X-RAY SPECTRAL STATE EVOLUTION IN IGR J17091–3624 AND COMPARISON OF ITS HEARTBEAT OSCILLATION PROPERTIES WITH THOSE OF GRS 1915+105

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ABSTRACT

In this work, we study the X-ray timing and spectral evolution of the transient low-mass X-ray binary IGR J17091–3624 during the first 66 days of its 2011 outburst. We present results obtained from observations with two instruments, the Rossi X-ray Timing Explorer Proportional Counter Array and SWIFT X-Ray Telescope, between 2011 February 9 and 2011 April 15. Using quasi-periodic oscillation classifications, power density spectrum characteristics, time-lag behavior, and energy spectral properties, we determine source states and their transitions at different times of the outburst. During the first part of the evolution, the source followed trends that are usually observed from transient black hole X-ray binaries (BHXBs). Interestingly, a gradual transition is observed in IGR J17091–3624 from the low-variability soft intermediate state, commonly seen in BHXBs, to a high-variability state with regular, repetitive, and structured pulsations, seen only from GRS 1915+105 (also known as “p” class variability/“heartbeat” oscillations). We study the time evolution of the characteristic timescale, quality factor, and rms amplitude of heartbeat oscillations in IGR J17091–3624. We also present a detailed comparison of the timing and spectral properties of heartbeat oscillations and their evolution in IGR J17091–3624 and GRS 1915+105.

Key words: accretion, accretion disks – black hole physics – X-rays: binaries – X-rays: individual: (IGR J17091-3624, GRS 1915+105)

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1. INTRODUCTION

IGR J17091–3624 was detected as a bright, variable, transient source with flaring activity in 1994 October (Mir/KVANT/TTM), 1996 September (BeppoSAX/WFC), 2001 September (BeppoSAX/WFC; In’t Zand et al. 2003), 2003 April (INTEGRAL/IBIS; Kuulkers et al. 2003), and 2007 July (Capitanio et al. 2009). In 2003 April, IBIS, the Gamma-ray imager on board the INTEGRAL satellite, detected the transient X-ray binary IGR J17091–3624 at the position of 17°09′1 (R.A. (J2000.0)), −36°24′63 (decl. (J2000.0)) while monitoring the Galactic center (Kuulkers et al. 2003). A transition between soft and hard states and the presence of a blackbody component during source softening were observed during a joint spectral analysis of INTEGRAL/IBIS and the Rossi X-ray Timing Explorer/Proportional Counter Array (RXTE/PCA) data by Capitanio et al. (2006). They found that the different spectral states, their transitions, and time variability of the source were similar to those of the black hole candidate H1743–322. The approach which is commonly used to define the spectral states of a source during an outburst evolution is based on energy spectral properties as well as power density spectral (PDS) properties including low-frequency quasi-periodic oscillations (LF QPOs) features and classifications (Fender et al. 2004). Depending on QPO frequency, coherence and strength, three main types of LF QPOs are observed in black hole X-ray binaries (BHXBs)—type-A (weak with few percent of rms amplitude) and broad (q-factor < 3) QPO around 7–9 Hz; Casella et al. 2005; Soleri et al. 2008), type-B (relatively strong (4%–7% rms amplitude) and relatively narrow (q-factor ∼ 5–7) QPO around 5–7 Hz appeared with a weak red noise; Casella et al. 2005; Soleri et al. 2008) and type-C (strong (up to 21% rms amplitude) and narrow (q-factor ∼ 5–12) features with the variable centroid frequency between 0.1 and 15 Hz, superimposed on a strong flat-top noise; Casella et al. 2005; Soleri et al. 2008).

Type-B QPOs are generally associated with a relatively soft state or soft intermediate state (SIMS; Belloni et al. 2005; Fender et al. 2004) while type-C QPOs carry the signature of the hard intermediate state (HIMS; Belloni et al. 2005; Fender et al. 2004). Along with different types of QPOs, one important difference, which has also been used in this work to distinguish the HIMS from the SIMS is that type-B QPOs always show hard lag (hard photons lag soft photons) at the fundamental QPO frequency between 5 and 7 Hz, but a type-C QPO, if detected in the frequency range 5–7 Hz during the HIMS, always shows soft lag at the fundamental QPO frequency (Casella et al. 2005; Pahari et al. 2013b; Reig et al. 2000). The low/hard state (LS) is usually characterized by strong band-limited noise where noise component can be decomposed into a few broad Lorentzian components (Belloni et al. 2005). Lutovinov et al. (2003) found that the PDS of IGR J17091–3624 could be well described with the standard model of band-limited noise with the break frequency of 0.31 ± 0.04 Hz. They fitted the energy spectrum with the power-law model having the power-law index of 1.43 ± 0.03. These timing and spectral properties are commonly observed in the LS of BHXBs (Sunyaev & Revnivtsev 2000). Using combined RXTE/PCA and INTEGRAL/IBIS data, Capitanio et al. (2006) showed that a single thermal Comptonization component (compTT) or saturated Comptonization (compST in XSpec) or the combination of soft multi-color disk blackbody and hard power law (diskbb+powerlaw) are a good description of the X-ray spectra of IGR J17091–3624. However, they noticed that the model-derived electron temperature was ∼ 20 keV, which was less than the typical electron temperature of BHXBs (∼ 50–100 keV; Zdziarski & Gierliński 2004). SWIFT/X-Ray Telescope (XRT) observations of IGR J17091–3624 during the outburst in 2007 revealed another state transition from hard to soft and refined the X-ray position of this source, which is consistent with the position of the infra-red counterpart observed...
with the ESO New Technology Telescope (Chaty et al. 2008) as well as the compact radio counterpart in the Very Large Array archived data (Capitanio et al. 2009).

The renewed activity of the source was first detected with the SWIFT/BAT when the hard X-ray flux (15.0–60.0 keV) increased up to 60 mcrab on 2011 February 3 (Krimm et al. 2011). Later, using the SWIFT/XRT observation, Krimm & Kennea (2011) confirmed that the outburst occurred in the source IGR J17091–3624, and not in IGR J17098–3628, which is also an X-ray transient 9.6 away from IGR J17091–3624. The INTEGRAL/IBIS also detects the source simultaneously with the SWIFT/XRT (Del Santo et al. 2011). The preliminary spectral data during the recent outburst of IGR J17091–3624 in 2011 showed that a soft spectral component is necessary to describe the spectrum along with the hard power-law component (Del Santo et al. 2011). Later, using the data from the IBIS/ISGRI imager and the JEM-X Telescope on board the INTEGRAL satellite on 2011 February 7–8, Capitanio et al. (2011) described the combined ISGRI and JEMX2 spectrum (5.0–300.0 keV) with a power law having the high energy cut-off at 110$^{+47}_{-27}$ keV. In spite of several efforts, little is known about the compact nature of this source or the nature of its binary companion (but see Bodaghee et al. 2012).

From the beginning of RXTE/PCA observations on 2011 February 9, several rich features in timing and spectral domain of the source have been noticed. QPOs at 94 ± 3 mHz and 0.105$^{+0.004}_{-0.003}$ Hz with a quality factor of ∼9.1 and ∼7.4, respectively, were reported using RXTE/PCA observations on 2011 February 9–12 (Rodriguez et al. 2011b) although a source contamination problem exists with the RXTE data during this period. Apart from this, fast QPO evolution (Shaposhnikov 2011), 10 mHz QPOs (Altamirano et al. 2011c) and an evolving power density spectrum with multiple peaks (Pahari et al. 2011a) were also noticed. High-frequency QPO at 66 Hz (Altamirano & Belloni 2012a) was detected with a significance of 8.5σ. Interestingly, a quasi-regular oscillation in the light curve of IGR J17091–3624 is noticed which is very similar to the “$\rho$” class variability seen only in the light curve of the Galactic micro-quasar GRS 1915+105 (Altamirano et al. 2011a). Later, Altamirano et al. (2011b) claimed a few more variabilities similar to those found in GRS 1915+105. Two new variabilities, which are unique to IGR J17091–3624, were reported by Pahari et al. (2011b). Using Chandra spectroscopy of IGR J17091–3624 during the soft, disk-dominated state, King et al. (2012) showed that accretion disk wind is not correlated with relativistic jets. This disk wind was observed to be highly ionized, dense, and had a typical blue-shift of ∼9300 km s$^{-1}$ or less, projected along our line of sight. Dips in the X-ray intensity, which are observed in the $\kappa / \rho$ class of GRS 1915+105, were also found in IGR J17091–3624 with similar properties (Pahari et al. 2011c).

GRS 1915+105 is a Galactic micro-quasar which has shown spectacular X-ray variabilities and superluminal radio jets (Mirabel & Rodríguez 1994; Yadav 2006) since its discovery in 1992 (Castro-Tirado et al. 1994). Among different variability classes in GRS 1915+105 (Belloni et al. 2000), the “$\rho$” class shows regular, repetitive bursts in the light curve with a recurrence time between ∼31 s and ∼106 s. These recurring burst structures were observed for an extended duration and have been discussed by several authors (Taam et al. 1997; Paul et al. 1998; Yadav et al. 1999). Using the data from the Indian X-ray Astronomy Experiment on board the Indian Satellite IRS-P3, as well as RXTE, Yadav et al. (1999) showed that these bursts, which could be categorized as irregular, quasi-regular and regular, have a slow exponential rise and sharp decay. Using flux-resolved spectroscopy, Pahari et al. (2013a) showed that large, repetitive oscillations in GRS 1915+105 appearing on the top of persistent emission, are consistent with the slim accretion disk approximations. Using the BeppoSAX data, Massaro et al. (2010) concluded that the process responsible for the pulses produces the strongest emission between 3.0 and 10.0 keV, and the emission at the rising phase of the pulse dominates the lower and higher energies. However, this hypothesis is not tested. Hence, consensus on the resolution of the issue with the origin of “$\rho$” class activity in GRS 1915+105 is yet to be achieved. The similarity of the “$\rho$” class of GRS 1915+105 with the variability observed in IGR J17091–3624 motivates us to perform a detailed analysis of the current outburst of IGR J17091–3624.

In the present work, we consider all observations of IGR J17091–3624 between 2011 February 9 and 2011 April 15 with the RXTE/PCA and the SWIFT/XRT. We have analyzed both timing and spectral properties of the source after confirming that the contamination from the nearby source IGR J17098–3628 is usually very small. In Section 2, we describe our analysis methods. Section 3 summarizes results regarding the HIMS and SIMS, a fast source evolution and the transition to a “$\rho$”-like class via an intermediate variability state, observed from IGR J17091–3624. Finally, we compare the timing and spectral properties of the “$\rho$”-like class in IGR J17091–3624 with the “$\rho$” class characteristics seen from GRS 1915+105, and we discuss their implications in Section 4. We give our conclusions in Section 5.

2. OBSERVATIONS AND DATA ANALYSIS

We analyze all RXTE/PCA observations of IGR J17091–3624 between 2011 February 9 (MJD 55601) and 2011 April 15 (MJD 55666). Because of insufficient good time intervals (GTIs) and inferior quality, we are unable to extract the background data file for all High-Energy X-Ray Timing Experiment (Rothschild et al. 1998) observations. Hence, we use only the RXTE/PCA Standard-2 Science Array data and event mode GoodXenon data for our analysis. Observation details are given in Table 1. We also analyze five RXTE/PCA observations of GRS 1915+105 between 1997 May 26 and 1997 June 25 when the source was in the “$\rho$” class. RXTE/PCA consists of an array of five proportional counters (PCU0-4) filled with xenon gas, with total effective area of ∼6500 cm$^{2}$, operating in the 2.0–60.0 keV energy range (Jahoda et al. 1996). We use data observed with all xenon layers of PCU2. During the start or the stop of any PCU unit, many observations show large count rate fluctuations in the light curve due to instrumental effects. To address this, we first create an xte filter file for each PCA observation and calculate GTI from the exposure time by applying all standard filtering criteria including breakdown events. Calculated values of GTI are provided in Table 1. Using GTI values of individual observations, we extract the background-subtracted light curve from GoodXenon data having a resolution of 125 μs. Observations with the background-subtracted PCA intensity $\geq$ 15 counts s$^{-1}$ PCU$^{-1}$ are considered. We also analyze 28 archival data sets of SWIFT/XRT between 2011 February 3 and 2011 March 30. The XRT instrument on board the SWIFT satellite has an effective area of 110 cm$^{2}$ at 1.5 keV; the position accuracy is ∼5 arcsec and operates in the 0.2–10.0 keV energy range (Burrows et al. 2005). The typical spectral resolution of this instrument is ∼140 eV.
| Observation Date (DD-MM-YY) | MJD      | Instrument | Observation ID | Good Time Interval (s) | Average Soft Color | Average Hard Color | Spectral State/Class | PDS Features | Features                                                                 |
|-----------------------------|----------|------------|----------------|------------------------|--------------------|--------------------|---------------------|--------------|--------------------------------------------------------------------------|
| 09-02-11                    | 55601.06 | XRT(WT)    | 00031921005    | 1467.4                 | ···                 | ···                 | LS?                 | Band-limited noise observed   |                                                           |
| 10-02-11                    | 55602.58 | XRT(WT)    | 000319211006   | 2200.4                 | ···                 | ···                 | LS?                 | Strong band-limited noise (rms amplitude (%)) 9.4 ± 0.6  |                                                           |
| 12-02-11                    | 55604.21 | XRT(WT)    | 00031921008    | 2198.1                 | ···                 | ···                 | LS?                 | Band-limited noise observed  |                                                           |
| 13-02-11                    | 55605.21 | XRT(WT)    | 00031921009    | 2151.2                 | ···                 | ···                 | LS?                 | Band-limited noise observed  |                                                           |
| 14-02-11                    | 55606.16 | XRT(WT)    | 000319211010   | 1877.6                 | ···                 | ···                 | LS?                 | Band-limited noise observed  |                                                           |
| 15-02-11                    | 55607.23 | XRT(WT)    | 00031921111    | 2101.6                 | ···                 | ···                 | LS?                 | Band-limited noise and a break in PDS is observed (~0.19±0.03 Hz) |                                                           |
| 16-02-11                    | 55608.23 | XRT(WT)    | 00031921102    | 2182.3                 | ···                 | ···                 | LS?                 | Band-limited noise & broad QPO-like and feature observed (0.18±0.02 Hz, 2.37±0.18, 13.9±2.6) |                                                           |
| 18-02-11                    | 55610.17 | XRT(WT)    | 00031921103    | 2176.5                 | ···                 | ···                 | LS?                 | Strong band-limited noise & broad QPO-like and feature observed (0.22±0.03 Hz, 2.25±0.18, 8.7±1.3) |                                                           |
| 20-02-11                    | 55612.25 | XRT(WT)    | 00031921104    | 2104.2                 | ···                 | ···                 | HIMS                | PDS fitted with \(\text{lore+bknpower}(122.1/125)\), type-C QPO (0.51±0.13 Hz, 5.25±0.12, 12.8±0.6) and flat top noise (~7%) detected |                                                           |
| 22-02-11                    | 55614.19 | XRT(WT)    | 00031921105    | 2050.2                 | ···                 | ···                 | SIMS                | Broad Lorentzian (~1.89 Hz) and weak red noise detected |                                                           |
| 23-02-11                    | 55615.99 | PCA        | 96065-03-01-03  | 3184.4                 | 0.73 ± 0.01         | 0.36 ± 0.02         | SIMS                | PDS fitted with \(\text{lore+bknpower}(225.9/224)\), transient type-B QPO (4.16±0.08 mHz, 5.71±0.34, 6.68±0.79) with weak red noise (rms amplitude(%)) 4.25±0.18 |                                                           |
| 24-02-11                    | 55616.25 | XRT(WT)    | 00031921106    | 1065.6                 | ···                 | ···                 | SIMS                | PDS fitted with \(\text{lore+bknpower}(117.3/122)\), transient type-B QPO (4.32±0.37 Hz, 7.17±0.36, 5.28±0.32) broad Lorentzian noise (0.83±0.14 Hz, 7.82±0.27) |                                                           |
| 26-02-11                    | 55619.01 | PCA        | 96065-03-02-00  | 1712.2                 | 0.75 ± 0.01         | 0.41 ± 0.02         | HIMS                | PDS fitted with \(\text{lore+bknpower}(213.5/224)\), type-C QPO (3.73±0.09 Hz, 4.76±0.14, 16.9±0.6) with strong flat-top noise (rms amplitude(%)) 7.83±0.18 |                                                           |
| 28-02-11                    | 55621.34 | XRT(WT)    | 00031921107    | 2576.6                 | ···                 | ···                 | SIMS                | PDS fitted with \(\text{lore+bknpower}(121.8/125)\), transient type-B QPO (3.84±0.11 Hz, 6.79±0.23, 5.31±0.55) with weak red noise (rms amplitude(%)) 3.96±0.49 |                                                           |
| 02-03-11                    | 55622.59 | PCA        | 96420-01-01-00  | 3744.3                 | 0.72 ± 0.04         | 0.39 ± 0.08         | HIMS                | PDS fitted with \(\text{lore+bknpower}(234.2/224)\), type-C QPO (3.67±0.26 Hz, 4.17±0.56, 21.3±0.5) with strong flat-top noise (rms amplitude(%)) 8.19±0.47 |                                                           |
| 03-03-11                    | 55623.28 | PCA        | 96420-01-01-01  | 2064.5                 | 0.68 ± 0.03         | 0.36 ± 0.02         | SIMS                | PDS fitted with \(\text{lore+bknpower}(229.9/224)\), transient type-B QPO (4.85±0.08 Hz, 7.67±0.68, 6.14±0.29) with weak red noise (rms amplitude(%)) 3.43±0.59 |                                                           |
| 04-03-11                    | 55624.56 | PCA        | 96420-02-01-00  | 1584.2                 | 0.62 ± 0.03         | 0.33 ± 0.01         | SIMS to HIMS transition | PDS fitted with \(\text{lore+bknpower}(212.6/224)\), type-B/ type-C QPO (5.32±0.46 Hz, 6.38±0.56, 6.31±0.37) with flat-top noise (rms amplitude(%)) 6.58±0.79 |                                                           |
| 06-03-11                    | 55626.39 | PCA        | 96420-02-01-00  | 65.5                   | 0.67 ± 0.03         | 0.35 ± 0.01         | HIMS                | PDS fitted with \(\text{lore+bknpower}(217.3/224)\), transient type-C QPO (5.15±0.11 Hz, 4.98±0.27, 9.11±0.09) with strong flat-top noise (rms amplitude(%)) 7.12±0.35 |                                                           |
Table 1 (Continued)

| Observation Date (DD-MM-YY) | MJD     | Instrument | Observation ID | Good Time Interval (s) | Average Soft Color | Average Hard Color | State              | PDS Features                                                                 |
|-----------------------------|---------|------------|----------------|------------------------|--------------------|-------------------|-------------------|------------------------------------------------------------------------------|
| 08-03-11                    | 55628.47| PCA        | 96420-01-02-02 | 3202.2                 | 0.64 ± 0.01         | 0.36 ± 0.01       | HIMS              | PDS fitted with (lore+bknpower)(226.4/224), transient type-C QPO (5.40 ± 0.23 Hz, 8.85 ± 0.39, 8.87 ± 0.69) with strong flat-top noise (rms amplitude(%)) 7.12 ± 0.35 |
| 10-03-11                    | 55630.84| CALC       | 96420-01-03-01 | 1520.4                 | 0.63 ± 0.02         | 0.33 ± 0.02       | SIMS              | PDS fitted with (lore+bknpower)(218.1/224), transient type-C QPO (5.23 ± 0.09 Hz, 5.31 ± 0.23, 10.9 ± 0.7) with strong flat-top noise (rms amplitude(%)) 8.89 ± 0.49 |
| 12-03-11                    | 55632.54| XRT(WT)    | 00031921025    | 2009.8                 | ···                | ···               | SIMS              | No QPO is detected and weak red noise observed (rms amplitude(%)) 2.55 ± 0.34 |
| 14-03-11                    | 55634.72| CALC       | 96420-01-04-00 | 2164.6                 | ···                | ···               | IVS               | PDS fitted with (lore+bknpower)(114.6/225), characteristic QPO (13.3 ± 1.4 mHz, 8.6 ± 2.3, 7.39 ± 0.41) with weak red noise (rms amplitude(%)) 3.65 ± 0.33 |
| 19-03-11                    | 55639.71| XRT(WT)    | 00031921026    | 1481.2                 | ···                | ···               | IVS               | PDS fitted with (lore+bknpower)(231.8/225), characteristic QPO (11.5 ± 0.8 mHz, 4.46 ± 0.58, 5.72 ± 0.18) with weak red noise (rms amplitude(%)) 3.65 ± 0.33 |
| 22-03-11                    | 55642.20| XRT(WT)    | 00031921030    | 2352.5                 | Variable state/ρ class | Variable state/ρ class | IVS               | PDS fitted with (lore+bknpower)(118.3/125), transient type-B QPO (4.46 ± 0.21 Hz, 6.09 ± 0.53, 7.81 ± 0.86) with weak red noise (rms amplitude(%)) 2.99 ± 0.35 |
| 23-03-11                    | 55643.78| CALC       | 96420-01-04-01 | 1152.4                 | Variable state/ρ class | Variable state/ρ class | SIMS              | PDS fitted with (lore+bknpower)(223.4/224), characteristic QPO (12.7 ± 1.1 mHz, 11.6 ± 1.6, 6.87 ± 0.49) with weak red noise (rms amplitude(%)) 2.67 ± 0.19 |
| 24-03-11                    | 55644.75| CALC       | 96420-01-04-03 | 2752.8                 | Variable state/ρ class | Variable state/ρ class | IVS               | PDS fitted with (lore+bknpower)(227.5/218), νf (11.6 ± 0.9 mHz, 2.89 ± 0.10, 6.02 ± 0.39) broad Lorentzian noise (60.1 ± 3.7 mHz, 4.15 ± 0.21) and transient type-A QPO (8.18 ± 0.62 Hz, 3.75 ± 0.29, 5.26 ± 0.18) |
| Observation Date (DD-MM-YY) | MJD     | Instrument | Observation ID | Good Time Interval (s) | Average Soft Color | Average Hard Color | Spectral State/Class | PDS Features                                                                                     |
|-----------------------------|---------|------------|----------------|------------------------|--------------------|--------------------|--------------------|-----------------------------------------------------------------------------------|
| 25-03-11                    | 55645.86| PCA        | 96420-01-05-02 | 3312.3                 | 0.58 ± 0.01        | 0.37 ± 0.05        | SIMS               | PDS fitted with (lore+bknpower)(214.4/224), transient type-A QPO (7.78 ± 0.45 Hz, 4.28 ± 0.87, 4.57 ± 0.29) with weak red noise (rms amplitude(%)) 4.13 ± 1.16 |
| 26-03-11                    | 55646.89| XRT(WT)    | 00031921034    | 2160.1                 | ···                | ···                | IVS                | PDS fitted with (lore+bknpower)(123.8/125), characteristic QPO (14.1 ± 0.2 mHz, 8.97 ± 1.1, 6.10 ± 0.66) with weak red noise (rms amplitude(%)) 3.23 ± 0.26 |
| 27-03-11                    | 55648.01| PCA        | 96420-01-05-00 | 32990.4                | 0.52 ± 0.04        | 0.27 ± 0.03        | Variable state/ρ class | PDS fitted with (lore+lore+lorentzian+ bknpower)(228.4/218), heartbeat νf (21.1 ± 1.4 mHz, 14.8 ± 1.1, 13.3 ± 1.2) heartbeat νh1 (44.2 ± 2.9 mHz, 13.3 ± 1.2, 4.89 ± 0.57) heartbeat νh2 (85.6 ± 5.5 mHz, 16.8 ± 1.5, 6.15 ± 0.74) |
| 29-03-11                    | 55649.06| PCA        | 96420-01-05-03 | 2640.3                 | 0.55 ± 0.01        | 0.33 ± 0.02        | Variable state/ρ class | PDS fitted with (lore+lorentzian+ bknpower)(237.2/221), heartbeat νf (23.8 ± 1.9 mHz, 5.39 ± 0.69, 15.9 ± 1.4) heartbeat νh1 (49.7 ± 2.2 mHz, 11.8 ± 3.6, 6.89 ± 0.56) |
| 30-03-11                    | 55650.98| PCA        | 96420-01-05-01 | 2304.5                 | 0.48 ± 0.02        | 0.28 ± 0.02        | Variable state/ρ class | PDS fitted with (lore+lorentzian+ bknpower)(213.5/218), heartbeat νf (24.1 ± 1.6 mHz, 13.5 ± 0.3, 15.9 ± 1.4) heartbeat νh1 (50.6 ± 2.8 mHz, 16.8 ± 0.6, 7.88 ± 0.71) heartbeat νh2 (75.7 ± 5.3 mHz, 9.54 ± 0.93, 5.06 ± 0.48) |
| 31-03-11                    | 55651.88| PCA        | 96420-01-05-04 | 3968.1                 | 0.51 ± 0.02        | 0.35 ± 0.04        | Variable state/ρ class | PDS fitted with (lore+lorentzian+ bknpower)(222.8/218), heartbeat νf (26.3 ± 1.4 mHz, 14.1 ± 0.5, 16.8 ± 1.7) heartbeat νh1 (52.8 ± 3.9 mHz, 12.7 ± 0.3, 7.53 ± 1.05) heartbeat νh2 (79.6 ± 4.4 mHz, 9.41 ± 0.23, 9.19 ± 1.16) transient type-A QPO (8.36 ± 0.26 Hz, 4.79 ± 0.38, 3.66 ± 0.31) |
| 02-04-11                    | 55653.70| PCA        | 96420-01-06-00 | 3488.7                 | 0.50 ± 0.01        | 0.29 ± 0.01        | Variable state/ρ class | PDS fitted with (lore+lorentzian+ bknpower)(226.5/218), heartbeat νf (33.6 ± 1.3 mHz, 11.2 ± 0.3, 22.3 ± 1.3) heartbeat νh1 (67.8 ± 2.6 mHz, 5.84 ± 0.21, 10.9 ± 2.6) heartbeat νh2 (0.11 ± 0.01 Hz, 3.19 ± 0.17, 6.23 ± 0.13) |
| 03-04-11                    | 55654.89| PCA        | 96420-01-06-01 | 6112.3                 | 0.53 ± 0.01        | 0.31 ± 0.04        | Variable state/ρ class | PDS fitted with (lore+lorentzian+ bknpower)(207.4/215), heartbeat νf (36.6 ± 0.7 mHz, 9.95 ± 0.54, 29.3 ± 1.3) heartbeat νh1 (75.9 ± 4.1 mHz, 4.21 ± 0.19, 15.3 ± 1.1) broad Lorentzian noise (0.21 ± 0.05 Hz, 9.83 ± 0.79) transient type-A QPO (7.28 ± 0.14 Hz, 3.21 ± 0.17, 4.89 ± 0.14) |
| 05-04-11                    | 55656.71| PCA        | 96420-01-06-02 | 5136.3                 | 0.54 ± 0.01        | 0.27 ± 0.04        | Variable state/ρ class | PDS fitted with (lore+lorentzian+ bknpower)(231.5/221), heartbeat νf (39.1 ± 1.6 mHz, 6.89 ± 0.32, 32.5 ± 2.2) heartbeat νh1 (81.3 ± 3.8 mHz, 3.95 ± 0.23, 14.9 ± 1.4) |
| 06-04-11                    | 55657.31| PCA        | 96420-01-06-03 | 1812.8                 | 0.55 ± 0.01        | 0.25 ± 0.02        | Variable state/ρ class | PDS fitted with (lore+lorentzian+ bknpower)(225.8/218), heartbeat νf (35.8 ± 2.1 mHz, 4.56 ± 0.19, 14.5 ± 1.6) heartbeat νh1 (64.8 ± 4.7 mHz, 4.80 ± 0.13, 23.6 ± 1.1) transient type-B QPO (4.02 ± 0.12 Hz, 2.15 ± 0.17, 13.9 ± 0.8) |
| 10-04-11                    | 55661.75| PCA        | 96420-01-07-00 | 3376.6                 | 0.58 ± 0.01        | 0.28 ± 0.03        | Variable state/ρ class | PDS fitted with (lore+lorentzian+ bknpower)(230.3/218), heartbeat νf (45.9 ± 2.1 mHz, 8.47 ± 0.76, 33.8 ± 1.6) heartbeat νh1 (94.2 ± 3.4 mHz, 9.33 ± 0.36, 11.6 ± 1.7) transient type-A QPO (7.76 ± 0.35 Hz, 2.48 ± 0.22, 7.53 ± 0.45) |
### Table 1 (Continued)

| Observation Date (DD-MM-YY) | MJD | Instrument | Observation ID | Good Time Interval (s) | Average Soft Color | Average Hard Color | Spectral State/Class | PDS Features |
|-----------------------------|-----|------------|----------------|------------------------|--------------------|--------------------|----------------------|--------------|
| 11-04-11                    | 55662.56 | PCA | 96420-01-07-01 | 3375.2 | 0.56 ± 0.01 | 0.27 ± 0.02 | Variable state/ρ class | PDS fitted with \((\text{lore+lore+lore+bknpower})(210.7/218)\), heartbeat \(\nu_f\) (45.2 ± 0.7 mHz, 4.61 ± 0.25, 31.8 ± 2.2) heartbeat \(\nu_{h1}\) (90.4 ± 3.5 mHz, 3.22 ± 0.25, 11.2 ± 0.9) broad Lorentzian noise (5.52 ± 1.38 Hz, 9.98 ± 1.13) |
| 12-04-11                    | 55663.34 | PCA | 96420-01-07-02 | 3278.5 | 0.58 ± 0.01 | 0.28 ± 0.02 | Variable state/ρ class | PDS fitted with \((\text{lore+lore+lore+bknpower})(224.4/218)\), heartbeat \(\nu_f\) (44.5 ± 0.6 mHz, 2.69 ± 0.13, 30.4 ± 1.7) heartbeat \(\nu_{h1}\) (90.1 ± 0.2 mHz, 13.8 ± 1.6, 8.63 ± 0.73) transient type-B QPO (4.93 ± 0.09 Hz, 2.46 ± 0.22, 4.39 ± 0.11) |
| 15-04-11                    | 55666.55 | PCA | 96420-01-08-00 | 1513.6 | 0.59 ± 0.03 | 0.29 ± 0.03 | \(\rho\) to other class transition (may be \(\kappa/\lambda\)) | PDS fitted with \((\text{lore+lore+lore+bknpower})(211.6/218)\), broad Lorentzian noise (56.73 ± 3.43 mHz, 30.1 ± 2.4), broad Lorentzian noise (0.22 ± 0.07 Hz, 19.4 ± 1.5) and broad QPO-like feature (3.09 ± 0.05 Hz, 3.25 ± 0.36, 9.65 ± 1.23) |

**Notes.** LS, HIMS, SIMS, and IVS stand for the low/hard state, hard intermediate state, soft intermediate state, and intermediate variable state, respectively. In the last column, quantities in braces represent frequency with error, \(q\)-factor with error, rms amplitude with error for quasi-periodic oscillations (QPOs) and frequency with error, rms with error for noise components. \(\nu_f\), \(\nu_{h1}\), and \(\nu_{h2}\) represent a fundamental QPO of \(\rho\)-like/variable state oscillations, its first and second harmonics, respectively. Models used to fit PDS and \(\chi^2/\text{dof}\) are also provided.
at 6.0 keV. To avoid the pile-up problem while observing luminous X-ray sources, all observations (except the first one) are performed with a Windowed Timing (WT) mode which has a time resolution of 2.2 ms and a flux limit of ~600 mcrab (~200 counts s\(^{-1}\); Mineo et al. 2006). For our analysis, we use level 2 cleaned event data which have been extracted from level 1 calibrated data after applying screening criteria on specific parameters like CCD temperature, Sun angle, elevation angle, etc. For all WT mode data, we assign grade 0–2 and select good event with STATUS==0. We extract source and background light curves and spectra separately using xselect v2.4b in FTOOLS 6.10.

The top panel of Figure 1 shows the background-subtracted average RXTE/PCA count rate between 2.0 and 60.0 keV, while the middle panel shows the background-subtracted average SWIFT/XRT count rate between 0.3 and 10.0 keV. HIMS and SIMS, the intermediate variable state (IVS), and the variable state are shown with open circles, stars, and triangles, respectively, in the top and bottom panels. Vertical lines separate the LS/HIMS and the HIMS and SIMS and the variable state/\(\rho\)-like class.

For each PCA observation, we create an rms-normalized and a white noise-subtracted PDS to study variability features and to track the spectral evolution of the source state with time. The dead-time corrections are applied to the light curves. For GoodXenon data, the dead time per event is approximately 10 \(\mu\)s. For details of the procedure, refer to the RXTE cookbook.\(^1\) To improve the signal-to-noise ratio in the PDS, we use the geometric re-binning of frequency bins by the factor of 1.02.\(^2\) The expected white noise is subtracted from the PDS, and they are normalized such that their square root of integral over the range of frequencies provide fractional rms variability. We produce PDS from the SWIFT/XRT data using the background-subtracted light curve in the 0.2 and 10.0 keV energy range. Since one cannot compare the 2.0–60.0 keV PDS from the PCA

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\(^1\) http://heasarc.nasa.gov/docs/xte/recipes/pca_deadtime.html

\(^2\) http://heasarc.nasa.gov/xanadu/xronos/help/powspec.html
data with 0.2–10.0 keV PDS from SWIFT/XRT data, we extract only SWIFT/XRT PDS for observation dates when no RXTE/PCA data are available. Different types of QPOs and noise components are noticed in the PDS of different RXTE/PCA observations. The details of PDS features are given in Table 1.

2.2. Spectral Evolution

The color–color diagram (CD), the hard color versus soft color plot and the hardness intensity diagram (HID) are created using the PCA GoodXenon data with 1.0 s bin time. The soft color is computed by dividing the background-subtracted PCA count rates in the energy band 5.0–12.0 keV by those in the energy band 2.0–5.0 keV. Similarly, the hard color is defined as the ratio of the background-subtracted count rate in the energy band 12.0–60.0 keV and 2.0–5.0 keV. X-ray intensity is defined as the background-subtracted PCA count rate in the 2.0–60.0 keV energy range. Since the channel gain varies from epoch to epoch, we use absolute channel ranges corresponding to each of the energy ranges to calculate soft color, hard color and X-ray intensity for the present epoch. For each RXTE/PCA observation, mean count rate (top panel of Figure 1), and mean value of hard color and soft color are provided in Table 1, with errors.

2.3. Spectral Fitting

In the case of RXTE/PCA, we perform the spectral analysis using the Standard-2 data. While fitting, we add 1% systematic errors. In case of SWIFT/XRT data, we first extract a one-dimensional image of the source. Then choosing a suitable source region and background region, we extract the source spectrum and background spectrum separately from the cleaned and pointed WT mode event file. We use the latest standard response matrix file (rmf) and create an auxiliary response file (arf) using an exposure map for the WT mode data between 0 and 2 grade values. We use XSpec v 12.6.0 for the spectral fitting of RXTE/PCA and SWIFT/XRT data. We use the 3.0–25.0 keV energy range for RXTE/PCA spectral analysis since the source count rate statistics are poor outside this range. We use SWIFT/XRT spectra in the energy range 0.6–10.0 keV.

We tried different single component models like diskbb, compTT, or powerlaw as well as dual component models like diskbb+powerlaw, diskbb+compTT, or compTT+powerlaw to fit the source spectra. The reason for selecting and testing different models is discussed in Section 1. We found that the single SWIFT/XRT spectrum could be fitted well with a combination of the diskbb and powerlaw model. Fitting with the rest of the model combination yields unacceptably large reduced $\chi^2 (>1.5)$, or sometimes it will over-fit the spectra due to the large number of parameters. This is also true for RXTE/PCA spectra. Using INTEGRAL energy spectra, a high energy cut-off (>30 keV) was detected in this source (Rodriguez et al. 2011a). A broadband BHXB spectrum, during a SIMS or HIMS, should be well described also by a combination of disk and Comptonization. Since we restrict our RXTE/PCA spectral analysis to 25 keV, we are unable to detect cut-off or Comptonization where electron temperature is high. Thus, a relatively simple model can describe our spectra well. It is noted that Remillard & McClintock (2006) showed that RXTE/PCA spectra in transient BHXBs can be well described with a multi-temperature disk blackbody emission and a hard power-law emission with/without cut-off. While fitting RXTE/PCA spectra, we use a small Gaussian component at 6.4 keV in order to improve the reduced $\chi^2$. To account for the effect of absorption by neutral hydrogen, all model components are multiplied by a photo-electric absorption model. The Galactic absorption column density in the direction of 17h 11m 12.5 s (R.A. (J2000.0)) $-36^\circ 24′ 6″$ (decl. (J2000.0)) is calculated as $0.79 \times 10^{22}$ cm$^{-2}$. From spectral analysis, we find that for all observations, absorption column density varies between 0.82 ± 0.2 and 0.99 ± 0.3. Thus, we keep this value fixed at $0.9 \times 10^{22}$ cm$^{-2}$ for all spectral fitting.

3. RESULTS

SWIFT/XRT observations of IGR J17091−3624 show a transition of the source from low to high count rate variability (see the lower top panel of Figure 1). Later, a gradual transition in the variability, i.e., from an irregular, less-variable state, to a regular, repetitive, and large variability state was observed. The large variability looks very similar to the unique variability observed during the “$\rho$” class in GRS 1915+105 (Altamirano et al. 2011a). This motivates us to perform a detailed study on the source spectral state evolution and to compare it with that of GRS 1915+105. To distinguish among variability classes, we perform the count rate fractional rms analysis of different observations (by dividing the square root of the variance by the mean count rate) from RXTE/PCA which is shown in the bottom panel of Figure 1. Later, comparing to timing and spectral properties, we show that observations which have fractional rms values less than 5 are consistent with the SIMS and HIMS, and observations with fractional rms significantly higher than 5 are consistent with the variable state/$\rho$-like class. A few observations show the transition between the SIMS and the variable state/$\rho$-like class, and hence, it is described as “IVS.” The details are discussed below.

3.1. Low/Hard State, Hard Intermediate and Soft Intermediate State

From 2011 February 14–24, a gradual rise in the SWIFT/XRT flux between 0.3 and 10.0 keV is observed in IGR J17091−3624 (see the middle panel of Figure 1). Up to 2011 February 14, the average SWIFT/XRT count rate was $\sim 10$ counts s$^{-1}$. Then it gradually increased to $\sim 45$ counts s$^{-1}$ on 2011 February 24. To check whether this rise in flux led to any state transition, we performed a detailed study on the timing properties of the source using SWIFT/XRT data. From 2011 February 9 to 2011 February 18 the PDS usually show band-limited noise, sometimes with the rms amplitude as strong as $\sim 9\%$ (see Table 1) and can be decomposed into multiple broad Lorentzians. Apart from this, a break in the PDS is observed once at $\sim 0.19$ Hz. Broad but strong QPO-like features are observed at least twice at $\sim 0.2$ Hz (with $q$-factor $>2$; see Table 1). All these features in the PDS can easily be associated with the LS (Belloni et al. 2005). On 2011 February 20, a type-C QPO at $\sim 0.51$ Hz along with the strong flat-top noise ($\sim 7\%$ rms) was observed in the PDS, which carries the signature of the HIMS. This implies that the source undergoes a state transition from the LS to the HIMS. On 2011 February 22, a broad Lorentzian ($q$-factor $<2$) was observed at $\sim 1.8$ Hz along with weak red noise ($\sim 2\%$–$3\%$ rms) in the SWIFT/XRT spectra which may indicate that the source undergoes another transition from the HIMS to the SIMS. Detection of the type-B QPO on 2011 February 23 using RXTE/PCA (see Table 1) confirmed the transition (Belloni et al. 2005). Rodriguez et al. (2011a) also observed the LS/HIMS to SIMS transition based on the detection of optically thin ra-
dio emission on MJD 55623.57 (2011 March 3). From 2011 February 24 to 2011 March 13, the source usually showed a back-and-forth transition between the HIMS and the SIMS with the usual detection of type-C and type-B QPOs, respectively (see Table 1). In Figure 3, we show an example of the HIMS observed on 2011 February 26 and the SIMS observed on 2011 March 3.

Figure 3. SIMS and HIMS in IGR J17091—3624 as observed by RXTE/PCA. Top panel: power density spectra, fitted with a broken power law and Lorentzians, are shown during the hard intermediate state (HIMS) as observed on 2011 February 26 (top left panel) and during the soft intermediate state (SIMS) as observed on 2011 March 3 (top right panel). Middle panel: frequency-dependent time-lag spectra, calculated between 1.8–4.2 keV and 5.0–13.0 keV energy bands, are shown for the same observations during the HIMS (middle left panel) and the SIMS (middle right panel). Dotted vertical lines show the fundamental QPO frequency in both panels. Bottom panels: RXTE/PCA spectra fitted with diskbb+powerlaw in the range 3.0–25.0 keV are shown for the HIMS (bottom left panel) and the SIMS (bottom right panel) along with their fitted model components and residuals.

The top panels show the PDS where the HIMS shows strong flat-top noise (~8% rms amplitude) with a strong type-C QPO at 3.73 ± 0.09 Hz, but the SIMS shows weak red noise (~3% rms amplitude) with a transient type-B QPO at 4.85 ± 0.08 Hz. For a more accurate determination of the state, we performed a time-lag analysis between the soft energy band (1.8–4.2 keV)
and the hard energy band (5.0–13.0 keV) using GHATS v1.0.2 (T. Belloni 2012, private communication) where the lag formulation is based on the cross-spectra technique. At the fundamental QPO frequency, HIMS shows the soft-lag (soft photons lag hard photons) of ∼8 ms (middle left panel of Figure 3) while the SIMS at the fundamental QPO frequency shows a hard-lag of ∼22 ms (middle right panel of Figure 3). In both panels, lags at the fundamental QPO frequency are shown by dotted vertical lines. These observations are in accord with the characteristics of these states.

We also carried out an energy spectral analysis of observations between 2011 February 9 and 2011 March 25. From the fitted parameters in Table 2, we find that the disk component is not significant while fitting the spectra observed between 2011 February 9 and 2011 February 20. A single power law can adequately describe these spectra. From 2011 February 20 onward, a soft disk component is essentially present in all spectral fitting and the power law becomes steeper (see Table 2). This indicates that a hard-to-soft state transition takes place. This is consistent with the PDS characteristics where a transition from the LS/HIMS to the SIMS is observed. An example of RXTE/PCA spectral fitting of the HIMS and the SIMS are shown in the bottom left and bottom right panel of Figure 3, respectively. From Table 2, it is clear that all low flux state observations (to 2011 February 19) have a photon index value less than 1.8 and no disk component is present at the detectable limit of Swift/XRT. These along with the detection of band-limited noise meet the criteria of an LS as observed in transient BHXBs (Homan & Belloni 2005; Remillard & McClintock 2006; Belloni et al. 2005). However, a single power law still provides a good fit (an F-test between the powerlaw and diskbb+powerlaw models yields a probability of 1.7 × 10⁻¹⁰) of the energy spectra on 2011 February 20, where the LS to the HIMS transition is observed. The insignificant disk contribution during this transition may be due either to a very low disk flux of the source or a very low temperature of the disk (<0.6 keV). The disk flux contribution is ∼10%–20% of the total flux in other HIMS where the disk is detected clearly (see Table 2).

It is noted that the X-ray spectral state transition observed between 2011 February 18 and 22 is based only on Swift/XRT data in the energy range 0.3–10.0 keV since there are no simultaneous observations of RXTE/PCA between 2011 February 9 and 22. Hence, the robustness of the result, based on XRT PDS, cannot be established confidently although it is consistent with the detection of radio flares on MJD 55601.3 and 55605.6 (Rodriguez et al. 2011a), and it shows a correct trend in spectral evolution, usually observed from normal transients (Homan & Belloni 2005; Belloni et al. 2005). Because of this ambiguity, we put question marks on the first five observations of the state classification column in Table 1, where the PDS features

### Table 2

Best Fit Parameters (with 1σ Error Bars) Obtained by Fitting the Low/Hard State, Hard Intermediate, and Soft Intermediate State Spectra of IGR J17019–3624 with the powerlaw and the diskbb+powerlaw Models, Respectively

| Instrument Used | Observation ID | Date (DD-MM-YY) | State/Class | $\Gamma^*$ | $K_{\text{in}}$ (keV) | $N_{\text{disk}}$ | Flux$_{\text{total}}$ | Flux$_{\text{powerlaw}}$ | Flux$_{\text{diskbb}}$ | $\chi^2$/dof |
|-----------------|----------------|-----------------|-------------|-----------|-----------------|----------------|----------------|----------------|----------------|-------------|
| XRT 00031921005 | 09-02-11 LS?   | $1.66^{+0.03}_{-0.04}$ | ···         | 0.61      | ···              | 657.98/632    |
| XRT 00031921006 | 10-02-11 LS?   | $1.75^{+0.02}_{-0.03}$ | ···         | 0.45      | ···              | 573.58/632    |
| XRT 00031921008 | 12-02-11 LS?   | $1.63^{+0.03}_{-0.04}$ | ···         | 0.87      | ···              | 728.57/632    |
| XRT 00031921009 | 13-02-11 LS?   | $1.69^{+0.03}_{-0.04}$ | ···         | 0.98      | ···              | 667.64/632    |
| XRT 00031921101 | 14-02-11 LS?   | $1.73^{+0.04}_{-0.05}$ | ···         | 0.71      | ···              | 694.01/632    |
| XRT 00031921011 | 15-02-11 LS    | $1.67^{+0.03}_{-0.04}$ | ···         | 0.95      | ···              | 726.74/632    |
| XRT 00031921012 | 16-02-11 LS    | $1.62^{+0.03}_{-0.04}$ | ···         | 1.11      | ···              | 629.34/632    |
| XRT 00031921013 | 18-02-11 LS    | $1.66^{+0.03}_{-0.04}$ | ···         | 1.03      | ···              | 586.28/632    |
| XRT 00031921014 | 20-02-11 HIMS  | $1.79^{+0.04}_{-0.05}$ | ···         | 0.98      | ···              | 609.43/632    |

Notes. $\Gamma^*$ is the power-law index, $K_{\text{in}}$ is temperature of the inner disk edge in units of keV and $N_{\text{disk}}$ is the disk blackbody model normalization. Flux$_{\text{total}}$ is the total unabsorbed flux, Flux$_{\text{diskbb}}$, Flux$_{\text{powerlaw}}$ are unabsorbed fluxes due to the disk and power-law components, respectively. All fluxes are calculated in the energy range 2.0–60.0 keV for a combined RXTE/PCA and Swift/XRT spectra and 0.3–10.0 keV for Swift/XRT spectra only. Fluxes are given in units of 10⁻⁹ erg s⁻¹ cm⁻².
are not clear. However, our spectral analysis agrees well with spectral parameters obtained from the joint spectral analysis of INTEGRAL/IBIS and SWIFT/XRT data by Capitanio et al. (2012). The relatively small difference between both results may be due to (1) the use of a cut-off power law (where the cut-off energy >70 keV, see Table 1 of Capitanio et al. 2012), and (2) the different absorption column density (1.1 ± 0.3).

The outburst evolution of the source through the LS, HIMS and SIMS, and frequent to and fro transition between the HIMS and the SIMS (see Table 1) indicate that the disk is unstable and the evolution pattern roughly follows the outburst evolution observed in normal transient BHXBs (Homan & Belloni 2005; Belloni et al. 2005).

3.2. Intermediate Variable State

During the continuous monitoring of the PCA light curve in IGR J17091−3624, we find a gradual transition in the count rate variability pattern from 2011 March 12 to 19 in the energy range 2.0–60.0 keV. On 2011 March 12, the source is in the SIMS when the light curve is less variable and very similar to the typical light curves seen in canonical BHXBs (see the top left panel of Figure 4). On 2011 March 19, the light curve shows a very regular repetitive pattern, high variability (peak count rate ∼3–4 times higher than the count rate at the persistent level; see the lower-middle left panel of Figure 4), and high count rate fractional rms (see bottom panel of Figure 1). We denote it as a variable state/ρ-like class. Observations of an average count rate that belong to the HIMS/SIMS and variable state/ρ-like class are separated by a dashed vertical line in Figure 1.

The transition between the SIMS and the variable state occurs through some semi-oscillatory intermediate stage on 2011 March 14. The random noisy pattern which is observed during the SIMS on 2011 March 12, appears to be superimposed on an X-ray intensity oscillation with a timescale of ∼80–100 s in the light curve on 2011 March 14 (upper-middle left panel of Figure 4). The superimposed pulsations on random fluctuations are called the IVS. Although these intermediate phases are transient, they have been observed a few times, for example on 2011 March 18, 23, 24, and 26, when the source oscillates between the SIMS like random fluctuations and the highly variable ρ-like pulsations (see Table 1). The rms normalized PDS during the IVS show characteristic oscillations in the frequency range of ∼11–14 mHz with a variable quality factor between 3 and 9. They are usually associated with very weak red noise having rms amplitude 2%–4% and weak, narrow QPOs (see Table 1 and upper-middle right panel of Figure 4). The IVS on 2011 March 24 shows broad Lorentzian noise along with a type-A QPO at ∼8 Hz. Recently, an 11 mHz oscillation is discovered in the PDS using Chandra data during the HIMS in the BHXB 4U1743-322 (Altamirano & Strohmayer 2012b). However, the origin of 11 mHz oscillations in both sources may be different. From the middle right panels of Figure 4, it is clear that the IVS is distinctively different from the variable state/ρ-like class because (1) 1 mHz pulsations in the IVS never show harmonics which, on the other hand, is frequently observed in the variable state (lower middle right panel of Figure 4). The absence of harmonics in the IVS may be due to very low count rate statistics associated with the PDS. (2) The characteristic oscillation frequency of the variable state is always higher than that of the IVS, and (3) rms amplitude of the continuum in the variable state (∼10%–15%) is significantly higher than that of the IVS (∼5%–7%). The term “intermediate” is used as it is observed between the SIMS, where no mHz QPOs are observed (top right panel of Figure 4), and the ρ-like class where very strong mHz oscillations are noticed. Thus, IVS can be treated as the beginning of the ρ-like class in IGR J17091−3624. To trace any change in spectral state during this transition, we plot the HID (bottom left panel of Figure 4) and the CD (bottom right panel of Figure 4). From the CD and the HID, it is noted that both IVS and SIMS nearly coincide with each other (shown in red and black), while the variable state shows a softer and brighter part (shown in blue) which is absent in both the SIMS and IVS. Hence, the IVS has similar characteristics of the SIMS with large amplitude oscillations superimposed to random fluctuations. The energy spectral analysis of the IVS between 3.0 and 25.0 keV on 2011 March 14 shows that the spectrum can be well fitted by the diskbb+powerlaw model which shows parameters similar to the SIMS. Using numerical solutions, Janiuk & Misra (2012) noticed that limit cycle oscillations are observed when the viscosity fluctuation amplitude are small in an unstable disk. The pulsating behavior disappears and random fluctuations are restored when the stochastic fluctuation amplitude exceeds a critical limit. However, random fluctuations and mHz oscillations can also co-exist. This model can qualitatively explain the results from Figure 4.

3.3. Variable State/ρ-like Class

The new variable state/ρ-like class remains stable for almost 25 days (2011 March 19–2011 April 12; see Table 1) except for 2011 March 23–26. The recurrent timescale of this variability is found to change with time. Figure 5 shows the evolution of the source via five RXTE/PCA light curves from 2011 March 19 to 2011 April 10. On 2011 March 19, the variability timescale of recursive bursts is ∼33.8 s, and the ratio of the peak count rate to the persistent level count rate is 2.92 ± 0.05. These bursts have simple profiles with slow rise and fast decay. The light curves in Figure 5 show that, as these bursts evolve with time, the flaring frequency roughly increases. On 2011 April 10, the recurrence timescale of the variability becomes ∼21.7 s, and the burst becomes more structured. The ratio of the peak count rate to the persistent level count rate becomes 3.38 ± 0.06. Careful observation of the burst profiles in Figure 5 reveals two unique burst structures: (1) the burst profile seen on 2011 March 31 has a single peak, and the count rate rises slowly (∼30 s) to the peak of the burst; (2) the burst profile seen on 2011 April 3 can be characterized by double peak and shows a faster rise in count rate (∼15–20 s). This behavior and the variation in the burst profile structures of the source has so far been seen in the “ρ” class of GRS 1915+105. From Table 1, it is clear that ρ-like variabilities in IGR J17091−3624 becomes stronger (i.e., rms amplitude of characteristic oscillations increases from ∼6% to ∼32%) and faster (i.e., recurrence timescale decreases from ∼80 s (on 2011 March 24) to ∼22 s (2011 April 12)) with time.

For each variable state observation, we fit the PDS continuum with the broken power-law model (since the low-frequency break is prominent; see the top panel of Figure 6), and we use a Lorentzian to fit characteristic pulsation peaks and broad noise components. From Table 1, the PDS fit shows that most of the time, the characteristic pulsation frequency appears along with the first harmonic (e.g., ∼30 and 62 mHz on March 19, ∼24 and 50 mHz on March 29, etc.), and a few times with both first and second harmonics (e.g., ∼31, 63, and 110.4 mHz on March 20, ∼34, 68, and 110.2 mHz on April 2, etc.). We also detect type-A QPOs around 7–9 Hz during this state. An example of fitted PDS during the variable state on 2011 March 31 is shown in the top left panel of Figure 6. In the bottom left panel of Figure 6, we show the time evolution of
Figure 4. Transition from low-variability class (soft intermediate state) to high-variability class (variable state) via intermediate in IGR J17091−3624. The top three left panels show 2.0–60.0 keV RXTE/PCA light curves of the SIMS, IVS and variable state, respectively. The top three right panels show 2.0–60.0 keV RXTE/PCA rms normalized power density spectra of the SIMS, IVS and variable state, respectively, fitted with a broken power law and a Lorentzian. Bottom left and right panels: evolution of classes from the SIMS to the variable state/ρ-like class in the hardness intensity diagram (HID) and the color–color diagram (CD), respectively. Each point in the HID and CD are created using 1 s time binning for the entire observation and errors are $\leq 7\%$. (A color version of this figure is available in the online journal.)
characteristic oscillation frequencies of the $\rho$-like class in both IGR J17091−3624 and GRS 1915+105. This panel indicates that IGR J17091−3624 shows faster time evolution of the characteristic pulsation frequency than that of GRS 1915+105 by a factor of $\sim 1.3$ (measured by the change in characteristic oscillation frequencies in the given period provided in the bottom left panel of Figure 6). In order to check how these recurrent bursts lose their quality factors with time, we plot the $q$-factor and fractional rms amplitude (%) of the variable state characteristic oscillations with time in the top right panel of Figure 6. It shows a random fluctuation in the $q$-factor, which is unrelated with the fractional rms amplitude as well as the pulsation period. A closer inspection show that from day 20 onward, the quality factor of characteristic pulsations overall drops by a factor of $\sim 6$, while during the same time, the fractional rms amplitude roughly increases. Thus, highly coherent characteristic pulsations in the variable state/\rho-like class seem to be changed into the broad Lorentzian component at the end of their evolution. This is also reflected from the PDS fit on 2011 April 15 (see Table 1) when multiple broad Lorentzian components appear during the transition from the $\rho$-like class to some other variability classes (perhaps similar to the $\kappa$/$\lambda$ class in GRS 1915+105). A correlation in IGR J17091−3624 is observed between the pulsation frequency of characteristic oscillations and its fractional rms amplitude (%) (shown in bottom right panel of Figure 6) with the Pearson product moment correlation coefficient of 0.91 (Sheskin 2003).

In the following section, we explore other properties of the variable state/\rho-like class and compare them with those of GRS 1915+105.

### 3.3.1. Properties of the Variable State/\rho-like Class in Comparison to GRS 1915+105

As the variable state/\rho-like class in IGR J17091−3624 looks similar to the “$\rho$” class of GRS 1915+105, we make a comparative study between them.

All panels of Figure 7 show the 2.0–60.0 keV light curve in both sources. To track the change in variability pattern, we consider two observations of the variable state/\rho-like class in IGR J17091−3624 which show a transition from the slow variability and low peak flux (2011 March 31; top left panel of Figure 7) to the fast variability and high peak flux (2011 April 10; bottom left panel of Figure 7). Similar transitions from the slow variability and low peak flux on 1997 May 26 (top right panel of Figure 7) to the fast variability and high peak flux on 1997 June 22 (bottom right panel of Figure 7) are observed in GRS 1915+105. However, it is interesting to observe that the average peak count of bursts in GRS 1915+105 increases significantly while transiting from the slow variability to the fast variability ($\sim 4000$ counts s$^{-1}$ PCU$^{-1}$ to $\sim 5000$ counts s$^{-1}$ PCU$^{-1}$) while it is increased slightly ($\sim 400$ counts s$^{-1}$ PCU$^{-1}$ to $\sim 430$ counts s$^{-1}$ PCU$^{-1}$) in IGR J17091−3624 during the variable state/\rho-like class. It may be noted that the variability in IGR J17091−3624, although repetitive, is irregular, less structured (as the source is fainter than GRS 1915+105), and less coherent (i.e., $q$-factor is lowered by a factor of $1.4$–$1.8$) compared to the “$\rho$” class of GRS 1915+105. In both sources, double-peak bursts are more frequent during the fast variability regime.

Previously, a strong anti-correlation between the X-ray intensity and the hardness ratio (defined as the ratio of the count rate between 12.0–60.0 keV and 2.0–12.0 keV) was found in the “$\rho$” class of GRS 1915+105 (Yadav et al. 1999). This anti-correlation is also found in the variable state/\rho-like class of IGR J17091−3624. Figure 8 shows the comparative result of the anti-correlation found in IGR J17091−3624 on 2011 March 31 (top and bottom left panels) and in GRS 1915+105 on 1997 June 22 (top and bottom right panels). It is clear that at every second on the burst profile, the hardness ratio is higher in IGR J17091−3624 than that observed in GRS 1915+105.

To study the nature of the bursts in detail, we study the rise and decay profiles from both sources. The top left panel of Figure 9

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**Figure 5.** Light-curve evolution of the variability pattern during variable state/\rho-like class in IGR J17091−3624. All five panels show the 2.0–60.0 keV background-subtracted PCA light curve for five different observations from 2011 March 19 to 2011 April 10 with 1 s bintime.
Figure 6. Top left panel: an example of the PDS of a variability state/ρ-like class, fitted with a broken power law and multiple Lorentzians (see Table 1 for parameter values), is shown as observed on 2011 March 31. Fitted model components are shown in dotted lines along with the residuals. Top right panel: the time evolution of the quality factor and the rms amplitude (%) of the characteristic pulsation at the fundamental frequency during variable state/ρ-like class observations are shown in the upper and lower top right panels, respectively. Bottom left panel: the time evolution of the characteristic oscillation frequencies in the variable state/ρ-like class observations is shown for both IGR J17091-3624 (hollow circles) and GRS 1915+105 (solid squares). Bottom right panel: the plot of characteristic oscillation frequencies in the variable state/ρ-like class observations is shown as a function of the rms amplitude (%) of the characteristic pulsation for both IGR J17091-3624 (hollow circles) and GRS 1915+105 (solid squares).

shows the combined rise profiles of several bursts and combined decay profiles of the same bursts in IGR J17091-3624 on 2011 March 31. To study the average behavior of the rise profiles, we normalize the starting time of each profile to 0 s. Similarly, to study the average behavior of the decay profiles, we normalize the starting time of the decay of each profile to 15 s. We repeat the same procedure for the ρ class observation in GRS 1915+105 on 1997 June 22 (shown in the top right panel of Figure 9) except for the fact that the starting time of each decay profile is normalized to 70 s. We fit the combined rise profile with the exponential rise function \( f_{\text{rise}}(t) = ae^{-t/t_{\text{rise}}} \) (red continuous line), the combined decay profile with the exponential decay function \( f_{\text{decay}}(t) = ae^{-t/t_{\text{fall}}} \) (blue continuous line), and all profiles with a straight line (red and blue dotted line). In case of GRS 1915+105, the exponential function fits better than a straight line in both the rise and decay profiles with the significance of \( >10\sigma \) and \( >8\sigma \), respectively, where the significance is estimated using an \( F \)-test. For IGR J17091-3624, the corresponding significance values are \( 3.2\sigma \) and \( 5.1\sigma \), respectively. The slope of the exponential function, for both rise and decay, are found to be similar in both sources (see Table 3). If the burst structures depend on physical processes associated with the origin of the bursts (Neilsen et al. 2012), then our results indicate that the origin of the burst structure may be similar in both sources. We also study energy-dependent light-curve variance spectra in both sources during their “heartbeat” oscillations. The variance spectrum in IGR J17091-3624 on 2011 March 31 (bottom left panel of Figure 9) shows that the light-curve variance decreases monotonously with energy. However, the variance spectrum in GRS 1915+105 on 1997 June 22 (bottom right panel of Figure 9) shows an initial increase in variance with the energy up to \( \sim 6\text{ keV} \), then it decreases significantly, at least up to \( \sim 14\text{ keV} \). This is remarkable as it may indicate that although a similar parameter may trigger bursts in both sources, the spectroscopic evolution of the bursts is different, which needs to be explored further.

The top panels of Figure 10 show that the low frequency (0.1–10.0 Hz) continuum power, characteristic pulsation and its harmonics and the nature of low-frequency noise components are similar during the ρ class in both sources. White noise
Figure 7. Comparative study between the variable state $/rho$-like class in IGR J17091$-3624$ and the "$rho$" class of GRS 1915+105. The left panel figures correspond to 2.0–60.0 keV RXTE/PCA light curve of IGR J17091$-3624$ on 2011 March 31 (top) and 2011 April 10 (bottom) and the right panel figures corresponds to 2.0–60.0 keV RXTE/PCA light curve of GRS 1915+105 on 1997 May 26 (top) and 1997 June 22 (bottom). A decrease in variability timescale with time is common to both sources as they evolve.

Figure 8. Comparative study between the variable state $/rho$-like class variability class of IGR J17091$-3624$ and the "$rho$" class of GRS 1915+105. The top panels show the 2.0–60.0 keV RXTE/PCA light curve of IGR J17091$-3624$ (left) and GRS 1915+105 (right). The bottom panels show the plot of hardness ratio (defined as the ratio of RXTE/PCA count rate between 12.0–60.0 keV and 2.0–12.0 keV) with time for IGR J17091$-3624$ (left) and GRS 1915+105 (right). Strong anti-correlation between X-ray flux and hardness ratio is found in both sources.
subtraction is not applied only for PDS shown in the top panels of Figure 10. High-frequency power in the noise continuum becomes very weak above 1 Hz in the case of IGR J17091−3624 (top left panel of Figure 10 and top right panel of Figure 4) although type-A/type-B QPOs are observed a few times in the PDS. On the other hand, the strong, power-law-like noise continuum in GRS 1915+105 continues at higher frequencies (at least up to 10 Hz; top right panel of Figure 10) along with a type-B QPO at 6.7 ± 0.4 Hz (middle right panel of Figure 10). Interestingly, the 6.7 ± 0.4 Hz type-B QPO in GRS 1915+105 also has a harmonic at 13.2 ± 0.8 Hz with the q-factor of 3.8 ± 0.4 (middle right panel of Figure 10). Along with characteristic heartbeat oscillations, IGR J17091−3624 shows 7−10 Hz type-A QPOs on 2011 March 24, 25, and 31 and 2011 April 3 (see Table 1) and type-B QPO once at ~5 Hz on 2011 April 12 (see Table 1). Perhaps because of the statistical limit, harmonics in type-A/type-B QPOs are not visible in IGR J17091−3624. An example of type-A QPO observed during the ρ-like class on 2011 March 31 at ~8.4 Hz is shown in the middle left panel of Figure 10. Harmonics at the mHz frequency are seen in both sources. The lower panels of Figure 10 show a comparative study of the HIDs between the two sources. We find a similar trend in the HID evolution but a different range in hard color for both sources. Results on comparative study of both sources are summarized in Table 3.

During the 2011 outburst, IGR J17091−3624 evolves from the LS/HIMS to the SIMS state and finally from the SIMS to the variable state/ρ-like class (similar to the ρ class in GRS 1915+105) as X-ray flux increases (see Table 1 of Capitanio et al. 2012 and Tables 1 and 2 from our analysis). Detection of the accretion disk wind as well as quenching of radio emission during the disk-dominated state may suggest that IGR J17091−3624 is approaching the high soft state (King et al. 2012; Rodriguez et al. 2011a).

According to X-ray observations, IGR J17091−3624 passes through the SIMS state during radio flares observed on MJD 55623.57 (Rodriguez et al. 2011a). Generally, HIMS to SIMS transitions are followed by radio flares (Belloni et al. 2005). Following the SIMS, large-amplitude X-ray oscillations appear via the IVS and continue for ~25 days (MJD 55638 − MJD 55663). Similarly, GRS 1915+105 was in the HIMS state during 1997 March 26−1997 May 8 (Rao et al. 2000) and the ρ
X-ray class activity started on 1997 May 26 and continued till 1997 June 25 (Yadav et al. 1999). Between these periods (i.e., 1997 May 8–26), for a short time, GRS 1915+105 showed radio flares on 1997 May 15 (Mirabel et al. 1998). We analyze and fit the RXTE/PCA PDS on 1997 May 13 using the combination of broken power law and Lorentzian and find a type-B QPO at 5.87 ± 0.12 Hz, with the $q$-factor of 7.89 ± 0.62 and fractional rms amplitude (%) of 4.84 ± 0.36. The PDS is associated with weak red noise. These two observations show that the source was in the SIMS state on 1997 May 13. Thus, GRS 1915+105 also passes through the SIMS before its large amplitude oscillations begin. This indicates that the X-ray spectral evolution prior to the $\rho$ class activity in both sources are roughly similar. This also strengthens that the spectroscopic nature of the origin of $\rho$ class activities in both sources may be similar.

### 4. DISCUSSION

In this paper, we study the evolution of the X-ray activity in IGR J17091−3624 from 2011 February 3 to 2011 April 15. Initially, with the increase in the SWIFT/XRT count rate, a transition from the low/hard and HIMS to the SIMS was detected. In transient BHXBs, this transition is usually accompanied by radio flares (Fender et al. 2004; Belloni et al. 2005). Our results show that the source makes a to and fro transition between the HIMS and the SIMS a few times. This may represent the disk instability which occurs due to the increasing mass accretion rate. A few days later, a transition takes place from the SIMS to regular, repetitive and highly variable pulsations similar to the $\rho$-class variability, previously observed only from GRS 1915+105. A few observations between variable state/$\rho$-like class and the SIMS show $\sim 11–14$ mHz quasi-periodic variabilities with low-rms amplitude which are termed IVS.

In addition to the structural similarities of “heartbeat” oscillations in both sources, we find that they show similar time evolution in the burst structure. With time, the characteristic pulsation frequency increases in both sources and the ratio of the peak flux to the persistent level flux also increases. In both cases, the average rise profile of the burst shows a slow exponential rise while the average decay profile shows a fast decay. Interestingly, we find a strong anti-correlation between the hardness value and the X-ray flux during variabilities in both sources. The evolution of the burst structure in the HID of both sources is identical. The PDS below 1 Hz shows similar noise continuity as well as pulsation peaks. Both sources have strong mHz QPOs along with harmonics and strong flat-top noise along with the presence of type-A/type-B QPOs in the PDS.

In other BHXBs, the transition from the canonical LS to the steep-power-law (SPL) state (highest flux regime of the outburst; Remillard & McClintock 2006) is a commonly observed phenomenon, where SPL sometimes coincides with the SIMS (Fender et al. 2004; Belloni et al. 2005). IGR J17091−3624 also shows a transition from the LS/HIMS to the SIMS and the high soft state. Spectral properties of the LS, HIMS and SIMS in IGR J17091−3624 also match with those of other BHXBs (Remillard & McClintock 2006; Belloni et al. 2005). Lutovinov et al. (2003) showed evidence that previously IGR J17091−3624 was in the LS. A recent report (Altamirano et al. 2013) claims that IGR J17091−3624 is going back to quiescence similar to normal transient BHXBs. It is important to note that GRS 1915+105 was discovered as a normal transient in 1992 (Lochner et al. 1992). It was detected at an intensity level as low as $\sim 90$ mcrab and gradually increased up to 300 mcrab over a month (Greiner 1994). Hence it is possible that at the beginning, similar to IGR J17091−3624 and normal transients, GRS 1915+105 also evolved from quiescence and, passing through the low/hard, HIMS and SIMS, it entered different variability classes. Following the fate of IGR J17091−3624 and other normal transients, GRS 1915+105 may also fade into quiescence in the future. Therefore, it is possible that at the beginning, the spectral evolution of GRS 1915+105 and IGR J17091−3624 were similar to normal transients. With the RXTE/PCA, GRS 1915+105 has usually been seen in the HIMS/SIMS state, but it is never seen in the typical LS. From the HIMS and SIMS state, IGR J17091−3624 deviates from the canonical BHXB track and shows regular repetitive variabilities similar to the $\rho$ class variability observed in GRS 1915+105. Besides, within the RXTE era, IGR J17091−3624 shows six variability classes (Altamirano et al. 2011b) out of 14 classes in GRS 1915+105 (Belloni et al. 2000; Klein-Wolt et al. 2002). Thus, considering the evidence, IGR J17091−3624 do show spectral evolution and properties similar to GRS 1915+105, but, during the first $\sim 40$ days of the outburst, it also clearly exhibits outburst evolution properties similar to other canonical BHXBs (more evidently than GRS 1915+105).

Our results tentatively indicate that the central object in the IGR J17091−3624 system may be a black hole. One such indication is the detection of type-B QPOs from six different

### Table 3

| Characteristic Parameters | IGR J17091−3624 (Variable state/\$\rho\$-like class) | GRS 1915+105 (\$\rho\$-class) |
|---------------------------|---------------------------------------------------|-----------------------------|
| Oscillation timescale     | $\sim 20\ s - 50\ s$                              | $\sim 40\ s - 110\ s$      |
| Change in timescale       | Increases with time $\sim 1.32\ \text{mHz}\ \text{day}^{-1}$ | Increases with time $\sim 0.36\ \text{mHz}\ \text{day}^{-1}$ |
| Peak to minimum flux ratio | $\sim 2.91-3.82$                                  | $\sim 3.38-4.28$            |
| X-ray flux and hard color relation | Strong anti-correlation found                      | Strong anti-correlation found |
| Variability pattern (fitting with $f(t) = a e^{t/t_i}$) | Slow exponential rise ($t_i = t_{\text{rise}} \sim 14.67$) fast decay ($t_i = t_{\text{fall}} \sim 3.62$) | Slow exponential rise ($t_i = t_{\text{rise}} \sim 13.68$) fast decay ($t_i = t_{\text{fall}} \sim 2.48$) |
| QPOs                      | 26.3 mHz and 52.8 mHz (on 2011 Mar 31)             | 9.7 mHz and 19.2 mHz (on 1997 May 26) |
|                          | 36.6 mHz and 75.9 mHz (on 2011 Apr 3)              | 12.1 mHz and 24.3 mHz (on 1997 Jun 3) |
|                          | 45.9 mHz and 94.2 mHz (on 2011 Apr 10 etc.)        | 18.5 mHz and 37.9 mHz (on 1997 Jun 22 etc.) |
observations and type-C QPOs from eight different observations (see Table 1). These QPOs are often observed from BHXBs rather than from NSXBs (Casella et al. 2005; Belloni et al. 2005). Besides, the observation of the low-frequency break in the PDS of this source on 2011 February 15 (see Lutovinov et al. 2003) and flat power-law spectra from INTEGRAL (Lutovinov et al. 2005) further decreases the chance of being an NSXB. Moreover, from our analysis, type-I X-ray bursts are not found.

Figure 10. All left panel figures correspond to IGR J17091−3624 and all right panel figures correspond to GRS 1915+105. Top panels: 2.0–60.0 keV RXTE/PCA rms normalized power density spectra. Middle panels: typical type-A 7–10 Hz QPO in the PDS of IGR J17091−3624 (left) and a type-B QPO in the PDS of GRS 1915+105 (right) during the variable state/ρ class. Lower panels: hardness intensity diagrams for the same definition of hard color and intensity. Both panels show that both sources evolve in a similar way in the PDS as well as in HIDs as the characteristic oscillation frequency changes.

(A color version of this figure is available in the online journal.)
in any observations within about two months. These bursts are unique characteristics of neutron star LMXBs (Fujimoto et al. 1981; Lewin et al. 1995; Bhattacharyya 2010). This gives indirect evidence that the source may not be a neutron star.

We find a few dissimilarities between the variable state/\(\rho\)-like class of IGR J17091–3624 and the “\(\rho\)” class of GRS 1915+105. They are listed below:

1. The CD of the “\(\rho\)” class shows a loop-like pattern (see Belloni et al. 2000) while the CD of the variable state/\(\rho\)-like class in IGR J17091–3624 shows a patchy pattern (see the bottom right panel of Figure 4). A low count rate and irregular burst structure may cause such randomness in the CD. In the HID, GRS 1915+105 traverses a clockwise loop while the IGR J17091–3624 traverses anti-clockwise (Altamirano & Belloni 2012a). The X-ray flux from IGR J17091–3624 is significantly lower than that observed from GRS 1915+105 even considering a distance as large as \(\sim 17\) kpc.

2. An interesting difference between the two systems is that the hardness ratio during \(\rho\) class activity is higher \((\sim 2\) times\) in IGR J17091–3624 than that observed in GRS 1915+105. One possible reason for this higher hardness value, as discussed in Altamirano et al. (2011b), is the larger distance of IGR J17091–3624 compared to that of GRS 1915+105. However, using SWIFT/XRT data, we find that the absorption column density is \(0.9–1.02 \times 10^{22}\) cm\(^{-2}\) for IGR J17091–3624 while this value is \(5–13.6 \times 10^{22}\) cm\(^{-2}\) for GRS 1915+105. Hence, along with large distance, effects like the presence of a strong disk wind or large disk inclination angle (King et al. 2012) may cause the observed flux difference between the two sources. Contamination from a nearby source is not favored since the hardening of the light curve during the heartbeat oscillations has also been observed with SWIFT/XRT (Capitanio et al. 2012).

3. Typical LS observations where disk emission is not visible are commonly seen in canonical BHXBs but have never been seen in GRS 1915+105 during the RXTE era. Earlier outbursts in IGR J17091–3624 started with the LS (Lutovinov et al. 2003; Capitanio et al. 2006). In the case of the 2011 outburst, SWIFT/XRT spectral fitting of IGR J17091–3624 shows that, from 2011 February 9 to 20 (see Table 2) the disk component is not visible in the spectra. Apart from this, a break in the PDS continuum and detection of a broad Lorentzian also indicate that the present outburst started with the LS, although accurate determination of the spectral state is not possible due to unavailability of RXTE data.

4. A systematic study of the occurrence of different classes in GRS 1915+105 (J. S. Yadav & M. Pahari 2013, in preparation) shows that the \(\rho\) class variability eventually arises from the \(\alpha\) or \(\omega\) class after transiting from the SIMS. These are different X-ray classes with large variation in the variability timescale as well as X-ray flux (Belloni et al. 2000; Klein-Wolt et al. 2002; Pahari & Pal 2010). Until now, the \(\rho\) class-like activity in IGR J17091–3624 has arisen from the SIMS through the IVS, omitting any other variabilities as observed in GRS 1915+105.

5. From Table 1, the total GTI of variable state/\(\rho\)-like class observations in IGR J17091–3624 can be estimated as \(\sim 19.87\) hr. Once in the entire \(\rho\) class period (2011 March 19 to 2011 April 12), it goes back to the non-variable SIMS (2011 March 25). During the rise phase of the 1997 outburst, GRS 1915+105 was also in the SIMS prior to the \(\rho\) class on 1997 May 26 and showed a transition from the \(\rho\) class to the \(\kappa\) class on 1997 June 18 (J. S. Yadav & M. Pahari 2013, in preparation). In GRS 1915+105, the total GTI of the \(\rho\) class observation is found to be \(\sim 7.36\) hr. Unlike IGR J17091–3624, GRS 1915+105 occasionally makes a transition to the \(\alpha\) or \(\kappa\) class within the \(\rho\) class period (J. S. Yadav & M. Pahari 2013, in preparation). These observations, in both sources, indicate that \(\rho\) class variability may represent a very stable X-ray class. If frequent observations and the total GTI are assumed to represent the stability of a state, then the possible reason for prolonged stability of IGR J17091–3624 in the variable state/\(\rho\)-like class compared to GRS 1915+105 may be the lower mass accretion rate in IGR J17091–3624 compared to GRS 1915+105 which, however, needs to be explored further.

Using the radio data, Rodriguez et al. (2011a) found the distance of IGR J17091–3624 to be 10–17 kpc assuming the black hole mass to be \(10 M_\odot\). Later, Rebusco et al. (2012) estimated the mass of \(6 M_\odot\). We assume here that the black hole mass is \(8 \pm 2 M_\odot\). We use the distance of IGR J17091–3624 to be \(14 \pm 3\) kpc to calculate the mass accretion rate of IGR J17091–3624 relative to the GRS 1915+105. In the case of GRS 1915+105, we assume the mass, the distance and the disk inclination angle with respect to the observer’s line of sight to be \(10.1 \pm 0.4 M_\odot\) (Steeghs et al. 2013), \(12.5 \pm 2.1\) kpc and \(70^\circ\) (Muno et al. 1999), respectively. The mass accretion rate at the inner disk can be derived using the energy conservation law and the virial theorem. Using a simple analytical approach and assuming the disk radiation to be blackbody and considering both side of the disk, the mass accretion rate is (Frank et al. 2002):

\[
\dot{m} = 8\pi R_{\text{in,km}}^3 \sigma T_{\text{in,keV}}^4 / 3GM_{\text{bh}} M_\odot \text{ yr}^{-1},
\]

where \(\sigma\) is the Boltzmann constant, \(G\) is the gravitational constant, \(T_{\text{in,keV}}\) is the inner disk temperature in keV, and \(R_{\text{in,km}}\) is given by the equation

\[
R_{\text{in,km}} = C^2 \times \sqrt{N_{\text{diskbb}}} \times D_{10,kpc} / \sqrt{\cos i},
\]

where \(C\) is the color correction factor (assumed to be \(\sim 1.8\) in the case of a black hole (Kubota et al. 1998)), \(N_{\text{diskbb}}\) is the normalization corresponds to the diskbb model component in XSpec, \(D_{10,kpc}\) is the distance to the source in the unit of 10 kpc, and \(i\) is the disk inclination angle with respect to the observer’s line of sight. Inserting Equation (2) in (1), we get

\[
\dot{m} = \frac{8\pi \sigma T_{\text{in,keV}}^4}{3GM_{\text{bh}}} \times (C^2 \times \sqrt{N_{\text{diskbb}}} \times D_{10,kpc} / \sqrt{\cos i})^3.
\]

To obtain a qualitative idea, we compare accretion parameters of both sources using the above equations. For example, the spectral analysis of a less-variable HIMS observation in GRS 1915+105 on 1997 September 9 using RXTE/PCA yields a disk temperature of \(1.24 \pm 0.03\) keV and an inner disk radius of \(57 \pm 3\) km (Muno et al. 1999). Using Equation (2), the equivalent normalization would be \(211.3 \pm 26.5\). From the spectral analysis of non-variable HIMS in IGR J17091–3624, observed on 2011 March 8, we find the value of \(N_{\text{diskbb}}\) to be \(13.87 \pm 1.35\) and the disk temperature to be \(1.24 \pm 0.03\) keV (See Table 2). Using these values in Equation (3) and assuming the disk inclination angle \((i)\) to be \(70^\circ\) in IGR J17091–3624 (King et al. 2012;
Capitanio et al. 2012), we find $m_{\text{GRS1915+105}} / m_{\text{IGRJ17091} - 3624} \sim 48.3 \pm 8.7$. Hence, the mass accretion rate in GRS 1915+105 is significantly higher (perhaps an order of magnitude) compared to that of IGR J17091 – 3624. This may be consistent with very high X-ray flux observed in GRS 1915+105 rather than that seen from IGR J17091 – 3624 even considering IGR J17091 – 3624 at a larger distance. We also calculate the relative viscous timescale of the accretion flow using the following relation (Frank et al. 2002):

$$t_{\text{vis}}^d = 4.3 \times 10^{-4} \alpha^{-1} m_{\text{g}}^{-1} M_{\text{bh}}^{-1} R_{\text{in,km}}^2 s,$$

(4)

where $t_{\text{vis}}^d$ is the dynamic viscous timescale, and $\alpha$ is the viscosity parameter. We consider the typical value of $\alpha$ to be 0.01 for both sources. Using relation (4) and the above parameters, we find the value of $t_{\text{vis}}^d / t_{\text{vis}}^d(\text{GRS1915+105}) / t_{\text{vis}}^d(\text{IGRJ17091} - 3624) \approx 0.37 \pm 0.13$ when the disk inclination angle of IGR J17091 – 3624 is $\sim 70^\circ$ (King et al. 2012; Capitanio et al. 2012). Hence the viscous timescale of GRS 1915+105 is smaller relative to IGR J17091 – 3624 in a non-variable state.

5. CONCLUSIONS

From our analysis of SWIFT/XRT and RXTE/PCA data during the 2011 outburst of IGR J17091 – 3624, and using results from the comparative study of timing and spectral properties with GRS 1915+105, we conclude the following points.

1. We find that IGR J17091 – 3624 is the only known transient LMXB which shows regular, repetitive, and structured variability in the intensity pattern similar to the $\rho$-type variability seen from GRS 1915+105. Various parameters like burst frequency evolution, burst structure profile, rise and decay profile, peak-to-minimum flux ratio, harmonics of mHz characteristic pulsations, and PDS characteristics show remarkable similarity. The entry to the $\rho$-type variability in IGR J17091 – 3624 is from the SIMS via the intermediate variability state which shows $\sim 11 – 14$ mHz coherent pulsations with the presence of weak red noise/type-A QPO, while the exit from the $\rho$-type variability is through the soft state with several broad Lorentzian noise components and QPO-like features at $\sim 3$ Hz (similar to the $k/\lambda$ class; see Table 1). GRS 1915+105 also was in the SIMS prior to the $\rho$ class on 1997 May 26 and showed a transition from the $\rho$ class to the $k$ class on 1997 June 18 (J. S. Yadav & M. Pahari 2013, in preparation). However, significant differences in the hardness ratio as well as variance spectra are also observed.

2. Several evidences like the power-law-dominated spectra, the detection of type-B and type-C QPOs, the break in the PDS continuum along with $\rho$ class activity (as seen in GRS 1915+105 which is a BHXB) are consistent with the black hole identification of the source.

3. The source shows an increase in the flux while transitioning from the LS/HIMS to the SIMS. Later, a transition occurs from a typical irregular variability state (SIMS), seen commonly in most of the BHXBs to the regular, repetitive large-variability state, seen only in GRS 1915+105 ("$\rho$"-type variability) via an intermediate state. However, X-ray bursts during the variability state/$\rho$-like class are spectrally harder than that found in GRS 1915+105. The central black hole mass, its distance, disk inclination angle, absorption column density, etc., may be important to explain the observed hardness ratio, but at present we do not know the exact answer. It is a topic for future investigations if these parameters or some unknown parameter/mechanism are responsible for a higher hardness ratio during $\rho$ class activity in IGR J17091 – 3624.

4. From Table 1, it is clear that we detect several QPOs ranging from a few mHz to 10 Hz or so. Moreover, there are to and fro transitions between the HIMS and the SIMS and the source shows evolution of characteristic oscillations in the $\rho$ class faster than GRS 1915+105.

5. In both sources, $\rho$ class activity is observed following the SIMS where disk emission in the energy spectra is visible and contributes significantly to the total flux. GRS 1915+105 during the RXTE era never shows a typical LS where disk emission is not visible, but IGR J17091 – 3624 shows an LS where disk emission is not significant. This result agrees well with the LS observations of other BHXBs. Similar to a normal transient, IGR J17091 – 3624 also seems to move to quiescence as observed with SWIFT/XRT (Altamirano et al. 2013). Hence considering the evidence, IGR J17091 – 3624, behaves similarly to GRS 1915+105 at a certain period of evolution whereas it behaves like other canonical BHXBs at some other period. Hence, this source may be an important bridge between GRS 1915+105 and other canonical BHXBs in understanding observational dissimilarities, as well as accretion and radiation mechanisms.

Thus, long-term and continuous observation of outbursts of this source in multi-wavelength band using ASTROSAT would reveal a lot of information regarding the radiation mechanism and accretion flow properties of BHXBs, and would help to construct a complete picture of accretion flow around black hole systems by connecting GRS 1915+105 with other canonical BHXB systems.

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