiple "disk-evacuation" events which are similar in nature to the "baby-jet" X-ray events (Mirabel et al. 1998; Eikenberry et al. 1998). These events started during the transition of the source state from a 'low-hard state' with the X-ray flux at 0.62 Crab at 1999 June 07 17.79 UT to a 'high-soft state' with a flux of 1.46 Crab at 19.22 UT. A simultaneous increase in radio flux was seen at 2.25 GHz from 0.029 Jy at 1999 June 07 10.94 UT to 0.478 Jy on 1999 June 08 05.54 UT (from the public domain data from the NSF-NRAO-NASA Green Bank Interferometer). The presence of multiple dips in the X-ray light curve during the transition of the state and the simultaneous occurance of flares in radio wavelength provide evidence of "disk-evacuation" process in the inner accretion disk of GRS 1915+105.

OBSERVATIONS AND RESULTS

The X-ray observations of GRS 1915+105 were carried out with the Pointed Proportional Counters (PPCs) of the IXAE on board the Indian satellite IRS-P3. The IXAE includes three co-aligned and identical, multi-wire, multi-layer proportional counters, filled with a gas mixture of 90% Argon and 10% Methane at a pressure of 800 torr, with a total effective area of 1200 cm^2, covering 2 to 18 keV energy range with an average detection efficiency of about 60% at 6 keV.

The source GRS 1915+105 was observed from 1999 June 6 – 15 with 1 s time integration mode and June

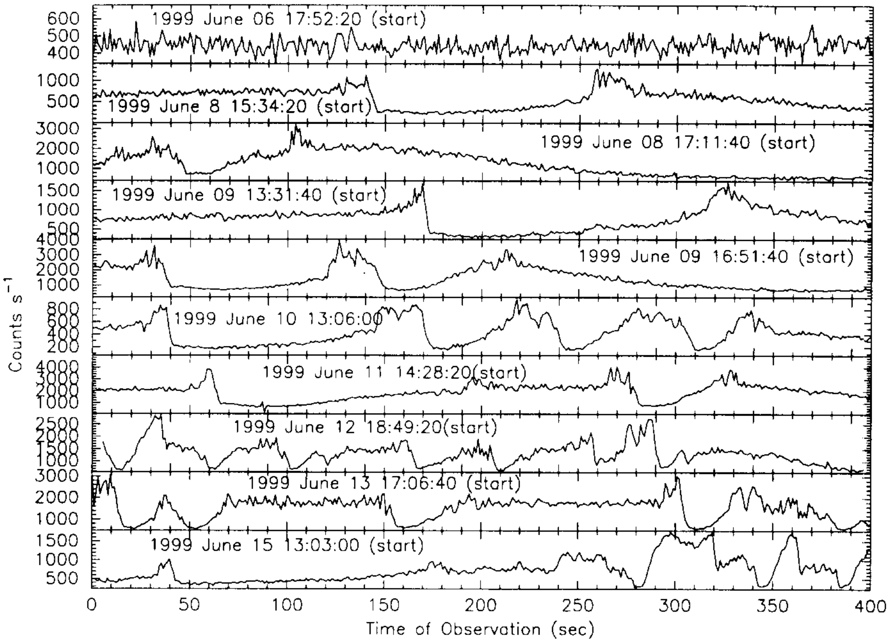

Fig. 2. The light curve of GRS 1915+105 with the PPCs with 1 s bin size in the energy range 2–18 keV. The presence of different types of dips with different periods in the light curve of the source are shown.

16 – 17 in 0.1 time bin, for useful period of 34,412 seconds.

X-ray Dips

The data, corrected for background and pointing offset, for PPC-1 and PPC-3, were added to construct the X-ray light curve for GRS 1915+105. The X-ray light curve for the source in the energy range of 2 – 18 keV for all the observations with the PPCs averaged over each orbit, is shown in Figure 1 (top panel). Also seen in the figure are the 1.3 – 12.2 keV energy range light curve obtained with the RXTE-ASM (middle panel) and the radio flux at the frequency 2.25 GHz (bottom panel) obtained from the public domain data from the Green Bank Interferometer The light curves for some of the individual observations of the source with the PPCs are shown in Figure 2. The following results are notable:

(I) It can be seen that the source made a transition from a 'low-hard state' to a 'high-soft state' in a short time (<1.5 hour) which is very different from the slow transition (about three months) of the source in 1997 May to July (Trudolyubov, Churazov and Gilfanov 1998). The ASM count rate increased from about 53 counts s^{-1} (low state) on MJD 51336.5 to 109.4 ASM counts s^{-1} (high state) on MJD 51336.8 which is also observed by the PPCs.

(II) From the radio light curve of the source, a sharp peak is clearly visible on MJD 51337, on the same day when the source made a transition from the low-hard state to the high-soft state. On MJD 51335 and 51336, when the source was in a low-hard state, the radio flux density at 2.25 GHz was about 0.03 Jy which is described as a 'plateau' state (Fender et al. 1999). After the radio peak, on MJD 51337, the flux decayed slowly over next 5 days. The exponential decay time of the radio flare is estimated to be 2.8 days.

(III) No bursts or dips are seen in the X-ray light curves of 1999 June 06 and 07 (MJD 51335 and 51336) when the source was in a low-hard state.

(IV) From 1999 June 08 onwards various types of dips of duration in the range of 20 to 160 seconds are seen in most of the observations as shown in Figure 2. During the dips, the X-ray flux decreases by a factor of about 3 within about 5 seconds, remains low for 20 to 160 s and then slowly recovers to the maximum. The short term variability in the X-ray light curves decreases during the dip.

(V) Details of two of the dips observed during the PPC observations in 2 – 18 keV, 2 – 6 keV and 6 –

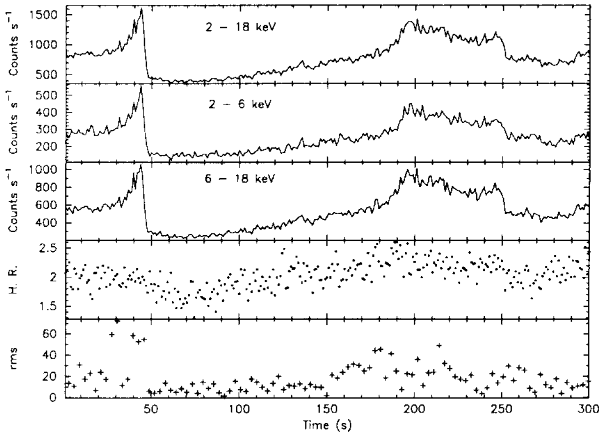

Fig. 3. The light curves of GRS 1915+105 during the dips observed with the PPCs with 1 s bin size in the energy range 2–18 keV, 2–6 keV and 6–18 keV. The dip is identical in shape in all the energy ranges. The hardness ratio (H. R.) is plotted in the fourth panel of the figure which indicates the soft nature of the spectrum during the dips. The lower panel shows the variation in the rms of the source during the dip and non-dip regions.

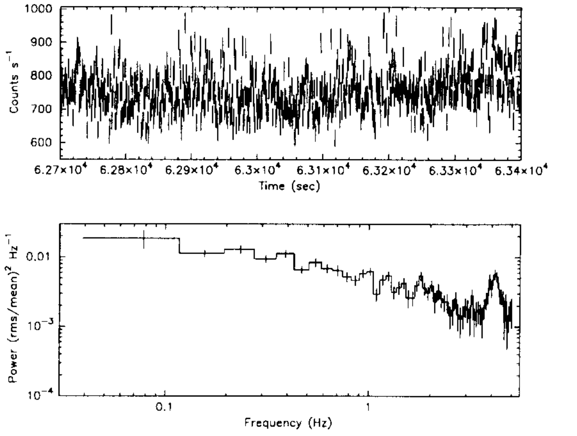

Fig. 4. The light curve and PDS of GRS 1915+105 with the PPCs in the energy range 2–18 keV on 1999 June 17. The presence of a QPO peak at frequency 4.5 Hz is seen during the non-dip period in the X-ray light curve.

18 keV energy ranges, co-added by matching the falling part of the dips are shown in fig.3. There is a sharp decrease in the X-ray flux to almost one third of its original value followed by a slow recovery. The rise time and decay times of the dips are found to be 110 s and 7 s respectively.

(VI) From plot of the hardness ratio (counts in 6 – 18 keV energy range/counts in 2 – 6 keV energy range) in the fourth panel of the Figure 3, it can be seen that during the dips the spectrum (hardness ratio) of the source is soft. Work on spectral fitting is in progress and will be presented later.

(VII) The rms variation in the source calculated from successive three data points in the light curve for 2 – 18 keV energy range during the dip and non-dip regions shown in the bottom panel of fig 4 indicates that there is a sharp decrease in the rms value at the beginning of the dip which recovers gradually as the flux increases. The dips detected in the X-ray light curves with the PPCs are similar to the dips which occurred after the spike in the X-ray light curve, observed on 1997 May 15 and Sept 09 (Mirabel et al. 1998; Markwardt et al. 1999) which is described as the "quiet" state by Markwardt et al. (1999). The properties of the source during this state are similar to those found during the dips observed in 1999 June with the PPCs.

QPOs in 'Dip' and Non-Dip Regions

The power density spectrum (PDS) constructed from 0.1 s time mode data of June 17, shows narrow QPOs at 4.5 Hz as shown in Figure 4 along with the 1s bin light curve. From the figure, it is clear that the QPOs are present in the source when there are no dips in the light curve. From the PDS constructed for observations with the dips and those without dips, it is seen that the rms variations are prominent above 0.1 Hz in data without dips in contrast to the period when the dips are present. The slow recovery during the dips is reflected as the rise in the power below 0.07 Hz in the PDS.

In Table 1, we summarise various properties of the source during the dip and non-dip periods. The average count rate during the dips is about half or one-third of the count rate during the non-dip regions. The values of the hardness ratio and rms variations of the source are always smaller for the dip periods compared to the non-dip periods.

During the multi-wavelength observation of the source carried out in 1997 May 15 and Sept 09, it was

Table 1. Properties of the source during the dip and non-dip periods

Obs. Date,	Count rate		rms		Avg Hardness Ratio.	
1999 June	during dip	during non-dip	during dip	during non-dip	during dip	during non-dip
08 15:36	253.2	713.5	13.9	28.6	—	—
17:09	781.5	1540.6	2.54	8.69	—	—
18:54	854.2	1842	2.5	5.95	—	—
09 13:24	361.3	791.6	2.32	3.27	1.8	2.1
16:48	782.2	2214.8	2.58	5.26	1.63	1.95
10 13:03	198.1	555.77	1.38	4.14	1.8	2.13
16:39	409.3	814.1	1.14	2.10	1.75	1.92
18:09	387.8	816.3	1.26	3.17	1.67	1.865
11 14:23	725.3	2029.2	1.97	4.52	—	—
17:46	257.1	615.0	1.91	1.77	—	—
12 12:20	267.2	635.8	2.6	2.36	1.9	2.1
19:13	724.3	1450.8	1.78	3.89	1.6	1.98
13 13:41	177.9	235.9	1.81	2.32	1.95	1.98
17:06	691.6	1769.9	2.75	3.98	1.75	2.04
14 11:39	221.4	526.6	2.2	4.45	1.98	2.52
16:44	721.2	1434	1.95	4.79	1.74	2.18
18:23	650.5	1563.2	2.64	5.8	1.75	2.06
15 12:59	400.5	784.7	1.79	2.42	1.89	2.40
14:41	286.3	462.4	1.11	2.07	1.65	1.95

found that an X-ray event is followed by non-thermal infrared and radio flares. Using the prescription of Mirabel et al (1998) we estimate whether a series of mini-jets similar to those observed in 1997 May 15 associated with the dips can account for the huge radio flare.

It is estimated that the total radio emission at 2.25 GHz ($\lambda = 13.3$ cm) in the radio mini-flare corresponding to a dip in X-ray flux as

$$F_{13.3} \simeq 40mJyhour. \tag{1}$$

If the total radio emission in the flare observed in 1999 June is a superposition of such mini-flares, we estimate the approximate number of dips in the X-ray light curve required to produce the radio flare as 720. If mini-flares in the radio are associated with the dips in the X-ray, this gives a rate of one dip in 12 minutes (in PPC).

DISCUSSION

Based on the studies of series of X-ray outbursts attributed to 'inner-disc evacuation' by Belloni et al (1997a) and short period (20-40 min) radio oscillations during the start of the jet emission (Fender et al 1999), there is suggestion of a casual connection between the disk and the jet. On the other hand Paul et al (1998) and Yadav et al (1999) have interpreted a variety of X-ray bursts detected with the IXAE in terms of two-component accretion flow model (Chakrabarti and Titarchuk 1995) and concluded there was no need for any mass ejection. From simultaneous observation in the radio, infrared and X-ray bands it is inferred that when the X-ray emission makes a transition from a high oscillating state (period $\simeq$ 10-20 s) to a low hard state (period $\simeq$ 100 s) there are X-ray dips characterized by hard spectrum and 0.5 Hz QPO which return gradually to the high state followed by synchrotron flares in infrared and radio (Mirabel et al 1998, Eikenberry et al 1998).

The peculiar dips presented in this paper provide an additional feature in the X-ray emission which, we argue, is related to mass ejection and the consequent jet production. There is a vast difference in the nature of the X-ray light curves of the source between the 1999 June observation reported in the present work and those seen in 1997 using PPCs (Paul et al. 1997; Yadav et al. 1999) and RXTE (Belloni et al. 1997a). During the present observations the spectrum was softer as the hardness ratio of the source was less, during the dips in comparison to the non-dip regions. The observed properties of the source during the non-dip periods i.e. rms variability in X-ray flux, presence of QPO at a centroid frequency of $4 - 6$ Hz disappear during the dips. There is a gradual return to the accretion-disk properties: the hardness ratio and the variability characteristics slowly change back to the pre-dip values.

Morphologically, these dips have properties very similar to those seen during the dips responsible for the infrared flares (Eikenberry et al. 1998; 2000; Mirabel et al. 1999). Fender et al. (1998) have worked back the onset time of the super-luminal blobs and during these times the radio emission shows oscillations in a time scale of $20 - 30$ minutes. Similar radio oscillations (at similar periods, but at lower intensity) are observed to be accompanied by a series of soft X-ray dips (see Figure 10. of Dhawan et al. 2000). Further, one of the superluminal blobs was thought to originate from the core on MJD 50750.5 (which is accompanied by radio oscillations) and the X-ray emission observed on MJD 50751.7 shows soft X-ray dips (see Muno et al. Figure 1e).

Since there is evidence to associate such dip events to radio emission, it is proposed that a series of dips can produce the complete radio flare lasting for a few days. The onset of dip events coincided with the onset of the radio flare within a few hours. A superposition of several disk evacuation events can produce the radio flare if one assumes a scaling for energy from single dip events. It would be interesting to see whether all radio flares are necessarily accompanied by such disk evacuation events.

To produce the observed radio light curve, one needs to assume that the number of dips produced as a function of time also follows a similar time profile. The present observations are not continuous enough to support this hypothesis. It is quite suggestive that during the superluminal jet events of 1997 October – November, the frequency of radio oscillations decreased from 2.9 hr^{-1} on MJD 50750.5 (when the radio flux was 200 mJy) to 1.9 hr^{-1} on MJD 50752.5 (when the radio flux decreased to 120 mJy - see Figure 4 of Fender et al. 1999). The smooth radio light curve and the steep spectrum could be due to the movement of the ejecta in the interstellar medium. For example, the 1997 October – November radio flare is the superposition of at least four ejecta and the start of each ejecta is associated with a series of radio oscillations.

The mass and energy estimate of the superluminal blobs emitted by GRS 1915+105 (Rodriguez and Mirabel 1994) is too large to be caused by a single isolated event in the accretion disk, and a series of accretion disk-driven events would be required, as suggested by Fender et al. (1999). The series of dips that we have observed could provide the necessary energy for the superluminal blobs, if they occur in a rapid series. A continuous X-ray monitoring during a radio flare will clarify this question. Also, the dips seen during the later part of the radio flare are of shorter durations and these events may not be ejecting matter in sufficient quantities. It is quite conceivable that only the long duration dips with a gradual recovery are responsible for jet emission. The start of the dips always shows similar observable parameters like count rates and hardness ratio indicating a causal relationship between disk parameters and the onset of dip events.

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