

## Class transitions and two component accretion flow in GRS 1915+105

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**Abstract.** The light curve of the galactic micro-quasar GRS 1915+105 changes in at least thirteen different ways which are called classes. We present examples of the transitions from one class to another as observed by the IXAE instrument aboard the Indian Satellite IRS-P3. We find that the transitions are associated with changes in photon counts over a time-scale of only a few hours and they take place through unknown classes. Assuming that the transitions are caused by variation of the accretion rates, this implies that a significant fraction of the matter must be nearly freely falling in order to have such dramatic changes in such a short time.

**Key words.** black hole physics – X-rays: binaries – radiation mechanisms: general – X-rays: individuals: GRS 1915+105

### 1. Introduction

GRS 1915+105 is well known for its diversity of light curves (e.g. Morgan et al. 1997; Belloni et al. 2000). RXTE has pointed at it numerous times and yet the light curve has remained largely unpredictable. Belloni et al. (2000), in a model independent way, classified most of the light curves into twelve classes which are designated as  $\chi$ ,  $\alpha$ ,  $\nu$ ,  $\beta$ ,  $\lambda$ ,  $\kappa$ ,  $\rho$ ,  $\mu$ ,  $\theta$ ,  $\delta$ ,  $\gamma$  and  $\phi$ . Naik et al. (2002a) showed that there is another independent class called  $\omega$ . Although the light curve was observed to change from one class to another, the actual transition was never reported and therefore, the actual physical process which triggers a specific class transition has never been investigated.

It was predicted in several earlier papers using the advective flow paradigm (Chakrabarti & Nandi 2000; Nandi et al. 2000; Chakrabarti et al. 2002) that variation of the Keplerian and the sub-Keplerian accretion rates might cause class transitions. It was pointed out that there are actually five fundamental states differing only by Keplerian and sub-Keplerian accretion rates. Ways in which the transition occurs between these states decide which class would be seen. It was also pointed out that the outflows play a major role in class transitions, since they interact with the soft photons and affect the spectral slopes as well. Recently, Chakrabarti et al. (2004a) presented two examples of class transitions from IXAE observations and concluded that a class transition always take place through some unknown class. In many of the classes that GRS 1915+105 exhibits, one could see the presence of Quasi-Periodic Oscillations (QPOs). Very recently, using extensive time-dependent numerical

simulation of accretion flows that include cooling effects, it has been shown (Chakrabarti et al. 2004b) that the so-called advective disk paradigm is capable of explaining QPOs very naturally. The prime cause of the quasi periodic oscillations (QPOs) of X-rays from compact objects is found to be quasi-coherent shock oscillations. The post-shock region (i.e., the so-called CENTrifugal pressure supported BOUNDary Layer, or CENBOL) outside a black hole horizon acts as the Compton cloud by intercepting soft photons from a Keplerian disk and reprocessing them to high energies (Chakrabarti & Titarchuk 1995). Along with the shock oscillations, the size of the CENBOL changes and therefore the number of intercepted soft photons oscillates, causing the observed QPO. Power density spectra of these “simulated” light curves directly show how QPOs occur at or near break frequency – a well-known observed phenomenon. The frequency of oscillation is thought to be related to the inverse of the infall time-scale (Molteni et al. 1996) and as such should increase with the increase of the sub-Keplerian accretion rate undergoing the shock transition as the cooling rate is increased. This general behaviour has also been observed (Remillard et al. 1999).

In this paper, we present a large number of examples of the “rare” class transitions, all of them being from the Indian satellite data, and analyze what happens during such a transition. In particular, we follow the light-curve, the power density spectra and the photon spectra throughout the transition. We found that: (a) A class transition is invariably accompanied by a significant variation of the average X-ray photon count

**Table 1.** Class transitions of GRS 1915+105 reported in this paper.

FIGURE	Satellite	Date Time (UT)	Orbit No. obs. ID	Class transition
1.	IXAE	22th June, 1997	1, 3, 5	$\kappa \rightarrow \rho$
		12:12 <sup>a</sup>		
2.	IXAE	25th June, 1997	3, 4, 5	“ $\chi$ ” $\rightarrow$ $\rho$
		11:12 <sup>a</sup>		
3.	IXAE	08th June, 1999	2, 3	“ $\chi$ ” $\rightarrow$ $\theta$
		11:02 <sup>a</sup>		
3.	RXTE	08th June, 1999	40702-01-03-00	“ $\chi$ ” $\rightarrow$ $\theta$
		13:52		
5.	IXAE	25th June, 2000	2, 3	“ $\rho$ ” $\rightarrow$ $\alpha$
		14:07 <sup>b</sup>		

<sup>a</sup> Observation time at the beginning of the first orbit; <sup>b</sup> Observation time at the beginning of the second orbit.

rate, indicating that either the Keplerian disk rate, or the sub-Keplerian flow rate or both may be changing; (b) In between two known classes, a class of unknown type appears for hundreds of minutes; and (c) During a transition, the photon index becomes noisy until the flow settles into a new class indicating the presence of turbulent behaviour during transition. At the same time, we also study the behaviour of QPOs and show how the frequency is changed consistently with the accretion rates as inferred from the spectra. In the next section, we present the observational results on class transition. Based on the new inputs from the observational results, in Sect. 3, we discuss what the nature of the accretion flows might be. We find that in order to enable class transition in a few hours, a significant fraction of the flow must be nearly freely falling, i.e., sub-Keplerian. Finally, in Sect. 4, we draw our conclusions.

## 2. Observation of class transitions

The results we discuss in this section were obtained by the Pointed Proportional Counters (PPCs) in the IXAE instrument aboard the Indian Satellite IRS-P3 (Agrawal 1998) which functioned during 1996–2000. The operating energy range is between 2 and 18 keV. The counts are saved in the archive only in two channels – one is 2–6 keV and the other is 6–18 keV. The time resolution in Medium mode could be 0.1 s but normally the time resolution was set to be 1 s. As a result of the presence of only two energy channels, only two points could be obtained in the spectrum and a so-called “mean photon index” (MPI)  $s_\phi$  can be calculated after each second. Similarly, 0.1 s time resolution in the Medium mode restricts the observation of QPOs up to 5 Hz only, while the 1 s resolution restricts the reporting of QPOs up to 0.5 Hz only. Nevertheless, the light curves are clear enough and the identification of the specific class can be done without ambiguity (e.g., Naik et al. 2001, 2002b; Paul et al. 2001). It is to be noted that (a) the counts in the high energy bin could be very low and the  $s_\phi$  suffers from low number statistics; and (b) the slope itself is known to vary in the 2–18 keV range, especially, the spectrum

becomes harder above 10–12 keV in the hard state. An assumption of a constant slope  $s_\phi$  will thus be erroneous. Therefore, while  $s_\phi$  gives an indication of how the slope changes (as a colour–colour diagram) its absolute value should be treated with caution.

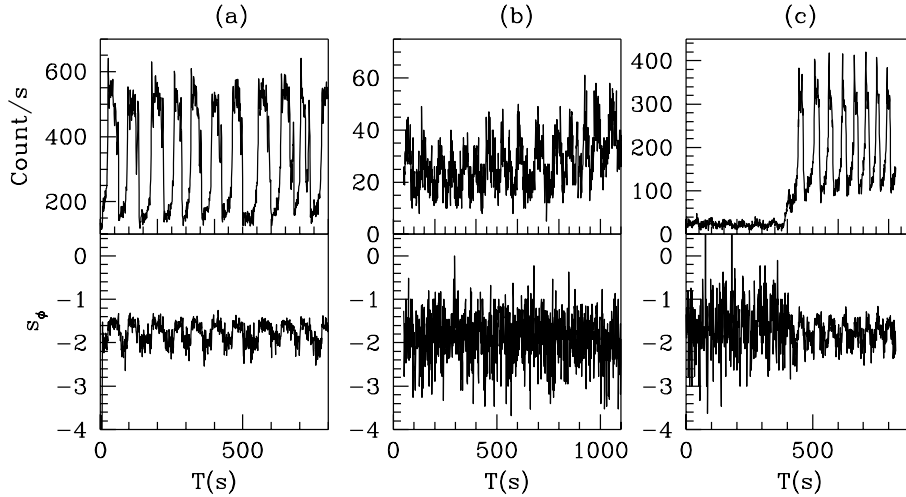
Before we present the IXAE observations, it is useful to give a brief description of the QPOs which are so far observed in GRS 1915+105. Broadly speaking, this can be subdivided into four classes: (i) low frequency QPO (LFQPO) in the range  $\sim 0.001$ – $0.02$  Hz; (ii) break frequency (BF) or intermediate frequency QPO (IFQPO) in the range  $\sim 0.1$ – $0.3$  Hz; (iii) high frequency QPO (HFQPO) in the range  $\sim 1$ – $10$  Hz; and (iv) the very high frequency QPO (VHFQPO) around 67 Hz.

In Table 1, we present the log of the observations we report in this paper which showed class transitions. The first column refers to the figure where the results are shown. The second column refers to the name of the Satellite. The third column shows the date of observation and the time when the observation started. The fourth column gives the orbit numbers (or, the Obs. ID in case of RXTE) plotted in the figure. Typically, the time interval between two successive observations is around 80 min. The fifth column gives the exact nature of class transition. Since during transition, 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.

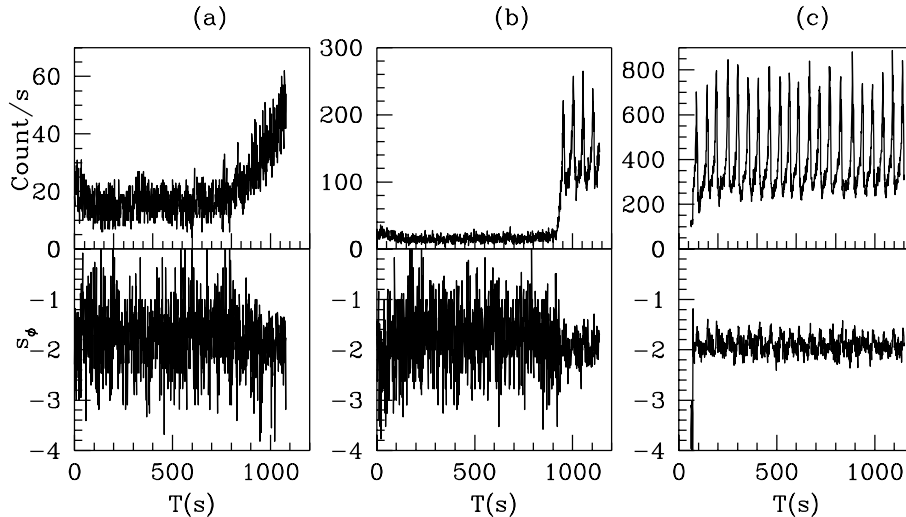
In Figs. 1a–c, we present the light curves (2–18 keV) of the June 22nd, 1997 observation in the upper panel and the mean photon index (MPI) in the lower panels. The MPI  $s_\phi$  is obtained using the definition:

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

where  $N_{2-6}$  and  $N_{6-18}$  are the photon count rates from the top layer of the PPC and  $E_1$  and  $E_2$  are the mean energies in each channel. Thus,  $E_1 = 4$  keV and  $E_2 = 12$  keV respectively. We have thus 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. The panel 1a is in the so-called



**Fig. 1.** 2–18 keV light curves as observed by IXAE (*upper panel*) and the mean photon spectral index  $s_\phi$  (*lower panel*) in 1st, 3rd and 5th orbits of June 22nd, 1997 (see, Table 1). GRS1915+105 was **a)** in the  $\kappa$  class; **b)** in an unknown class; and **c)** went to the  $\rho$  class on that day. Lower panels show how  $s_\phi$  distinctly change. Specifically it is noisy during the transition.



**Fig. 2.** Class transition of GRS 1915+105 as observed by IXAE on the 25th of June, 1997 in three successive orbits (see Table 1). It was **a)** in an unknown class similar to  $\chi$ ; **b)** in transition to  $\rho$ -type class with very low count rate; and **c)** in  $\rho$  class after stabilization in that class. In the lower panels are  $s_\phi$  showing noisy behaviour during transition before settling down in **c)**.

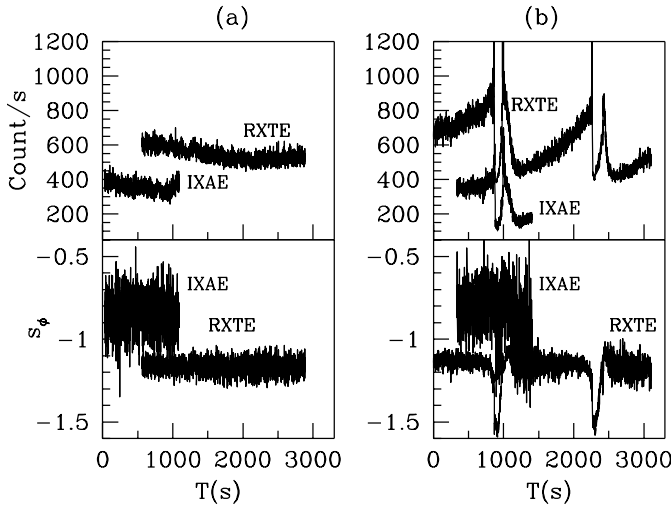
$k$  class (Belloni et al. 2000). The panel 1b is in a unknown class and the panel 1c clearly shows the transition from the unknown class to the so-called  $\rho$  class. The panels are separated by about three hours.

In the lower panels, the  $s_\phi$  oscillates between  $\sim 2.4$  to  $\sim 1.4$  in Fig. 1a very systematically. In Figs. 1b and c, the unknown class produced very noisy photon spectral slope variation. As soon as the  $\rho$  class is achieved after one “semi- $\rho$ ” oscillation, noise in  $s_\phi$  is reduced dramatically.

The IXAE observation of the 23rd, 24th and 25th of June, 1997 showed that the system was still in  $\rho$  class after the transition on 22nd of June, 1997. Subsequently, on 25th June, 1997 there was another transition to  $\chi$  and it returned back to  $\rho$ . It remained in  $\rho$  class on the 26th of June before returning to  $\kappa$  on the 27th. Thus  $\kappa \rightarrow \langle \text{unknown} \rangle \rightarrow \rho \rightarrow \langle \text{unknown} \rangle \rightarrow \rho \rightarrow \langle \text{unknown} \rangle \rightarrow \kappa$  transitions took place in a matter of five days.

The exact time and duration of the last transition mentioned above could not be seen because of the lack of observation.

In Figs. 2a–c the observation of IXAE on 25th of June, 1997 is presented. The panels are separated by about one and a half hours. Here too, the upper and lower panels represent variation of photon count rates and  $s_\phi$  respectively. In Fig. 2a, the GRS 1915+105 is in the so-called  $\chi$ -like class, though the photon count rate showed considerable variations, not characteristic of  $\chi$ . Correspondingly, the average spectra also softened as is suggested by the gradual decrease in  $s_\phi$ . In Fig. 2b, this trend continued until a “semi- $\rho$ ” class was achieved and the noise in the photon spectra went down. In Fig. 2c, after one full orbit, the count rate went up further by about a factor of four and a steady  $\rho$  state was achieved. The average (photon) spectral index  $s_\phi$  was  $\sim 1.75$  in Fig. 2a, but it became  $\sim 1.9$  in Fig. 1c, indicating general softening.

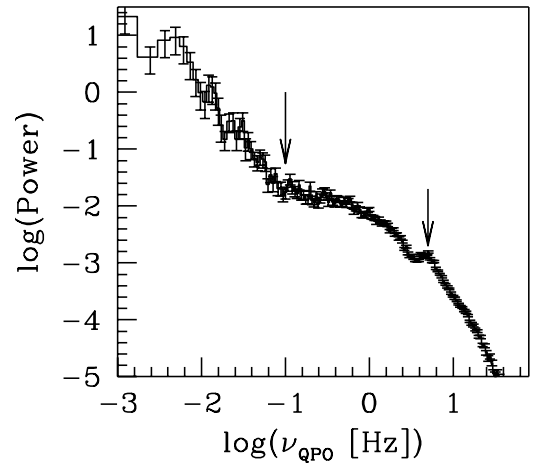


**Fig. 3.** Class transition as seen from IXAE and RXTE observations on the 8th of June, 1999 in two successive orbits (marked). RXTE photon count rates are divided by 50 and shifted upward by 200/s for comparison. In **a**), for a period of about 3000 s, there was no significant variation in light curve or spectral index. The object was in a class similar to  $\chi$  but the count rates were a factor of 10–20 times higher. There is a gap of 44 min in the two RXTE data presented in **a**) and **b**). In **b**), the object is distinctly in the  $\theta$  class. RXTE data is less noisy than the IXAE data because of higher counts. It was binned in 2–6 and 6–15 keV before computing  $s_\phi$  so that comparison with IXAE could be made.

In Figs. 3a–b we show the light curve and  $s_\phi$  from IXAE data obtained on the 8th of June, 1999. The two panels are from two successive observations  $\sim 80$  min apart. In Fig. 3a, the count rate was very high compared to what is expected from a typical  $\chi$  state although the power density spectrum (PDS) is typical of that of the  $\chi$  class. A QPO at 4.7 Hz is present. The  $s_\phi$  is 0.85 which is harder than what is observed in Fig. 2. When combined with RXTE data of that date (Fig. 3a), one finds that for a long time ( $\sim 3000$  s) there was no signature of any “dip” which is the characteristic of the  $\theta$  class. Hence, this must be in an unknown class, more close to  $\chi$  than any other. RXTE also observed this object on the 7th of June, 1999 and found the object to be in the  $\chi$  class. In Fig. 3b, the light curve in the next orbit of IXAE shows evidence of the so-called  $\theta$  class. Interestingly, the spectra gradually “hardened” to  $s_\phi \sim 0.6$  just before the “dip”. The spectra characteristically softened in the “dip” region with  $s_\phi \sim 1.4$  as the inner edge of the disk disappeared. This class transition is confirmed in the data of RXTE also shown in Fig. 3b. The lower panels showed that the spectral slopes obtained for RXTE data calculated in a similar way to  $s_\phi$  was calculated (Eq. (1)). Here, the photons were first binned in 2–6 keV and 6–15 keV (in epoch 4 of RXTE, the science data is available in a maximum of 35 channels. Thus the energy channel width could not be made identical to 6–18 keV as in IXAE) before computing  $s_\phi$  from

$$s_\phi = -\frac{\log(N_{6-15}/E_2) - \log(N_{2-6}/E_1)}{\log(E_3) - \log(E_1)}, \quad (2)$$

where  $E_1 = 4$  keV,  $E_2 = 9$  keV and  $E_3 = 10.5$  keV. Note that there is a large difference between the mean spectral slopes

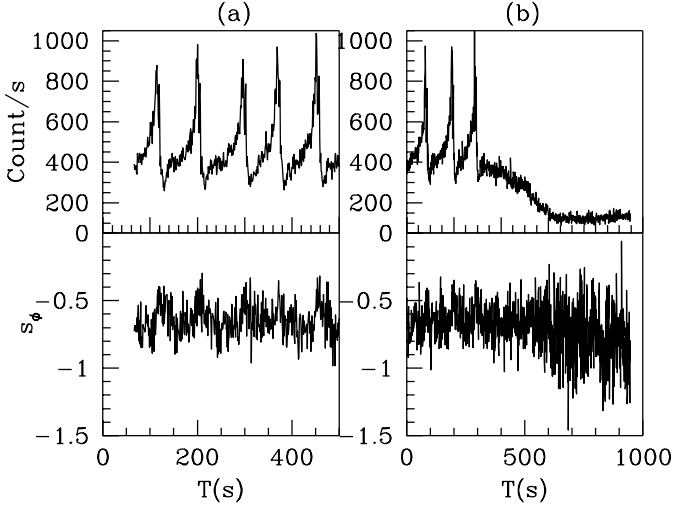


**Fig. 4.** The power density spectrum of the RXTE light curve of Fig. 3b. The signature of 0.1 Hz break and a kink (weak and broad QPO) at around 5.4 Hz are typical of a  $\theta$  class. These, along with softening of the spectrum at the dips (prominent in both the data) indicate that a class transition has indeed taken place.

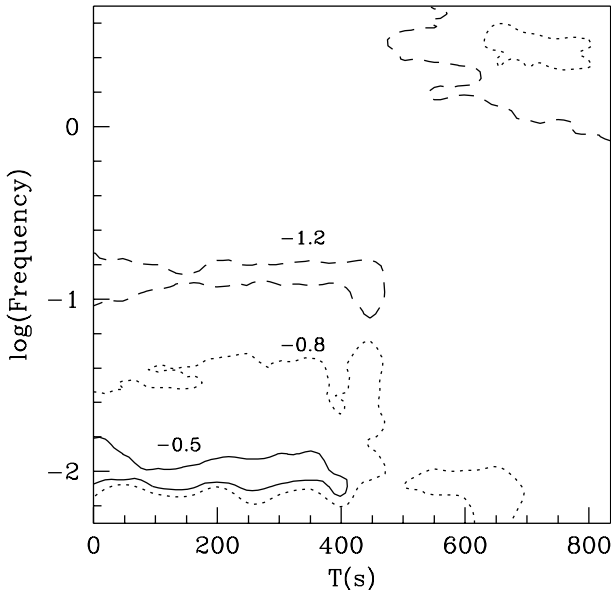
calculated from IXAE and RXTE data. The main reasons appear to be (a) by decreasing  $E_2$  from 18 keV in IXAE to 15 keV the value of  $s_\phi$  is increased by  $\sim 15$  per cent. (b) usually the spectrum in the low state (as in between the “dips” in the  $\theta$  class) has a harder tail for energy above 12 keV. Thus decreasing the binsize limit from 18 keV to 15 keV decreases the photon counts in harder parts of the spectrum. These two combined effects cause the mean spectrum of RXTE to be softer. Its lower noise is clearly due to its very high count rates (about 50 times higher than IXAE) for its higher effective surface area (6500 cm<sup>2</sup> as opposed to 400 cm<sup>2</sup> for one of the detectors of IXAE, result of which was used in the present paper) and its usage of xenon as opposed to a mixture of 90 per cent argon and 10 per cent methane.

To show that the class in Fig. 3b is indeed that of the  $\theta$  class, we plot in Fig. 4 the power density spectra. This showed a characteristic break at  $BF \sim 0.1$  Hz and the HFQPO at 5.4 Hz with a broad “Q” weak QPO at the break frequency. The PDS of the light curve (Fig. 3a) in the previous orbit is  $\chi$ -like and it does not show any LFQPO, BF/IFQPO or VHFQPO.

In Figs. 5a–b, we show another example of a class transition in which the light curve in the “ $\rho$ ” class (Fig. 5a) goes over to the so-called  $\alpha$  class (Fig. 5b). This is from the IXAE observation on the 25th of June, 2000. The count rate in this “ $\rho$ ” class was much higher than that seen in Figs. 1 and 2 and the photon spectral index in the lower panel also showed that the spectra are harder (average  $s_\phi \sim 0.65$  as compared to  $\sim 1.8$  in Fig. 1 and  $\sim 1.9$  in Fig. 2.). So, it could be an intermediate class. In the alpha class  $s_\phi$  became noisy and the transition is clearly obvious. This “ $\alpha$ ” lasted for a short time, since observations from 18th June, 2000 to 25th June, 2000 as reported in Naik et al. (2002b) always showed a  $\rho$  class with gradually increasing burst recurring time-scale. On the 25th, this trend reversed after this “ $\alpha$ ” class and from the 26th the recurrence time again went up. So the system might have experienced perturbations for only a short time.



**Fig. 5.** Two successive orbital IXAE data showing a class transition on the 25th of June, 2000. In **a**), the class is similar to  $\rho$  but the count rate is higher and the recurring time-scale between bursts is large ( $\sim 100$  s). In **a**), the spectral index is less noisy but in the beginning of **b**) it becomes noisy though superficially it is still in “ $\rho$ ” class. After transition it went to the so-called  $\alpha$  class and  $s_\phi$  becomes very noisy.



**Fig. 6.** Time dependence of the power density spectrum for the medium mode (0.1 s time resolution) IXAE observations presented in Fig. 5b. Along X-axis is the time after the observation started. The contours of constant power (in logarithmic scale) are plotted (marked on the contours). A strong peak at  $\log(\nu_{\text{QPO}}) \sim -2$  in the first half signifies the Low Frequency QPO (LFQPO) in the  $\rho$  state and another weak peak at  $\sim 0.1$  Hz (break frequency, see text) is also present. After the transition, the peak occurs at  $\sim 2.5$  Hz.

The change of class is also reflected in Fig. 6 where the time dependence of the power density spectra (PDS) is plotted. Along the Y-axis, the frequency ( $\nu$ ) of the PDS is presented. The power ( $P$ ) itself is marked on the contours plotted: solid curve, dotted curve and dashed curves are for  $\log(P) = -0.5$ ,  $-0.8$  and  $-1.2$  respectively. Note that the highest power remains at around  $\log(\nu) \sim -2$  in the  $\rho$  state. A weaker peak

occurs at around  $\log(\nu) = -0.85$ . However, after the transition, the dominant frequency seems to be at around  $\log(\nu) \sim 0.4$  which corresponds to  $\nu \sim 2.5$  Hz.

### 3. Possible nature of the accretion flow emerging from class transitions

The first and the most important point to note is the variation in the count rate in the pre-transition period and the duration of a transition. The variation in the count rate points to the variation in the accretion rate while the duration gives an indication of the infall time. Details of the possible nature of the flow geometry during transition will be discussed elsewhere (Nandi et al. in preparation). Given that there is a gap of more or less 80 min in between two successive observations of IXAE, the duration  $T_d$  could be at the most  $\sim 3$ – $5$  h i.e.,  $10\,000$ – $20\,000$  s. This is short even for a free falling gas from the outer edge of the disk located at  $r_d \sim 1.5 \times 10^6$  in units of  $r_g = 2GM/c^2$ , the Schwarzschild radius of the central black hole of mass  $M \sim 14 \pm 4 M_\odot$  (Greiner et al. 2001) since this is around

$$T_{\text{infall}} \sim r_d^{3/2} (r_g/c) \sim 2.6 \times 10^5 \left( \frac{r_d}{1.5 \times 10^6} \right)^{3/2} \left( \frac{M}{14 M_\odot} \right) \text{ s.} \quad (3)$$

The viscous time for a Keplerian disk of similar size must be at least ten to a hundred times larger, i.e., few  $\times 10^6$  s for any reasonable viscosity. This indicates that if the transition takes place in  $\sim 10^4$  s, the accretion flow must be nearly freely falling, i.e., sub-Keplerian, and must originate from intermediate distances, rather than from the outer edge, i.e., out of a Keplerian disk through energy deposition or otherwise. This flow is neither a static corona, nor a flow which is radiatively less efficient. Smith et al. (2001, 2002) indeed found observational signatures of the nearly free-falling matter in several black hole candidates which causes dynamical spectral state changes. We thus believe that the variation of the rate of the sub-Keplerian matter may be responsible for the class transitions we presented here.

### 4. Concluding remarks

In this paper, we presented several examples of variability class transitions in GRS 1915+105 as observed by the Indian X-Ray Astronomy Experiment (IXAE) aboard the Indian Satellite IRS-P3. We also presented one example from RXTE. We showed that while the signature of a class transition in the light curve may be abrupt, the process itself is gradual over a period of about 3–5 h during which the light curve passes through unknown classes. During the transition, the photon count rates change significantly which indicates changes in the accretion rates. In a model-independent way, we argue that probably only the rate of the sub-Keplerian flow changes since the duration of transition is  $\sim 2 \times 10^4$  s, much shorter than the viscous time by factor of ten to hundred. During the transitions, the photon count rates were found to be abnormal and were rapidly changing. For instance in Fig. 3a, the X-ray count rate was seen to vary by more than 25% in a matter of a few minutes in the unknown class. These are indications that nearly freely

falling (i.e., a low angular momentum) sub-Keplerian flow may be present in the accretion flow of GRS 1915+105, supporting earlier conclusions of Smith et al. (2001, 2002) in the context of several other black hole candidates.

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