Evidence of Class Transitions in GRS 1915+105 from IXAE Data

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ABSTRACT

GRS 1915+105 shows at least twelve distinct classes of light curves. By analysing the data obtained from Indian X-ray Astronomy Experiment (IXAE) instrument aboard IRS-P3 satellite, we show that in at least two days, transitions between one class to another were observed. In these days the so-called $\kappa$ class went to $\rho$ class and $\chi$ class went to $\rho$ class. In the frequency-time plane such transitions exhibited change in quasi-periodic oscillation (QPO) frequency. We could detect that low-frequency QPOs can occur in anticipation of a class transition several hundred minutes before the actual transition.

Subject headings: black hole physics – stars:individual (GRS 1915+105) – X-rays:stars

Published in Astrophysical Journal 607, 406, 2004

1. Introduction

GRS 1915+105 is being studied for almost ten years (see, Castro-Tirado et al. 1994; Mirabel & Rodriguez, L.F. 1994 for early papers) quite extensively, and yet, it continues to reveal new physical insights into the phenomenon of black hole accretion. This enigmatic X-ray transient source exhibits at least twelve classes of light curves, if not more (Belloni et al. 2000). These twelve types have been designated as $\chi$, $\alpha$, $\nu$, $\beta$, $\lambda$, $\kappa$, $\rho$, $\mu$, $\theta$, $\delta$, $\gamma$ and $\phi$ respectively. These classes were based on the nature of the hardness ratios exhibited in the light curve. In some class (e.g., $\chi$) only hard X-rays are seen, in some other classes (e.g., $\phi$) only soft X-rays are seen, while in the majority (such as $\kappa$, $\lambda$, $\rho$) there were photons coming in
the so-called ‘burst-on’ and ‘burst-off’ states which are similar to quick transitions between soft and hard states. Subsequently, Nandi, Manickam & Chakrabarti, (2000) rearranged these classes in a pattern more easily understandable by advective disk models (see also: Naik, Rao & Chakrabarti, 2002). While RXTE satellite has pointed to this object about a thousand times, it has not been able to pinpoint exactly how and when a class transition actually takes place.

In the present Letter, we show that observations by the Pointed Proportional Counters (PPC) in the IXAE instrument aboard IRS-P3 satellite, have revealed such class transitions several times. While the time-resolution and the number of energy bins of IAXE instrument are low, the observations nevertheless are good enough to identify the classes and the transitions. Presently we report two such ‘Class-Transitions’ from the archived data of IXAE. We also show that the source probably had ‘premonition’ about the class-transition about a few hundred seconds prior to the observation as is evidenced by the the presence of a drift in low-frequency (LFQPO) QPO in the Power Density Spectrum (PDS). We observed light curves of ‘unknown’ class just before the transition. We compare our results with RXTE observations in nearby times. We present two transitions: one is $\kappa \rightarrow \rho$ transition on the June 22nd, 1997 and the other is $\chi \rightarrow \rho$ transition on the June 25th, 1997. In both the days, we find evidence of the LFQPO in the pre- and post-transition Classes.

While the exact cause of the Class transition is not yet known, it has been pointed out by Nandi et al. (2000) that this is due to the variation in accretion rates in both the Keplerian and sub-Keplerian components. They actually re-arranged the overall 12 classes of Belloni (2000) into four major Classes: Hard Class, Soft Class, Semi-Soft Class and Intermediate Class and showed that the Class transitions could be understood by slow variation of the accretion rate of the sub-Keplerian component. Chakrabarti & Manickam (2000), while explaining the correlation between the duration and QPO frequency in burst-off states of $\kappa$ and $\lambda$ classes, pointed out that the real cause of QPO is most probably the oscillations of the standing shocks. Furthermore, the transition between the burst-off and burst-on states inside a class is most probably due to the cooling of the outflowing wind by soft-photons from the accretion disk. As a result, two QPO frequencies are expected in classes which have burst-on and burst-off states. The one at a high frequency (around $1 \sim 20$Hz or so) would be due to the shock oscillation, while the one at low frequency (say around $0.01 \sim 0.02$Hz) would be due to the quasi-periodic cooling of the outflows. If this is correct, then, it is possible that the basic nature of the quasi-periodic cooling of the outflow could continue to take place during a class transition, while the shock itself can be weakened. This would mean that the low frequency QPOs could persist across class transitions. In the next Section, we present results of our analysis and show that this is indeed the case.
In the next Section, we report the observations and show that such transitions actually took place on the same day in the data set from a single orbit. We perform FFT at various times of observation and plot time-frequency diagram for observations in each orbit. We also compare our results with those of RXTE (which missed the transitions) on the same date. Finally, in §4, we draw our conclusions.

2. Observational Results and Data Analysis

The Indian X-ray Astronomy Experiment or IXAE which was launched from Sriharikota Range on March 21st, 1996 and since then has carried out observations till the year 2000. It was flown on the Indian satellite IRS-P3, had three identical Pointed Proportional Counters (PPCs) (Agrawal, 1998). Each counter was filled with a gas mixture of 90% Argon and 10% Methane at a pressure of 800 torr with a total effective area of $1200 \text{cm}^2$. The operating energy range is between 2 and 18 keV with an average detection efficiency of 60% at 6keV. The counts are saved in the archive in two channels: in $2 - 6\text{keV}$ and in $6 - 18\text{keV}$. Although the time-resolution could be 0.1s in Medium mode, due to restrictions in data-storage onboard, usually observations have been carried out in 1s resolution to have the data for five consecutive orbits per day. This is a great advantage which allowed one to observe class transitions at the cost of fast variability behaviour for which Rossi X-ray Timing Explorer (RXTE) is undoubtedly the champion.

In Fig. 1(a-e), we show the light curves (upper panels) and time-frequency diagrams (lower panels) obtained in five successive orbits on June 22nd, 1997. The light curves were obtained by adding counts from all the three PPCs from both the energy channels $2 - 6$ and $6 - 18\text{keV}$. The lower panels were obtained by Fast Fourier Transform (FFT) of the photon counts in $6 - 18\text{keV}$. While in panel 1a, in the first orbit, the Class is $\kappa$, in panel 1e, the Class is $\rho$. In between, the light curves do not appear to belong to any known class. The data has been analyzed by using FTOOLS and XSPEC packages of NASA. Since the time resolution of the observation is only 1s, we are unable to identify the high-frequency QPOs in IXAE data. However, the LFQPOs, in burst-on/burst-off sources, has been detected. For each panel of Figs. 1(a-e), we divide the data in segments of 306s and stagger each segment by 51 seconds. For each segment of 306s we take the Fast Fourier Transform (FFT) and place the PDS at its mean time. Finally, we plot contours of constant normalized power $P$ as a function of the frequency and time of observation in each panel.

The times of observations have been taken from Table 1 of Yadav et al. (1999). There is an error of 1 day in the Date column in that Table. This we have corrected. The observation started at 12:12:24 but Fig. 1a starts at 12:14:57, 153 seconds later, because of our choice...
of segment size. The observation ended at 19:20:50 while Fig. 1e ends at 19:18:17, 153 seconds earlier. There is no available record of the exact beginning and end times of each gap between orbits. Two successive datasets are separated by \( \sim 83 \) minutes. Thus, the exact time of the observation cannot be given within 2-3 minutes of accuracy. Only the duration is known with certainty. However, this does not affect our conclusions.

The contours in lower panel of Fig. 1a are drawn for normalized power \( P = 2.0, 2.3, 2.6, 2.9, 3.2, 3.5 \) and \( 3.8 \) (highest power is with darkest shade) clearly indicating an LFQPO frequency \( \nu \) oscillating between \( \log(\nu) = -1.896 \) and \( \log(\nu) = -1.824 \). In Fig. 1b, contours are drawn for \( P = 1.7, 2, 2.3, 2.6, \) and \( 2.9 \). We note that in this unknown class the LFQPO frequency monotonically drifts from \( \log(\nu) = -1.937 \) to \( \log(\nu) = -1.793 \). In Fig. 1c, the contours are drawn for \( P = 1.7, 2.0, 2.3, 2.6 \) and \( 2.9 \) respectively. The drift of LFQPO frequency undergoes large amplitude fluctuation with high reaching up to \( \log(\nu) \sim -1.73 \). In Fig. 1d, which was drawn for \( P = 1.7, 2.0, 2.3, 2.6, \) and \( 3.2 \) respectively, the first failed attempt of the Class transition is seen after around 750s of the time the beginning of the observation where a large spike is seen in the light curve. The completely different power density spectra (PDS) in the pre- and post-transition region produces a ‘mixed’ PDS in the transition region, causing large scale noise of duration \( \sim 300 \)s, the size of our segments over which FFTs were taken. In the result of the final orbit in Fig. 1e, the contours are drawn for \( P = 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.1 \) and \( 2.4 \) respectively. It is very clear that even from \( \sim 400 \)s after the observation starts, the system started showing a LFQPO with frequency \( \log(\nu) \sim -1.78 \), while after transition, the
LFQPO drifts towards \( \log(\nu) \sim -1.70 \). The first harmonics can also be observed at around \( \log(\nu) \sim -1.4 \). Assuming the gaps between the orbits are of exactly equal duration, we estimate that this orbital observation ended at \( \sim 16:36:58 \).

In this case also RXTE has observed GRS 1915+105 a few minutes after this observation, from 17:05:20 to 17:15:04 for a period of ten minutes (Obs. ID=20402-01-34-00). Fig. 3 shows the light curve and the PDS. The nature of the light curve matches with IXAE observation and the PDS shows a clear peak at \( \log(\nu) \sim -1.63 \) with the first harmonics. It appears that the LFQPO frequency drifted a bit in the intervening half an hour.

3. Concluding Remarks

In this Letter, we have presented evidences of direct transition of GRS 1915+105 going from one class of light curve to another class of light curve. Three such occasions have been found in data obtained by IXAE on June 22nd and 25th, 1997. We find that every time such a transition takes place, the PDS in the pre- and post-transition look very different and the intervening period is characterized by a noise (induced due to mixing of these two types of PDS results) and in all the cases, the LFQPO frequency continues through the transition. On the 22nd of June, 2003 we found that an unknown class was sandwiched by the \( \kappa \) and \( \rho \) class and a ‘failed’ attempt was made for a class-transition about 90 minutes prior to the actual transition. In both the dates we verified that our results are consistent with RXTE observations also. Indeed, RXTE also observed on several occasions \( \chi \) state followed by \( \rho \) state (e.g. Obs IDs 20402-01-27-01 & 20402-01-27-02 and 20402-01-29-00 & 20402-01-30-00; see, Belloni et al. 2000) as in our observation of 22nd June, 1997, though exact transition time was not detected by RXTE.

This work is supported in part from a DST project (AN) and an ISRO project (SKC). AC and UC thank Dr. Achintya Chatterjee for discussions. The authors thank Prof. P.C. Agrawal of TIFR for making the IXAE data available to us.

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Fig. 1(a-e): Light curves (upper panel) and time-frequency plots (lower panel) of GRS 1915+105 as observed by IXAE in successive five orbits on the 22nd of June, 1997. In (a) the light curve is of $\kappa$ class while in (b), (c) and part of (d) the light curve is of unknown class. In (d), a failed attempt for transition was made where a ‘spike’ is seen (as is evidenced from the disparate power-density spectrum in the pre- and post-transition period). In (e), a real transition to $\rho$ class is seen. This is also reflected in the time-frequency plot.

Fig. 2: Light curves (upper panel) and time-frequency plots (lower panel) of GRS 1915+105 as observed by IXAE on the 25nd of June, 1997. Upper panel shows the transition from $\chi$ to $\rho$ class. The lower panel shows the characteristic noise in the power density spectrum at the transition.

Fig. 3: RXTE observation of GRS 1915+105 after half an hour of the IXAE observation as presented in Fig. 2. Upper panel shows that the light curve is still in $\rho$ class. The power density spectrum in lower panel shows the low frequency QPO as well close to where IXAE found it.
