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Different types of class transitions of GRS 1915+105 using IXAE data

Asit K. Choudhury[1*], Achintya K. Chatterjee[1,2], Anuj Nandi[3]
[1] *Centre For Space Physics, Malda Branch, Atul Market, Malda 732101, India*
[2] *Malda College, Malda 732101, India*
[3] *Centre For Space Physics, Chalantika 43, Garia Station Rd, Kolkata 700084, India*

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Abstract. The microquasar GRS 1915+105 exhibits at least 13 distinct classes of light curves. We observed different types of class transitions of light curves of GRS 1915+105 by analyzing the data obtained from the Indian X-ray Astronomy Experiment (IXAE) instrument aboard the Indian satellite IRS-P3 and with data from the Rossi X-ray Timing Explorer (RXTE) archives. We show seven different types of class transitions in the data obtained from IXAE. It is also observed that the QPO frequencies are changing during the transitions. Assuming that the transitions are caused by variations in the accretion rates, implies that a significant fraction of the matter must be nearly freely falling in order to have such transitions.

Keywords : Stars: individual: GRS 1915+105 - X-rays: stars - stars: binaries: general - stars: activity

1. Introduction

The X-ray transient source GRS 1915+105 was discovered in 1992 by the WATCH instrument on GRANAT (Castro-Tirado et al. 1992) satellite. Due to very large interstellar absorption, the optical counterpart of this source was not easily found. Greiner et al. (2001) reported the results of a spectroscopic analysis in the H and K bands, which suggest that the mass-donating star is a K-M III star, i.e. GRS 1915+105 belongs to the class of low-mass X-ray binaries. The mass of the compact object is estimated to be

*e-mails:- akc_malda@fastmail.fm, asit_mda@hotmail.com

14.0±4.4 $M_\odot$ (Harlaftis et al. 2004) and is at a distance of 12.5±1.5 kpc (Mirabel et al. 1994). Since its discovery, it has been continuously bright in X-rays, emitting a luminosity of more than 10^{39} ergs/sec for extended periods (Yadav et al. 1999). It has been exhibiting different types of X-ray variability characteristics (Morgan et al. 1997; Muno et al. 1999; Yadav et al. 1999; Belloni et al. 2000). The source has been monitored in the radio band (Mirabel et al. 1994; Pooley et al. 1997; Fender et al. 1999) and several episodes of high radio emission and huge flares associated with superluminal motions were observed in GRS 1915+105. Attempts were made to correlate the radio emission, presumably coming from jets, to the X-ray emission from the accretion disk (Fender et al. 1999; Naik et al. 2001; Naik & Rao 2000). Fender & Pooley (1998) showed that the IR emission, interpreted as the high energy tail of a synchrotron spectrum also varies on a similar time scale as the radio emission. In a matter of days the light curve changes its characteristics and within each day photon count shows variations by a factor of two to five or more (Morgan et al. 1997; Belloni et al. 1997; Paul et al. 1998; Manickam et al. 1999). The Power Density Spectrum (PDS) shows clearly the evidence of quasi-periodic oscillations (QPO) with frequency ranging from 0.001 Hz. to 67.0 Hz. (Morgan et al. 1997; Chakrabarti et al. 2000).

According to the Two Component Advective Flow model (TCAF) of Chakrabarti & Titarchuk (1995) the inner boundary condition of the black hole forces the matter to deviate from Keplerian distribution.Therefore the accretion disk consists of two parts, a Keplerian component (of high viscosity and high angular momentum) at the equatorial plane and a sub-Keplerian component (of low viscosity and low angular momentum) that resides above and below the Keplerian component.

As matter moves closer to the black hole at about few tens of Schwarzschild radii, the centrifugal force becomes comparable to the inward gravitational force and the supersonic inflow slows down. If this slowing down occurs in a thin region (Chakrabarti 1989) the flow is said to suffer a shock, the flow becomes subsonic from supersonic. As matter slows down, the kinetic energy is converted to thermal energy. As a result, the post shock flow becomes hot and puffs up in the form of a torus, which is called CENtrifugal pressure supported BOundary Layer (CENBOL). This CENBOL is a source of hot electrons, it intercepts soft photons from the Keplerian disk and reprocesses to hard X-rays by inverse Comptonization.

Since a lot of heat is stored in the CENBOL, Chakrabarti and his co workers have shown that (Chakrabarti 1999) the thermal pressure along the vertical direction pushes the matter in the form of outflow and jets. When the outflow rate is high, the slowly moving subsonic region could be catastrophically cooled down by the soft photons from the Keplerian disk. The sonic surface of the cooler outflow comes closer to the black hole horizon and the flow separates into two parts. Matter from the region above the new sonic sphere separates supersonically as blobs and matter below the new sonic sphere returns back to the accretion disk. This causes enhancement of accretion rate. As accretion rate

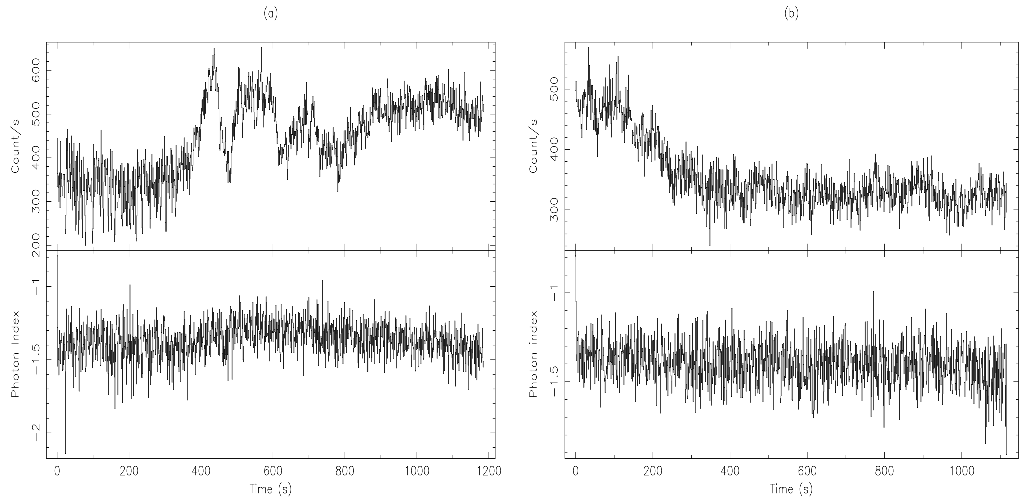

Figure 1. $2 \sim 18$keV light curves as observed by IXAE (upper panel) and the mean photon spectral index s_ϕ (lower panel) in 4th and 5th orbits of 1997 August 07 (see Table 1). GRS1915+105 (a) has a tendency to change from γ class to δ class, (b) in γ class on that day. Lower panels show how s_ϕ marginally changes. Specifically it is noisy during the transition.

changes locally, not the entire disk, with time the amount of outflow from the CENBOL also changes,which may be a cause of rich variations of the light curves of GRS 1915+105.

Belloni et al. (2000) in a model-independent analysis of the variability of GRS 1915+105 analyzed 163 observations with the RXTE in the period 1996-1997. They divided the light curves into twelve different classes which are designated as χ, α, ν, β, λ, κ, ρ, μ, θ, δ, γ and ϕ. Naik et al. (2002) showed that there is another independent class called ω. Chakrabarti et al.(2004) presented two examples of rare class transitions, using IXAE data, where they showed κ to ρ class and χ to ρ class transitions of GRS 1915+105. In 2005 Chakrabarti et. al. showed ρ to α class transition and in between two known classes sometimes a class of unknown type appears. They also showed that during class transitions the mean photon index s_ϕ becomes noisy.

In this paper, we are going to show some new types of class transitions, all of them being from the Indian satellite data. We found that (i) a class transition is invariably accompanied by a significant variation of the average X-ray photon count rate, which indicates that the Keplerian flow rate or the sub-Keplerian flow rate or both may change. (ii) During transition, the mean photon index becomes noisy until the flow settles into a new class indicating the turbulent behaviour during transition. We also study the behaviour of QPOs during and after the transition.

The Indian X-ray Astronomy Experiment (IXAE) was launched on-board the Indian Remote Sensing Satellite IRS-P3 using the Polar Satellite Launch Vehicle (PSLV) on 1996

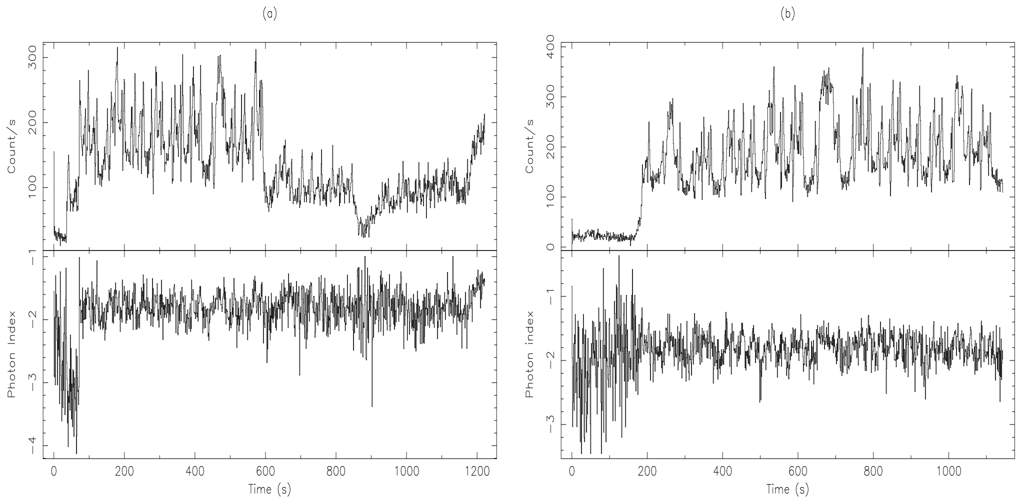

Figure 2. (a) Class transitions (μ) of GRS 1915+105 as observed by IXAE and (b) from unknown class to μ class during two successive orbits on 1997 August 09 (See Table 1). In the lower panels s_ϕ is showing noisy behaviour during transition before settling down.

March 21, from Sriharikota range in India (Agrawal 1998). The satellite is in a circular orbit at an altitude of 830 km and inclination 98^o. The IXAE includes the collimated Pointed Proportional Counters (PPCs) with an effective area of about 1200 sq cm filled with a gas mixture of 90% argon and 10% methane at a pressure of 800 Torr. Each PPC is a multi-anode, multi-layered detector with 54-anode cells of size 11cm $\times$ 11cm arranged in three layers with a wall-less geometry (Paul et al. 1997). The operating energy range lies between 2 and 18 keV, with an average detection efficiency of 60% at 6 keV. The counts are saved in the archive in two channels, $2 \sim 6$, $6 \sim 18$ keV. The time resolution in medium mode could be 0.1 sec. But normally the time resolution was set to be 1 sec. We have analysed those data that are out of the South Atlantic Anomaly region and also not belonging to the period of 'occultation' due to earth.

2. Observations and data analysis

The X-ray photon counts of the source GRS 1915+105 obtained from the IXAE of all channels $2 \sim 6$, $6 \sim 18$ and $2 \sim 18$ keV were analyzed. In Figs 1-4 and 6, there are two panels; in the upper panel we have plotted the light curves i.e. the photon count along y - axis and time along x - axis and in the lower panel the mean photon index s_ϕ vs time. The mean photon index s_ϕ is given by

$$s_\phi = -\frac{log(N_{6-18}/E_2) - log(N_{2-6}/E_1)}{log(E_2) - log(E_1)}, \quad (1)$$

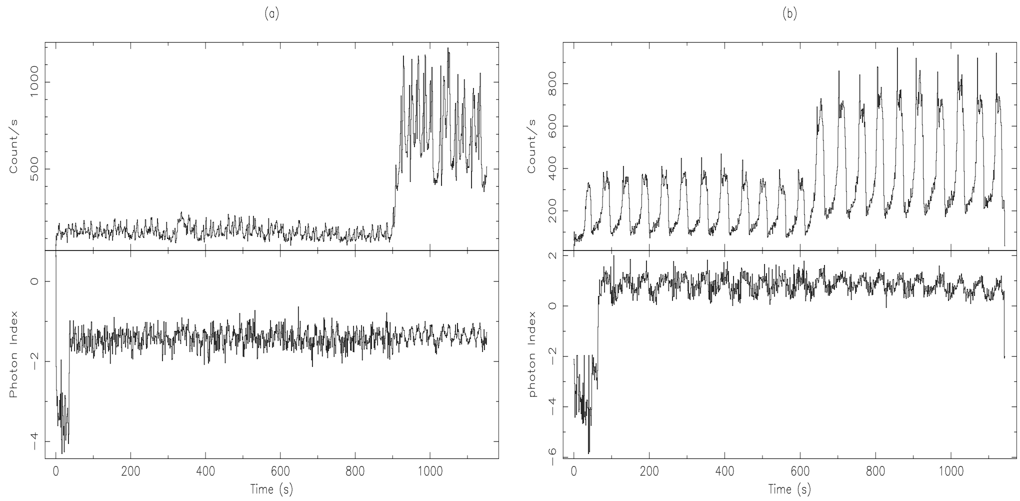

Figure 3. (a) A sub-class or may be a new class to μ class transition and (b) a same class (ρ) transition of GRS 1915+105 as observed by IXAE on 1997 August 10 and 2000 June 22 respectively. Lower panels show variations of s_ϕ.

where, N_{2-6} and N_{6-18} are the photon count rates from the top layer of the PPC, E_1 and E_2 are the mean energies in each channel. Thus, $E_1 = 4$ keV and $E_2 = 12$ keV respectively. We have normalized the count rate per keV and then obtained the slope in the log-log plot since we expect a power-law slope in the $4 - 12$ keV range. We have analyzed the data by using FTOOLS packages from NASA.

In Table 1, we present the log of observations of class transitions reported in this paper. The first column refers to the figure number. The second column shows the date of observations. The third column gives the orbit numbers plotted in the figure. Typically, the time interval between two successive orbits is approximately 80 minutes. The fourth column gives the exact nature of class transitions. Since, during transitions a given class is not found to be 'canonical' as defined by Belloni et al. (2000), we have put the class-names inside quotation marks.

The upper panels of Figs 1a and b indicate the light curves ($2 \sim 18$ keV) of the 4th and 5th orbit of 1997 August 7. In Fig.1a the nature of light curve has a tendency to change from γ class to δ class, here the average photon count rate changes from 350 to 500 per second but in Fig.1b it returns to its initial count rate.

In the lower panel of Fig. 1a we see that initially the values of photon index (s_ϕ) changes from ~ 1.2 to ~ 1.7 during transition and after transition it becomes ~ 1.3 to ~ 1.6 which is less noisy. But after completing one orbit i.e. after 80 minutes s_ϕ again it becomes ~ 1.2 to ~ 1.7 (Fig. 1b).

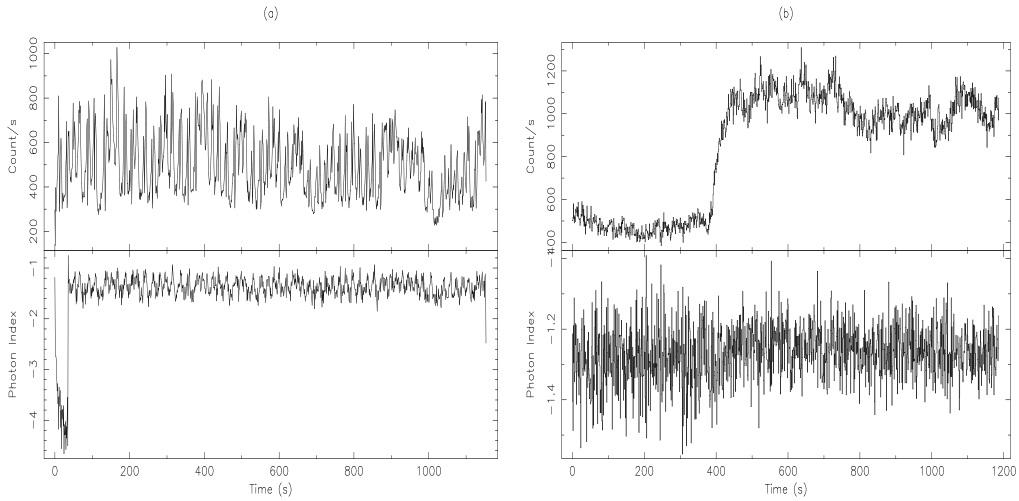

Figure 4. Another same class (δ) transition observed from low count to high count in the 4th orbit of 1997 August 11 which is shown in Fig.4b has no transition in the 3rd orbit of the same day(Fig. 4a).

Table 1. Class transitions of GRS 1915+105.

Figure	Date	Orbit No.	Class transitions
1.	7th August, 1997	4, 5	'γ' $\rightarrow$ 'δ'
2a.	9th August, 1997	4	'μ' $\rightarrow$ 'μ' (same class)
2b.	9th August, 1997	5	'Unknown' $\rightarrow$ 'μ'
3a.	10th August, 1997	3	'Sub Class or New class'$\rightarrow$ 'μ'
3b.	22nd June, 2000	4	'ρ' $\rightarrow$ 'ρ' (same class)
4b.	11th August, 1997	4	'δ'$\rightarrow$ 'δ' (same class)
5.	11th August, 1997	1,2,3,4	'δ'$\rightarrow$ 'δ' (PDS of class transition)
6a.	19th June, 2000	4	'χ' $\rightarrow$ 'ρ'
6b,c.	20th June, 2000	1	'Unknown' $\rightarrow$ 'ρ'
	22nd June, 2000	2	

The IXAE observations of the 4th orbit on 1997 August 09 showed that the system is in μ class with a change in high count to low count state i.e. a same class transition,

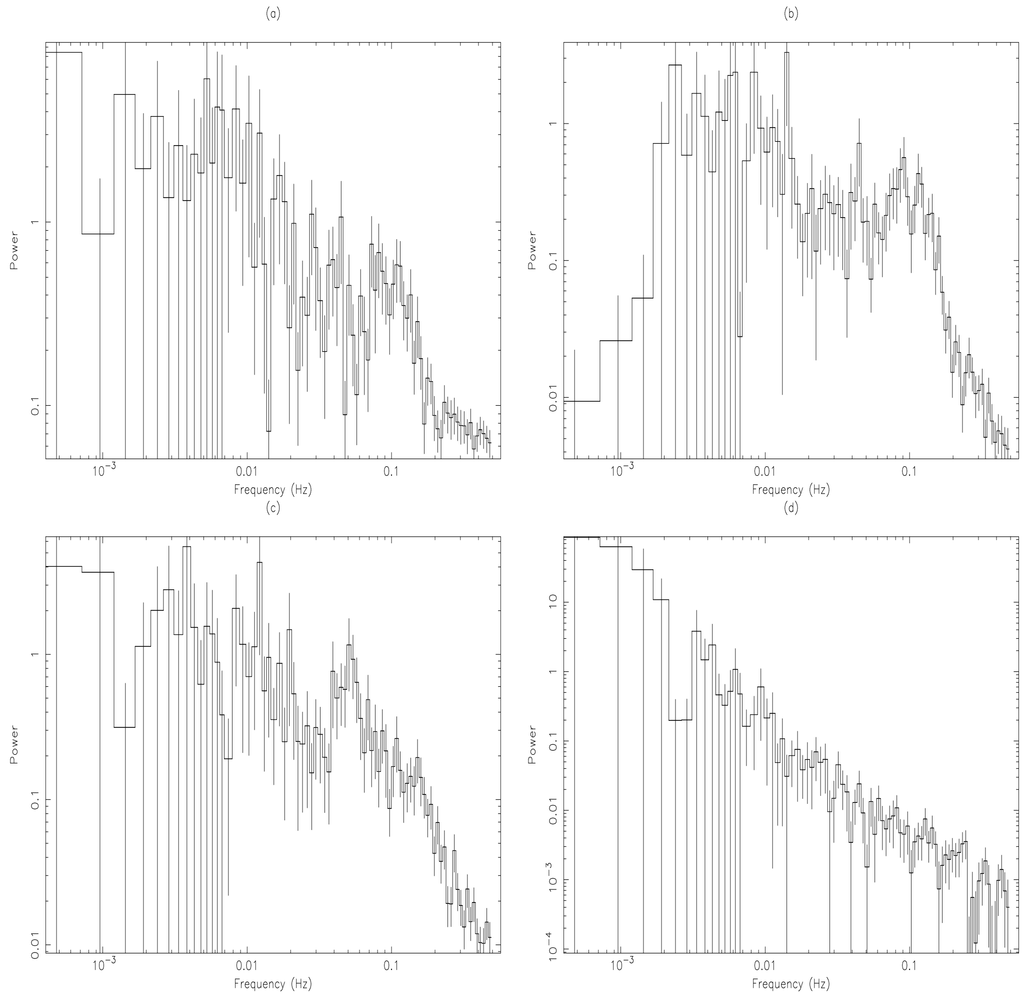

Figure 5. The Power Density Spectrum (PDS) of four successive orbits of 1997 August 11. There are QPOs in Figs. 5a - c but it is absent in Fig. 5d, during δ class transition.

which is depicted in Fig. 2a, but in 4th orbit of 2000 June 22 the same class (ρ type) transition observed from low count to high count (Fig. 3b).

In the 5th orbit of 1997 August 09, we found a clear evidence of transition of an unknown class to μ class as shown in Fig. 2b. The noisy character of photon index is reduced dramatically after transition. Again the 3rd orbit of 1997 August 10 showed a sub-class or may be new class to μ class transition (Fig. 3a).

In the upper panel of Fig. 4a, the 3rd orbit of 1997 August 11 the light curve is in δ class, but after 80 minutes in the 4th orbit the light curve suffers a same class transition

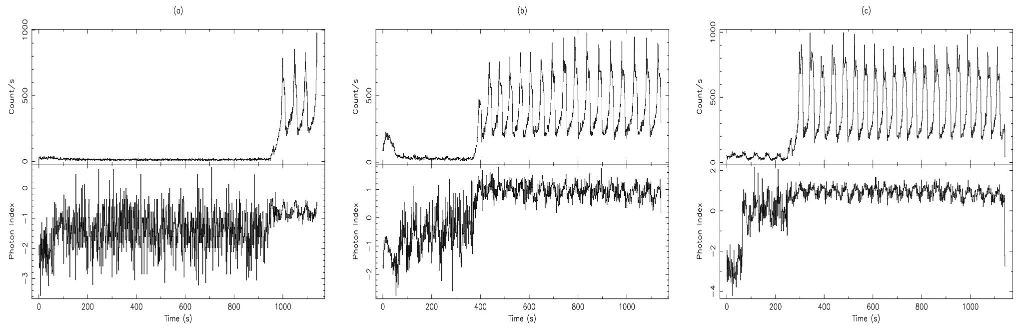

Figure 6. The class transitions and corresponding variations of s_ϕ of GRS 1915+105 as observed by IXAE on 2000 June 19, 20, and 22. These are (a) χ class to ρ (b) and (c) unknown class to ρ.

which is shown in the upper panel of Fig. 4b and confirmed by the nature of the photon index vs time curve (Fig. 4b, lower panel). In the power density spectra of 1997 August 11, we observed QPOs at the same frequency 0.04475 Hz in the first two orbits (Figs 5a and b), but in the third orbit the QPO frequency has shifted to 0.05074 Hz (Fig. 5c). The most important fact is that there is no QPO in the fourth orbit which is shown in Fig. 5d. So it can be said that the QPO frequencies are changing during transition and disappear after the transition. This behaviour has also been observed by Chakrabarti et al. (2004).

Again χ to ρ class transitions were observed in IXAE data in the 4th orbit of 2000 June 19. Unknown to ρ class transitions were observed in the 1st orbit of 2000 June 20 and 2nd orbit of 2000 June 22. The light curves and photon index variations are shown in Figs 6a-6c respectively.

3. Physical picture of the accretion flow emerging from class transitions

Chakrabarti & Titarchuk (1995), Ebisawa et al. (1996) and Chakrabarti (1997) showed that the two component advective flow (TCAF) model is adequate to explain the spectral state variation when the Keplerian rates $\dot{M}_d$ and the sub-Keplerian halo $\dot{M}_h$ rates are changed. In particular, the spectrum may become harder when either $\dot{M}_h$ increases, or $\dot{M}_d$ decreases or both happen at the same time. In this case, the disk becomes luminous in hard X-rays. The reverse is true when the rates change in opposite directions and the disk becomes luminous in soft X-rays. One of the advantages of the TCAF solution is that since the components have different infall time scales, it can also explain time-lags or leads of the luminosity vis-a-vis the photon index (Smith et al. 2001; Smith, Heindl & Swank 2002). With the change in the rates, the cooling rates also change causing a variation in the QPO frequencies (Chakrabarti, Acharyya & Molteni 2004).

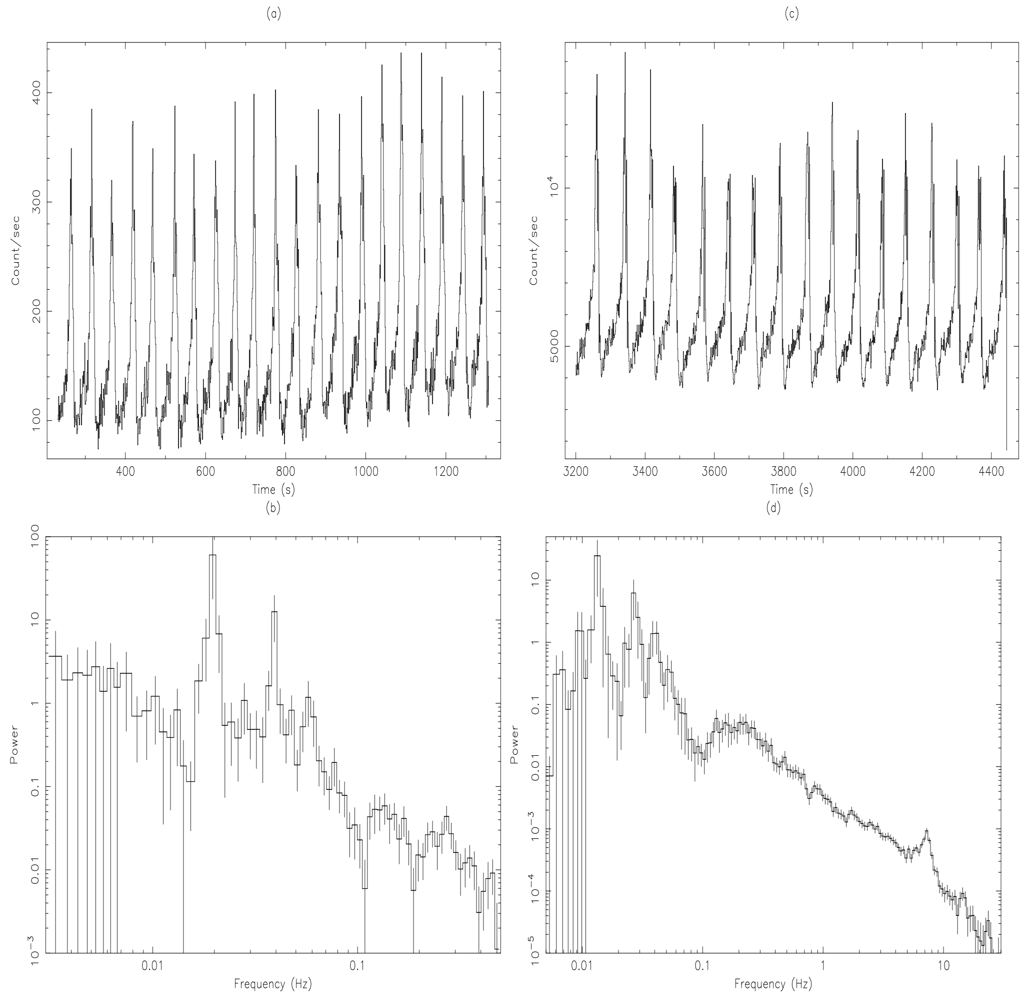

Figure 7. (a) 2 - 18 kev IXAE light curve of 2000 June 18 and (c) 2 - 15 keV RXTE light curve of 2000 June 25 in which GRS 1915+105 was in ρ class. In (b) and (d) the Power Density Spectrum are shown. In (b), due to low time resolution, only LFQPO at ~ 0.02Hz and a BF/IFQPO at $0.1 \sim 0.2$ Hz are seen. In (d), due to higher time resolution, a BF/IFQPO at ~ 7.6Hz is seen in addition to those frequencies. It is suggested that the LFQPO is due to the cooling time scale of the outflows by Comptonization, BF represents the oscillation of inner edge of the Keplerian disk and the HFQPO represents the oscillation of shock located farther inside.

While the light curves of GRS 1915+105 may be divided into as many as thirteen or more yet to be discovered classes, Chakrabarti & Nandi (2000) showed that perhaps there are only five fundamental states of accretion flow around a black hole and small variations of the accretion rates can cause a class variation. It appears that the TCAF model itself may be in any of the following. (i) Halo Dominated (HD): In this case, the flow has a large $\dot{M}_h$, and soft photon from $\dot{M}_d$ or synchrotron radiation in halo are not sufficient to cool the flow. A shock may not be present and QPOs may occur. Steady outflow at a low rate would be formed but the optical depth would be small enough so that it is not cooled by Comptonization. (ii) Shock Dominated (SD): In this case, the sub-Keplerian flow has a shock wave at a location determined by the angular momentum/viscosity of the flow (Chakrabarti 1996). QPOs will be seen and outflow will form at a low rate, not enough to be totally Compton cooled. A χ state may have an SD flow. (iii) Wind Dominated (WD): Here the shocks are weaker (compression ratio R $\sim 2-3$) as the Keplerian rate (or magnetic field which produces synchrotron radiation) is higher and the halo is cooler. The outflow rate is high (Chakrabarti 1999; Das et al. 2001) and easily cooled down. The QPO may be weak or absent. (iv) Return Flow Dominated (RFD): In this case, the outflow becomes cold enough to fall back on the disk and enhance local accretion rate. The α, ν, κ, λ & ρ classes may be due to alternating WD and RFD flows. (v) Soft Photon Dominated (SPD): In this case, the Keplerian rate is high (and /or magnetic field is high) and the sonic point at the inner edge can oscillate to produce high frequency QPOs. But in general, this may be weak or absent. Of course, high frequency QPOs may be seen in other classes when the accretion rates are high, but they may be too weak. ϕ and γ states are due to SPD flow. The remaining classes, namely, θ and β (and associate μ class) are special in the sense that some toroidal magnetic fields may play an important role in disrupting the inner part of an otherwise SD flow and producing blobby jets (Nandi et al. 2001; Vadawale et al. 2001).

In the scenarios described above, we see the emergence of several length scales in the system: (a) transition radius (r_{tr}) at which the Keplerian disk becomes sub-Keplerian before entering into the black hole, (b) the shock radius (r_{sh}) at which the flow changes discontinuously and (c) the sonic radius (r_s) at which the sub-sonic flow (either directly coming from a Keplerian disk or from the post-shock region) becomes super-sonic. These length scales introduce time scales at which the PDS changes significantly. Another time scale which also changes the PDS is determined by the time in which the sonic sphere in the outflow becomes optically thick to cool down by the soft photons from the Keplerian disk. This return-flow time scale can vary from a few tens of seconds to a few thousands of seconds, depending on the outflow rate and the supply of soft photons. Higher the outflow rate, shorter is the time scale. We now examine PDSs of both the IXAE (Fig. 7a,b) and RXTE (Fig. 7c,d) to show the presence of these time scales. The IXAE observations in Fig. 7a were made on 2000 June 18 (Naik et al. 2002). The GRS 1915+105 was in the ρ class with regular burst-on and burst-off phenomenon at an interval of $\sim$50s. The PDS shows a strong peak at this recurring return flow time scale of 0.02 Hz (and at the harmonics). This may be termed as a Low Frequency QPO (LFQPO). Because IXAE data was acquired every 1s, the PDS cannot be seen beyond 0.5 Hz. However, two broad-peaks at around 0.1 Hz to 0.2 Hz could be seen near the BF (Broad Frequency) or (Intermediate Frequency) IFQPO (Fig. 7b). On 2000 June 27 RXTE observed the same object in ρ class with similar characteristics and since RXTE has higher time resolution, the PDS is extended till very high frequency. Most importantly, it is not only confirmed

LFQPO and BF/IFQPO as seen by IXAE, at a higher frequency ∼7.6 Hz, it also showed a High Frequency QPO (HFQPO) where another break in the PDS takes place (Fig. 7d). We interpret the BF/IFQPO as due to r_{tr} and the HFQPO as due to r_{sh}. Occasionally, Very High Frequency QPOs (VHFQPO) are also seen at 67.0 Hz (Morgan et al. 1997) and this may be due to r_s.

4. Concluding remarks

In this paper, we have presented the evidence of direct transitions of GRS 1915+105 from one class of light curves to another class of light curves as well as in the same class. We found γ to δ on 1997 August 07, unknown to μ on 1997 August 09 (5th orbit) and sub class or may be new class to μ on 1997 August 10, χ to ρ on 2000 June 19, 20 and unknown to ρ types of class transitions on 2000 June 20 and 22 (2nd orbit). We observed the same class transitions μ to μ class on 1997 August 09 (4th orbit), δ to δ class on 1997 August 11 and ρ to ρ class on 2000 June 22 (4th orbit). We have also presented one example from RXTE. We showed that during the transition the photon count rates change significantly, which indicates the change in accretion rates. It is also observed that during transitions the photon count rates were found to be abnormal and were rapidly changing as for example in Fig. 4b, the X-ray photon count rate was seen to vary from 600 to 1100 per sec, in a matter of few minutes. This indicates that nearly free falling (i.e. a low angular momentum) sub-Keplerian flow may be present in the accretion flow of GRS 1915+105, supporting the earlier conclusion of Smith et al.(2001, 2002) in the context of several black hole candidates. We also found that the LFQPO changes during transition as in Fig. 5a-d.

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