DETECTION OF A SERIES OF X-RAY DIPS ASSOCIATED WITH A RADIO FLARE IN GRS 1915+105

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ABSTRACT

We report the detection of a series of X-ray dips in the Galactic black hole candidate 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 were made after the source made a transition from a steady low-hard state to a chaotic state which occurred within a few hours. Dips of about 20–160 seconds duration are observed on most of the days. The X-ray emission outside the dips shows a QPO at \( \sim 4 \) Hz which has characteristics similar to the ubiquitous 0.5–10 Hz QPO seen during the low-hard state of the source. During the onset of dips this QPO is absent and also the energy spectrum is soft and the variability is low compared to the non-dip periods. These features gradually re-appear as the dip recovers. The onset of the occurrence of a large number of such dips followed the start of a huge radio flare of strength 0.48 Jy (at 2.25 GHz). We interpret these dips as the cause for mass ejection due to the evacuation of matter from an accretion disk around the black hole. We propose that a super-position of a large number of such dip events produces a huge radio jet in GRS 1915+105.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — stars: individual (GRS 1915+105) — X-rays: bursts — X-rays: stars

1. INTRODUCTION

The X-ray transient source GRS 1915+105 was discovered by Castro-Tirado, Brandt, and Lund (1992) with the WATCH all sky X-ray monitor on-board the Granat satellite. The source has been exhibiting a wide variety of temporal variability in its X-ray and radio emission. GRS 1915+105, the first Galactic superluminal radio source, has characteristics of a micro-quasar and is located at a distance of about 12.5 ± 1.5 kpc (Mirabel & Rodriguez 1994). Besides the chaotic variability, narrow quasi-periodic oscillations (QPO) at centroid frequency in the range of 0.001–10 Hz were discovered in the X-ray emission from the source using the Indian X-ray Astronomy Experiment (IXAE) (Agrawal et al. 1996) and the RXTE (Morgan & Remillard 1996). A QPO at a centroid frequency of 67 Hz which does not change with time, was also detected in this source in the RXTE observations. It has been suggested that it is related with the innermost stable orbit in the accretion disk of the source. Chen, Swank, & Taam (1997) found that the intensity dependant narrow QPOs are a characteristic feature of the hard branch and it is absent in the soft branch which corresponds to the very high state similar to those of other black hole candidates. Trudolyubov, Churazov, & Gilfanov (1999) studied the 1996/1997 low luminosity state and transitions of states using the RXTE data. They found a strong correlation between the QPO centroid frequency and spectral and timing parameters similar to the one detected in other Galactic black hole candidates in

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the intermediate state. Munó, Morgan, & Remillard (1999) sampled the RXTE data over a wide range of properties and found that the 0.5 − 10 Hz QPOs are correlated with the temperature of the accretion disk. From the studied behavior of the source they distinguish two different states of the source: 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.

Paul et al. (1998) detected quasi periodic bursts with period of about 45 s using the IXAE data obtained in 1997 June − August and interpreted the slow rise and fast decay of bursts as evidence for matter disappearing into the event horizon of the black hole. Yadav et al. (1999) made a systematic analysis of these bursts and classified them into regular, irregular and quasi-regular based on the burst duration and recurrence time. They found the bursts to recur at a mean time of 20 − 150 s and they suggested that the irregular long duration bursts (recurrence time ∼ 120 s) during which the spectrum becomes harder and harder as the burst progresses and becomes hardest at the end of the decay, are characteristic of the change of state of the source. They calculated the rise time and the decay time for these bursts to be of the order of a few seconds (∼ 10s). The back and forth switching of the state of the source from a low-hard to a high-soft state within a time scale of a few seconds is explained by invoking the appearance and disappearance of the advective disk over its viscous time scale. These irregular bursts were also quasi-simultaneously observed by Belloni et al. (1997) 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). They found that the X-ray properties showed a drastic change coincident with the occurrence of the IR and radio flares. Similar episodes of X-ray and radio flares were detected by Feroci et al. (1999) using the BeppoSAX satellite. From the spectral analysis of the X-ray data, they found evidence for a temporary disappearance and subsequent restoring of the inner accretion disk during the flare. Such 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” (Eikenberry et al. 1998) from consideration of energy. On the other hand, the accretion disk phenomena giving rise to superluminal jets are not very clearly established. Harmon et al (1997) found an anti-correlation between the decrease in the hard X-ray flux (obtained from BATSE with a time resolution of ∼1 day) from the accretion disk and the subsequent jet production. Fender et al. (1999) worked back the time of occurrence of super-luminally moving jets and found rapid (20 − 30 minute) radio oscillations during the beginning of such jets. Though they attempted to associate these oscillations with the X-ray oscillations detected by Belloni et al. (1997), there are no simultaneous high time resolution observations in the radio and X-ray wave-bands during huge radio flares responsible for super-luminal jets. Though there are 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. Hence we can conclude that the disk-jet connection for jets with superluminal motion is indirect at best.

In this paper we report the detection of multiple X-ray dips interpreted as “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 steady low-hard state with the X-ray flux at 0.62 Crab at 1999 June 07 17.79 UT to a chaotic 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 after the transition of the state when a radio flare also occurred, suggest the presence of “disk-evacuation” process in the inner accretion disk of GRS 1915+105.

2. INSTRUMENT AND OBSERVATIONS

The X-ray observations of GRS 1915+105 were carried out with the Pointed Proportional Counters (PPCs) of the Indian X-ray Astronomy Experiment (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 accepted X-ray events are stored in counters in 2−6 keV and 2−18 keV band for the top layer, 2−18 keV band for the middle layer, > 18 keV (ULD counts) for all layers and > 2 keV counts from the veto layers. For a detailed description of the PPCs refer to Agrawal (1998) and Rao et al. (1998).

The IRS-P3 satellite is in a circular orbit at an altitude of 830 km and inclination of 98\°. Pointing towards any particular source is done by using a star tracker with an accuracy of ≤ 0\°.1. The useful observation time is limited to 5 of the 14 orbits outside the South Atlantic Anamoly (SAA) region to the latitude band of 30\°S to 50\°N to avoid the charge particle background. The high voltage to the detectors is reduced when the satellite enters the SAA region and the data acquisition is stopped.

Background observations were made at the end of the source observation by pointing the PPCs to a source-free region in the sky, close to the target source as the simultaneous background observation is not possible because of the co-alignment of the PPCs. The source GRS 1915+105 was observed from 1999 June 6 − 15 with 1 s time integration mode and June 16 − 17 in 0.1 s time bin, for useful period of 37,740 seconds. The log of the observations is given in Table 1.

3. ANALYSIS AND RESULTS

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 dead time correction is not done as it is less than 1\% for each PPCs as the event processing time for each PPCs is about 20 \(\mu\text{s}\). 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 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). The radio observations were taken from the public domain data from the NSF-NRAO-NASA Green Bank Interferometer.

As can be deduced from the low resolution ASM and GBI data, the source was in a steady low-hard state from June 2 to June 7 (MJD 51331 to 51336). It made a transition to a ‘chaotic state’ in a very short time which is very different from the slow transition (about three months) of the source in 1997 May to July (Trudolyubov, Churazov, & Gilfanov 1999). The source count rate increased from about 53 ASM counts s\(^{-1}\) on MJD 51336.5 (June 7 12.00 UT) to 109.4 ASM counts s\(^{-1}\) on MJD 51336.8 (June 7 19.2 UT). The onset of X-ray activity is further constrained by the PPC observations on June 7 17.50 UT, when the source showed a steady behaviour. Hence we can conclude that there was an abrupt change in the X-ray emission characteristics in less than 1.7 hours. From the radio light curve of the source, a sharp peak is clearly visible on MJD 51337 (June 8), on the same day when the source showed the X-ray transition as seen from the RXTE/ASM light curve. The onset of the radio flaring event is between June 7 10.94 UT and June 8 05.54 UT. 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. Though the low time resolution X-ray light curve appears like a flaring event, a closer examination of the high resolution data reveals that variations of much shorter duration are also present as indicated by a factor of 4 − 5 variation over a few days within a span of a few hundred seconds in a series of dips.

The light curves for some of the individual observations of the source with the PPCs are shown in Figure 2 and 3. 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. 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 and 3. During the dips, the X-ray flux decreases by a factor of about 3/2 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. The duration of the dips is not constant in all the observations. In some of the observations, short period dips of 20 − 60 seconds duration are observed after the occurrence of long dip with duration of more than 100 s. Towards the end of the observation, long duration dips lasting for more than 100 s are not seen but larger numbers of shorter duration dips are observed. A summary of the duration of dips observed in the light curves of the source is given
The dips observed during the PPC observations in the energy ranges, co-added by matching the falling part of the dips. In the figure, the sharp decrease in the X-ray flux to almost one third of its original value followed by a slow recovery is clearly seen. We have calculated the rise time and decay time for the dips by fitting exponential to the light curve. The values are found to be about and 110 seconds and 7 seconds respectively. The hardness ratio (counts in $6 - 18$ keV energy range / counts in $2 - 6$ keV energy range) for the same observation is shown in the fourth panel of the figure. It is seen from the figure that during the dips the spectrum (hardness ratio) of the source is soft. The bottom panel in Figure 4 shows the rms variation in the source calculated for successive three data points in the light curve for $2 - 18$ keV energy range during the dip and non-dip regions. There is a sharp decrease in the rms value at the beginning of the dip which recovers gradually as the flux increases.

The hardness ratio is computed for all the PPC observations. It is found that during the dips, the value of the hardness ratio is less in comparison to the non-dip regions for all the observation which indicates that the spectrum of the source is soft during the dips. There is no significant change in the value of hardness ratio averaged over each orbit. The timing behavior of the source was studied by taking the Fourier transform of 1 s and 0.1 s resolution mode data. From the power density spectrum (PDS) constructed from 0.1 s time mode data of June 17, narrow quasi-periodic oscillations (QPOs) are detected at 4.5 Hz as shown in Figure 5 along with the 1 s 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. As the time resolution is limited to 1 s for most of the observations, we could not study in detail the QPOs in the frequency range of $1 - 10$ Hz during those periods when the dips were present.

In Table 2, 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.

All the above properties of the source during the non-dip and dip regions are also seen in the publicly available RXTE/PCA data on 1999 June 08. The RXTE/PCA public archive contains only one observation during the radio flare (from June 8 to June 13) and we have analyzed this data to substantiate the properties of the dips. The first dip in X-ray band detected with the PPCs (shown in Figure 2, second panel) was also seen with RXTE/PCA at the same time. Figure 6 shows the X-ray light curve of the RXTE/PCA data in the energy range of $2 - 13$ keV (upper panel) and the hardness ratio (count rate in $5 - 13$ keV energy range / count rate in $2 - 5$ keV energy range) (lower panel) for the source. The PDS for the source for the different regions i.e. regions during the dips and during the absence of dips is shown in Figure 7. The first, third and fifth panels in the figure represent the PDS during the absence of the dips and second and fourth show the PDS during the dips. A narrow QPO peak at a centroid frequency in the range $4 - 6$ Hz is seen in the non-dip regions which is absent in the dips. The spectrum during the dips is softer in comparison to the non-dip regions. These properties are consistent with the PPC observations.

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.

During the multi-wavelength observation of the source carried out in 1997 May 15 and Sept 09, it was found that an X-ray event is followed by non-thermal infrared and radio flares. Here we estimate whether a series of mini-jets similar to those observed in 1997 May 15 (Mirabel et al. 1998) associated with the dips can account for the huge radio flare. From the simultaneous observation of the source in X-ray, IR and radio, Mirabel et al. (1998) estimated the value of spectral index of the relativistic electrons by applying the van der Laan (1966) model and derived a relation for the observed maximum flux density ($S_\lambda$) at a given wavelength $\lambda$ and the time since the ejection to reach the maximum flux at a particular wavelength ($t_\lambda$) given by

$$S_\lambda \propto \lambda^{-(7p+3)/(4p+6)}$$  \hspace{1cm} (1)
They found the value of spectral index $p \simeq 0$ by using the observed maximum flux density at 3.6 cm and 6 cm during the burst observed on 1997 May 15. They determined the time for $t_{\text{6cm}} \simeq 0.9$ h and $t_{\text{3.6cm}} \simeq 0.65$ h. Using these parameters we estimate the peak flux at 2.25 GHz ($\lambda = 13.3$ cm) as 26.5 mJy and $t_{\text{13.6cm}}$ as 1.6 hr. Assuming the time profile of the radio emission as seen by Mirabel et al. (1998) we estimate 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

$$F_{13.3} \simeq 40\text{mJyhour}.$$  

The total radio emission at 2.25 GHz during the 1999 June flaring is estimated by integrating the radio profile (for 6 days) by fitting an exponential to the decay phase of the light curve. If the total radio emission in the flare observed in 1999 June is a superposition of such mini-flares, we can calculate 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).

4. DISCUSSION

Galactic superluminal sources are ideal astrophysical laboratories to probe in detail the connection between jets and accretion disks, ubiquitously thought to be present in Quasars. There were several attempts in the past to isolate characteristics in the X-ray emission of these sources (assumed to be coming from an accretion disk) and relate them to the onset of jet emission. Also, evidence for a sudden mass ejection event from the accretion disk is sought in the X-ray emission characteristics. Belloni et al. (1997) have discovered a series of outbursts in GRS 1915+105 which were attributed to “inner-disk” evacuation. They found that the source makes transition to two intensity levels lasting from a few tens to a few hundred seconds with distinct and different inner disk radii (as obtained from spectral measurements) and they attributed this change to the disappearance of inner disk due to thermal-viscous instabilities. Fender et al. (1999) made a detailed analysis of the super-luminal jet ejection events observed in GRS 1915+105 in 1997 October/November and detected continuous short period (20–40 minute) radio oscillations shortly after the start of the jet emission. They proposed that these are indications of repeated ejection of inner accretion disk, quite similar to the events seen in X-rays by Belloni et al. (1997). A causal connection between disk and jet was thus attempted.

Paul et al. (1998) and Yadav et al. (1999) have made a detailed study of such intensity variations using the data obtained with the IXAE and contemporaneous to the burst events reported by Belloni et al. (1997). They found that the source spectrum i.e. the ratio between the count rate in $6 – 18$ keV energy range/count rate in $2 – 6$ keV energy range, was softer during the burst and harder during the quiescent phase. Yadav et al. (1999) concluded that the repeated intensity variation cannot be attributed to inner disk evacuation. This is due to the viscous time scale arguments as well as due to the fact that the two intensity states are quite similar to the low-hard and high-soft state of the source. They invoked the two component accretion flow model (TCAF) of Chakrabarti & Titarchuk (1995) to conclude that the rapid changes are due to the appearance and disappearance of advective disk covering the standard thin disk without any requirements of mass ejection. Further, these types of hard dips (with a transition time of a few seconds) are seen almost for about a month in 1997 June (Yadav et al. 1999) when the radio emission was low. We estimate an average radio emission for this month as 8 mJy at 2.25 GHz using the GBI data. There was also no evidence for any flares (flux < 20 mJy at all times). Hence the causal relationship between the disk instabilities and jet emission can be treated as not completely established.

In the next sub-section we summaries the available X-ray and radio observations which indicate the disk-jet connections.

4.1. Radio and X-ray emission in GRS 1915+105

1. There are periods of long durations when both the radio as well as the X-ray emissions are low. One example is from 1997 January-March when the X-ray flux was $\sim 0.25$ Crab and 2.25 GHz radio flux was 10 mJy. These are classified as the radio-quiet hard state observations in Muno et al. (1999).

2. There are durations when the X-ray and radio flux are higher, which are classified as radioloud hard-steady state. They are also known to

$$t_\lambda \propto \lambda^{(p+4)/(4p+6)}$$

(2)
RAPID STATE TRANSITIONS IN GRS 1915+105 exhibit optically thick radio emission and referred to as the “plateau” state (1996 July-August; 1997 October). For the 1997 October “plateau” state, the X-ray flux is 0.50 Crab and 2.25 GHz radio flux is 50 mJy. There is evidence for an AU scale radio jet observation in this state (Dhawan et al. 2000).

3. The X-ray flux changes from the steady-hard state to a flaring-state at various time-scales from a few hours (as seen in the present work) to a few months. During this time a variety of X-ray variations are seen.

3.1 The X-ray flux teeters between two intensity states in a short time (a few second) with a periodicity of $20 - 150$ s. These are called “inner-disk oscillations” by Belloni et al. (1997) and “irregular and quasi-regular” bursts by Yadav et al. (1999). There is no evidence for enhanced radio emission during these events.

3.2 A peculiar morphology of X-ray emission is associated with radio and infra-red flares. The X-ray emission changes from a high oscillating state (at a period of $10 - 20$ s) to a low hard state (in a time scale of about $100$ s). The X-ray intensity in the low-hard state gradually increases. There is a sudden dip characterized by low intensity, low hardness ratio and disappearance of the $0.5 - 10$ Hz QPO. The source gradually returns to the high oscillating state. These are associated with the synchrotron flares in radio (Mirabel et al. 1998; Fender & Pooley 1998) and infrared (Eikenberry et al. 1998). The peak intensities of these flares are in the range $100 - 200$ mJy from infrared to radio bands (Eikenberry et al. 2000). Eikenberry et al. (1998) strongly argue that the onset of radio/infrared flare is associated with the soft dip rather than the gradual change to the low-hard state.

3.3 Eikenberry et al. (2000) identify a series X-ray dips coincident with faint infrared flares. The peak amplitude of the observed mini-infrared flares are found to be $\sim 0.5$ mJy for a duration of a few hundred seconds. The period of the soft X-ray dips, producing the observed flares is found to be $\sim 20$ s. These soft dips have the X-ray characteristics identical to the dips seen during the synchrotron infrared flares (3.2 above).

4. The huge radio-flares producing superluminal blobs are associated with chaotic X-ray variability (as measured by low time resolution X-ray data). The radio spectrum is steep during these flares. There is, as yet, no strong morphological identification with detailed X-ray emission characteristics.

In the following sections we argue that these soft X-ray dips are responsible for the superluminal radio flares.

4.2. Radio flare as a collection of X-ray dips

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. 1998; Yadav et al. 1999) and RXTE (Belloni et al. 1997). 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 dip. 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 (see Figure 4).

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. 1998). Fender et al. (1999) have worked back the onset time of the superluminal 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 Fig 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. Fig 1e).

In view of strong evidence for association of such dip events to radio emission, it is suggested that a series of dips can produce the complete radio flare lasting for a few days. The onset of the first dip event detected with the PPCs on June 8, 15.51 UT and independently with the RXTE coincided with the onset of the radio flare within a few hours. It was shown in the previous section that a superposition of several disk evacu-
tion 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 X-ray dips interpreted as 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. Since the IXAE data are obtained for only 5 of the 14 orbits everyday, observations are not continuous enough to conclusively establish this hypothesis. It may be pointed out 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 Fig. 7 of Fender et al. 1998). The smooth radio light curve and the steep spectrum could be due to the movement of the ejecta in the interstellar medium. The radio flares of 1997 October – November seen by Fender et al. (1998) 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 estimates of the superluminal blobs emitted by GRS 1915+105 (Rodriguez & Mirabel 1999) 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.

4.3. \textit{TCAF model for the advection accretion}

We attempt to interpret the present results in the light of the TCAF model for the advective accretion disk around the black holes.

It has been recognized that very near to the black hole, accretion is necessarily advective and far away from the compact object it is believed that the accretion is through a geometrically thin accretion disk. In the ADAF (Advection Dominated Accretion Flow) model of Narayan & Yi (1994) the changeover occurs at a transition radius ($r_{\nu}$) whereas in the Two Component Accretion Flow (TCAF) model of Chakrabarti & Titarchuk (1995) a standing shock wave or a centrifugal barrier dominated dense region at $R_0$ separates these two. Das & Chakrabarti (1999) have included the effect of outflow in the TCAF model. GRS 1915+105 changes from hard to soft states at a variety of time scales and the observed properties of the source can be interpreted as the variation in $R_0$.

4.3.1. \textit{Time scales of the dip events}

Yadav et al. (1999) derived various time scales for the quiescent period, decay time and rise time for the different types of bursts observed by equating the inner disk radius ($R_{\nu}$) to $R_o$ from where the advection dominated halo component covers the thin accretion disk during the quiescent state. They obtained the viscous time scale for the standard $\alpha$ disk ($t_{\nu}^d$) as

$$t_{\nu}^d = 4.3 \times 10^{-4} \alpha^{-1} \dot{m}_d^{-1} m^{-1} R_o^2$$

where $\dot{m}_d$ is in the unit of Eddington accretion rate, $m$ is the mass of the source in the unit of solar mass and $R_o$ in km. They calculated this time scale ($t_{\nu}^d$) to be of the order a few hundred seconds for $\dot{m}_d = 1$, $m = 10$, $\alpha = 0.01$ and $R = 300$ km.

Similarly, the time scale for the advection disk for halo component $t_{\nu}^h$ (Yadav et al. 1999) as

$$t_{\nu}^h = 4.9 \times 10^{-6} \alpha^{-1} m^{-1/2} R_o^{3/2}$$

Using the parameters used to derive $t_{\nu}^d$, the free fall time scale is calculated to be order of seconds, which agrees with the decay time of the observed dips.

The recovery time of the dips ($\sim 110$ s) agrees with the calculated viscous time scale of the standard disk $t_{\nu}^d$.

The time-scale of the dip onset (a few seconds) is comparable to the free-fall time scale as well as the advective disk time scale (equation 5), for typical advection dominated disk parameters. Hence we can conclude that all the accretion disk characteristics suddenly disappear during the dips and
they reappear in a gradual way. We feel that a sudden disk evacuation and a gradual refilling is a natural explanation for this observation.

4.3.2. TCAF explanation for the outflow

To produce radio jets, a large amount of matter has to be expelled from the disk and this has to be accelerated to relativistic velocities. Das & Chakrabarti (1999) have proposed a combined inflow/outflow model in which the computation is done using combinations of exact transonic inflow and outflow solutions. Assuming free-falling conical polytropic inflow and isothermal outflows, they estimated the ratio of outflowing and inflowing rate to be

\[
\frac{\dot{M}_\text{out}}{\dot{M}_\text{in}} = \frac{\Theta_\text{out}}{\Theta_\text{in}} \frac{R}{4} e^{-f_0 + \frac{3}{2}} f_0^{3/2}
\]

(6)

where \(\Theta_\text{out}\) and \(\Theta_\text{in}\) are the solid angles of the outflow and inflow respectively, \(R\) is the compression ratio of the inflowing matter which is a function of the flow parameters such as specific energy and angular momentum (Chakrabarti 1990) and \(f_0\) is given by

\[
f_0 = \frac{R^2}{R - 1} = \frac{(2n + 1)}{2n} R
\]

(7)

\(n\) is the polytropic constant = \(1/(\gamma - 1)\), \(\gamma\) being the adiabatic index.

They found that the outflow rate depends on the initial parameters of the flow and in some cases the outflow rate can be higher than the inflow rate leading to disk evacuation. We propose that the dips that we have observed are a result of such disk evacuation phenomenon. It would be interesting to carry out a detailed spectral and timing analysis to extract the exact disk parameters leading to a disk evacuation event.

4.4. Jet acceleration

It is possible that the accretion disk magnetic field is responsible for accelerating the disk evacuated matter into radio emitting jets. Meier et al. (1997) have proposed a magnetic switch that can generate superluminal jet ejection. They have shown that when the coronal Alfven velocity exceeds a critical value, the jet velocity can become relativistic. We have calculated the Alfven velocity by assuming the advection dominated disk parameters given by Narayan et al. (1998).

The expression for Alfven velocity \(V_A\) and Escape velocity \(V_{\text{esc}}\) are

\[
V_A = \frac{B}{\sqrt{4\pi \rho}}
\]

(8)

\[
V_{\text{esc}} = \sqrt{\frac{2GM}{r}} = \frac{c}{\sqrt{r}}
\]

(9)

where \(B\) is the magnetic field, \(r\) is the radial distance, \(\rho\) is the plasma density and \(r\) is the distance in the unit of Schwarzschild radius.

Assuming an equipartition with the magnetic energy, the expression for \(B\) and \(n_e\) (number density) are given by (Narayan et al. 1998)

\[
B \simeq 7.8 \times 10^8 \alpha^{-1/2} \dot{m}^{-1/2} \dot{m}^{1/2} r^{-5/4} \text{ G}
\]

(10)

\[
n_e \simeq 6.3 \times 10^{19} \alpha^{-1} \dot{m}^{-1} \dot{m}^{1/2} r^{-3/2} \text{ cm}^{-3}
\]

(11)

where \(\alpha\) is Shakura & Sunyaev viscosity parameter, \(m\) is in the unit of \(M_\odot\), and \(\dot{m}\) is in the unit of Eddington accretion rate. For equipartition of magnetic field (i.e. \(\beta = 0.5\)),

\[
\alpha = c (1 - \beta) \simeq 0.3 \quad (\text{for } c \sim 0.5 - 0.6)
\]

Taking the values of \(m\) as 10 and \(\dot{m}\) as 0.1 to 1 for GRS 1915+105, we estimated the magnetic field and the density (assuming one proton corresponding to one electron in the plasma) as

\[
B = 4.51 \times 10^8 \dot{m}^{1/2} r^{-5/4} \text{ G}
\]

\[
\rho = 3.5 \times 10^{-5} \dot{m} r^{-3/2} \text{ g/cc}
\]

Using the values of \(B\) and \(\rho\), the Alfven velocity \(V_A\) is calculated to be

\[
V_A = \frac{B}{\sqrt{4\pi \rho}} = 2.1 \times 10^{10} \sqrt{\frac{\frac{c}{\sqrt{r}}}{\sqrt{r}}}
\]

(12)

Now, the ratio between \(V_A\) and \(V_{\text{esc}}\) is

\[
\frac{V_A}{V_{\text{esc}}} = \frac{2}{3}
\]

(13)

We find that the Alfven velocity is near the critical velocity for advection dominated flows indicating the operation of the magnetic switch. It should be noted that just before the detection of the superluminal jet ejection in GRS 1915+105 in November 1997 by Fender et al. (1998), the source was in a low-hard state as well as a radio-loud state. We can envisage a scenario where the accretion disk condition during a low-hard state makes the magnetic switch to operate and the
ejected material is accelerated to relativistic velocities. These accelerated blobs can move in the interstellar medium to give the steep spectrum superluminal ejecta. The transition period from a low-hard to a high-soft state provides critical conditions for a series of disk evacuation events to occur so that sufficient matter is ejected to produce relativistic jets. A continuous monitoring in X-ray and radio bands during a radio flare will clarify most of these questions.

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Trudolyubov, S., Churazov, E., & Gilfanov, M. 1999, Astr. L., 25, 718
van der Laan, H., 1966, Nat, 211, 1131
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.

Fig. 2.—
Fig. 3.—Fig. 2 and 3 show the light curves 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.
Fig. 4.— 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. 5.— 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.
Fig. 6.— The light curve of GRS 1915+105 obtained with the RXTE/PCA data on MJD 51337 in 2 – 13 keV energy range with 0.8 s time bin is shown for two dips (A & C). The hardness ratio (H. R.) of the source i.e. countrate in 5 – 13 keV energy range / countrate in 2 – 5 keV energy range is also shown (B & D).
Fig. 7.— The PDS of the source GRS 1915+105 in the energy range 5 – 13 keV for different regions of the light curve. The panels A, C, and E represent the PDS during the non-dip periods i.e. earlier to the first dip, between the two dips and beyond the second dip respectively, as seen with the RXTE/PCA on 1999 June 8. The panels B and D represent the PDS during the dip periods in the light curve. The figure shows the presence of QPOs in the frequency range 4 – 6 Hz during the non-dip regions which are absent during the dips.
**Table 1**

Log of X-ray Observation of GRS 1905+105 with IXAE

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<tr>
<th>Obs. Date, 1999 June</th>
<th>Start time (UT)</th>
<th>End Time (UT)</th>
<th>Count rate</th>
<th>Source intensity (in Crab)</th>
<th>Duration of dips (s)</th>
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**Note:** H. R. is for Hardness Ratio.