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THE FAINT "HEARTBEATS" OF IGR J17091–3624: AN EXCEPTIONAL BLACK HOLE CANDIDATE

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ABSTRACT

We report on the first 180 days of *Rossi X-Ray Timing Explorer* observations of the outburst of the black hole candidate IGR J17091–3624. This source exhibits a broad variety of complex light curve patterns including periods of strong flares alternating with quiet intervals. Similar patterns in the X-ray light curves have been seen in the (up to now) unique black hole system GRS 1915+105. In the context of the variability classes defined by Belloni et al. for GRS 1915+105, we find that IGR J17091–3624 shows the ν, ρ, α, λ, β, and μ classes as well as quiet periods which resemble the χ class, all occurring at 2–60 keV count rate levels which can be 10–50 times lower than observed in GRS 1915+105. The so-called ρ class "heartbeats" occur as fast as every few seconds and as slow as ~100 s, tracing a loop in the hardness–intensity diagram which resembles that previously seen in GRS 1915+105. However, while GRS 1915+105 traverses this loop clockwise, IGR J17091–3624 does so in the opposite sense. We briefly discuss our findings in the context of the models proposed for GRS 1915+105 and find that either all models requiring near Eddington luminosities for GRS 1915+105-like variability fail, or IGR J17091–3624 lies at a distance well in excess of 20 kpc, or it harbors one of the least massive black holes known ($<3\ M_{\odot}$).

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

Online-only material: color figures

1. INTRODUCTION

Observations with the *Rossi X-Ray Timing Explorer* (*RXTE*) have led to extraordinary progress in the knowledge of the variability properties of many different types of sources, particularly of black hole candidates (BHCs) and neutron stars (NSs) in low-mass X-ray binaries (e.g., van der Klis 2006). Both BHCs and NSs are known to exhibit distinct "accretion states" (usually defined in terms of their X-ray spectral shape and variability), whose characteristics are thought to be intimately related to the physics of the accretion flow and its interaction with the central compact object (e.g., Belloni 2010; Remillard & McClintock 2006; van der Klis 2006; Belloni et al. 2011).

Of all Galactic BHC X-ray binaries known today, one of the most prolific in terms of state transitions is GRS 1915+105. In outburst since its discovery in 1992 with WATCH (Castro-Tirado et al. 1992), it is a 33 day orbital period binary system (Greiner et al. 2001) harboring a $14 \pm 4.4\ M_{\odot}$ black hole (Greiner et al. 2001; Harlaftis & Greiner 2004). At a distance of ~12.5 kpc (Mirabel & Rodríguez 1994), GRS 1915+105 is very often at Eddington or super-Eddington luminosity (e.g., Done et al. 2004).

GRS 1915+105 is known to show quasi-periodic oscillations (QPOs) in the 0.001–70 Hz range, some of which are the same as those generally seen in other BHCs (Morgan et al. 1997; Markwardt et al. 1999; Reig et al. 2000; Strohmayer 2001; Soleri et al. 2008). However, so far GRS 1915+105 has been unique in that its X-ray light curves exhibit more than a dozen different patterns of variability, usually called "classes" (which are referred to with Greek letters), most of which have high amplitude and are highly structured (e.g., Belloni et al. 2000). Most of this structured variability is thought to be due to limit cycles of accretion and ejection in an unstable disk (see, e.g., Belloni et al. 1997; Mirabel et al. 1998; Tagger et al. 2004; Neilsen et al. 2011, and references within). Much effort has been expended in order to understand why GRS 1915+105 is so unusual among BHCs (e.g., Fender & Belloni 2004). It has been proposed that the high accretion rate estimated for GRS 1915+105 might be the determining factor (e.g., Done et al. 2004); however, the lack of any other source showing similar characteristics has prevented definite conclusions.

IGR J17091–3624 was discovered with *International Gamma-Ray Astrophysics Laboratory*/IBIS during a Galactic center observation on 2003 April (Kuulkers et al. 2003) and later again in 2007 (Capitanio et al. 2009). Reexamination of archival data from different missions showed that IGR J17091–3624 was also active in 1994, 1996, and 2001 (Revnivtsev et al. 2003; in't Zand et al. 2003; Capitanio et al. 2006). Although an NS could not be excluded based on spectral characteristics and the outburst radio/X-ray flux ratio, Capitanio et al. (2006) concluded that IGR J17091–3624 is most probably a black hole. A new outburst was detected with *Swift*/Burst Alert Telescope (BAT) in 2011 February (Krimm et al. 2011); the radio/X-ray characteristics during the first ~40 days, combined with the discovery of QPOs (Rodriguez et al. 2011a), further suggested that IGR J17091–3624 is a black hole.

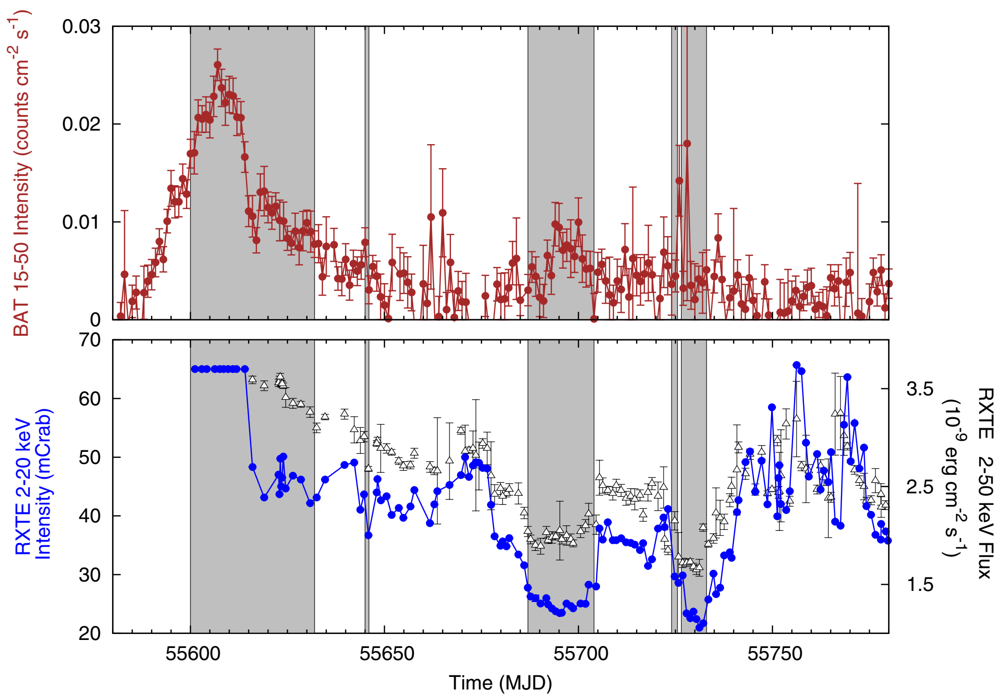

Figure 1. Upper panel: *Swift*/BAT light curve. Lower panel: Circles—*RXTE* Crab normalized 2–20 keV intensity. *RXTE* values are averaged per observation, background subtracted, and dead time corrected. Triangles—RXTE 2–50 keV flux *RXTE* observations between day 55601 and 55615 are affected by the nearby source GX 349+2 (Sco X-2); the intensity during this period was arbitrarily fixed to 65 mCrab and no X-ray flux is reported. Shaded areas mark quiet periods (see the text).
(A color version of this figure is available in the online journal.)

Recently we reported the discovery of 10 mHz QPOs in *RXTE* observations of IGR J17091–3624 (Altamirano et al. 2011c) which are very similar to those in GRS 1915+105. The suggested link between these sources was strengthened by our discovery of (1) a continuous progression of regular, quasi-periodic flares occurring at a rate of 25–30 mHz (Altamirano et al. 2011a), and (2) a broad variety of complex patterns alternating with quiet intervals (Altamirano et al. 2011a, 2011b), resembling, respectively, the so-called ρ class ("heartbeat") oscillations and the complex β class patterns, both so far seen only in GRS 1915+105.

The existence of a source showing similar X-ray variability to that seen in GRS 1915+105 opens a new window of opportunity to understand the physical mechanism that produces the highly structured X-ray variability. Multi-wavelength and high spectral resolution studies of IGR J17091–3624 as compared with GRS 1915+105 can help us gain further insights into the role of disk–jet coupling (e.g., review by Fender & Belloni 2004) and accretion disk winds (e.g., Neilsen et al. 2011) in accreting BHCs. Furthermore, it allows the possibility to test the role of the accretion disk size, evolutionary state of the companion star, and the evolution of the disk structure as an explanation of the long- and short-term X-ray variabilities seen in GRS 1915+105 (e.g., Done et al. 2004).

In this Letter we use *RXTE* data to describe the phenomenological similarities between IGR J17091–3624 and GRS 1915+105. We demonstrate that IGR J17091–3624 shows the same type of high-amplitude and highly structured variability previously observed only in GRS 1915+105, although at much lower count rates. The analysis presented here is the first step of a larger program to compare IGR J17091–3624 and GRS 1915+105 in detail using data obtained with *RXTE*, *Swift*, *XMM-Newton*, as well as optical facilities.

2. OBSERVATIONS, DATA ANALYSIS

IGR J17091–3624 has been observed with the Proportional Counter Array (PCA; Zhang et al. 1993; Jahoda et al. 2006) on board *RXTE* almost daily since the outburst began in 2011 February (at the time of submission of this Letter, IGR J17091–3624 was still active). We used the first 147 observations, covering ∼180 days. We also used 1700 archival *RXTE* observations of GRS 1915+105.

Power spectra and light curves were produced from the PCA using standard techniques (e.g., Belloni et al. 2000; Altamirano et al. 2008). Dead-time-corrected energy spectra averaged over each observation were created from PCU 2 data; a systematic error of 1% was added to all channels. Response matrices were created with `PCARSP (V11.7.1)` using the position reported by Kennea & Capitanio (2007), thereby taking into account a constant 0°.4 pointing offset used after 2011 February 23 (MJD 55615) to avoid a bright nearby source (see below). All spectra were satisfactorily fitted in the 3–25 keV band with an absorbed disk-blackbody plus power law model (`phabs*(diskbb + powerlaw)`) using Xspec 12 (Arnaud 1996) with N_h fixed to 1.1×10^{22} cm^{-2} (Krimm et al. 2011); some spectra required a Gaussian at 6.5 keV for a good fit.

3. RESULTS

Figure 1 (upper panel) shows the *Swift*/BAT (Barthelmy et al. 2005) daily light curve of the first 200 days of the outburst (assuming outburst onset on MJD ∼55580). The outburst reached a maximum of 0.026 counts cm^{-2} s^{-1} (15–50 keV) ∼27 days after onset, then decreased and remained below 0.01 counts cm^{-2} s^{-1}. The lower panel of Figure 1 shows the 2–20 keV, Crab-normalized intensity and the 2–50 keV un-absorbed flux from each *RXTE*/PCA pointed observation.

RXTE observations started 21 days after onset. The first 10 observations (until MJD 55615) are affected by the contribution of the bright, variable source GX 349+2 (Sco X-2) which was within the 1° PCA field of view (see, also, Rodriguez et al. 2011a). For reference, in Figure 1 we show these observations at an arbitrarily fixed intensity of 65 mCrab; we do not report their X-ray flux.

From the variability point of view, we find that during MJD 55601–55632, the X-ray light curves were well characterized by broadband noise and a QPO moving in time from 0.1 Hz up to ∼6 Hz. The evolution of the power spectral components (see, Pahari et al. 2011; Shaposhnikov 2011; Rodriguez et al. 2011a for more details) is similar to that seen in BHC transients in the hard state (e.g., Belloni 2010), further suggesting the black hole nature of IGR J17091–3624.

On MJD 55634, IGR J17091–3624 first showed a ∼10 mHz QPO. Since then, a broad variety of complex patterns occurred, including strong variability in the form of flares alternating with quiet intervals (Altamirano et al. 2011a, 2011b, 2011c). The variability shows remarkable similarities with that of GRS 1915+105 (e.g., Belloni et al. 2000) suggesting a common mechanism. In Figures 2 and 3 we show six different examples; the top and bottom frames of each panel correspond to data from IGR J17091–3624 and GRS 1915+105, respectively.

Based on the classification of Belloni et al. (2000), panel A shows segments of the ν class, and panels B and C two different varieties of ρ class. The ν and ρ variability classes in GRS 1915+105 are characterized by quasi-periodic "flares" recurring on timescales between ∼40 (e.g., Massaro et al. 2010; Neilsen et al. 2011) and ∼120 s (Belloni et al. 2000). The main differences between the ν and ρ classes are that (1) the shape and period of the flares in ν can be more irregular than in ρ and (2) that the ν flares show a characteristic structure in their profiles, notably a dip followed by a secondary peak after the main one (see Figure 2).

Panel D shows segments of the α class, in which "rounded-bumps" are sometimes accompanied by sharp peaks that last a few seconds. Note that in our observations of IGR J17091–3624 we do not see the typical ∼1000 s quiet interval which precedes the bumps in the α class of GRS 1915+105 (not shown, see, e.g., Figure 19(d) in Belloni et al. 2000). Panel E shows light curves from either the β class or the λ class. These light curves consist of quasi-periodic alternation of low-quiet periods with highly variable and oscillating ones. Panel F shows segments of the μ class, where we observe periods of very rapid (factor of 2–4 changes in count rate in less than 5 s) and almost incoherent variability.

In addition to the light curves shown in Figures 2 and 3, IGR J17091–3624 displays complex light curves combining characteristics of different classes. It also shows *quiet periods* in which 1 s light curves are flat ($<$10% fractional rms amplitude at $<$1 Hz). These periods are marked with gray shadowed areas in Figure 1 and coincide with the times when IGR J17091–3624 is detected most strongly by *Swift*/BAT, i.e., when the spectrum is hard. In terms of the GRS 1915+105 variability classes, these periods could correspond to the χ class.

Figures 2 and 3 not only shows the remarkable similarities in the shapes of light curves from both sources, it also shows two clear differences: (1) the timescales can be different (IGR J17091–3624 tends to be faster; see below) and (2) the average count rate (or flux) of the source can be much higher (factor 10–50) in GRS 1915+105. Some of the spectral and timing analysis performed for GRS 1915+105 on timescales

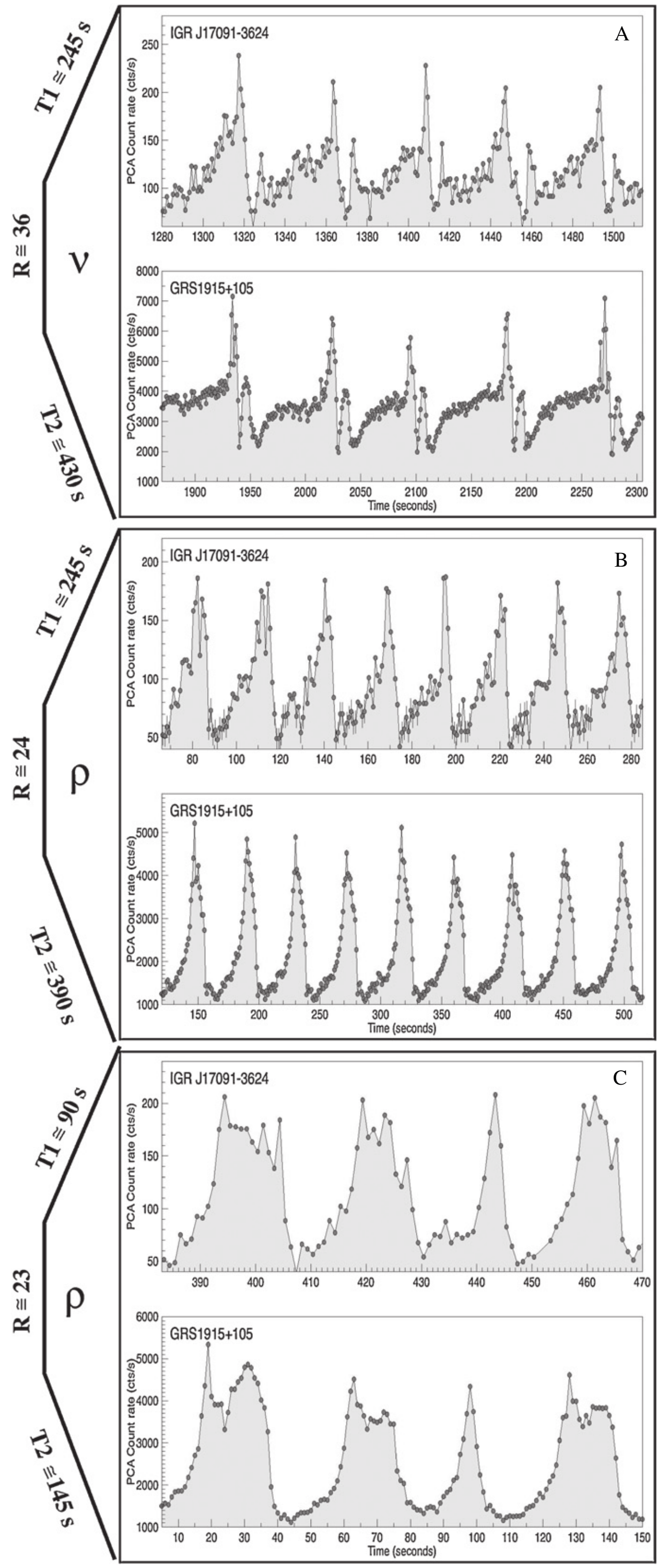

Figure 2. Upper and lower panels of each frame show a light curve of IGR J17091–3624 and GRS 1915+105, respectively. Count rates are given in 1 s bins, per PCU, 2–60 keV, and background subtracted. The IGR J17091–3624 A–C intervals last $T1$ seconds and come from observations 96420-01-05-00, -06-00, and -07-01, respectively. For GRS 1915+105 they last $T2$ seconds and come from observations 10408-01-40-00, 20402-01-34-00, and 93701-01-02-01, respectively. $R \equiv \mathrm{MIN}_{\mathrm{GRS\,1915+105}}/\mathrm{MIN}_{\mathrm{IGR\,J17091-3624}}$, where MIN is an average count rate during minima in the above light curve and is given for each frame as an order of magnitude estimate of the flux ratio. Greek letters on the side indicate the variability class.

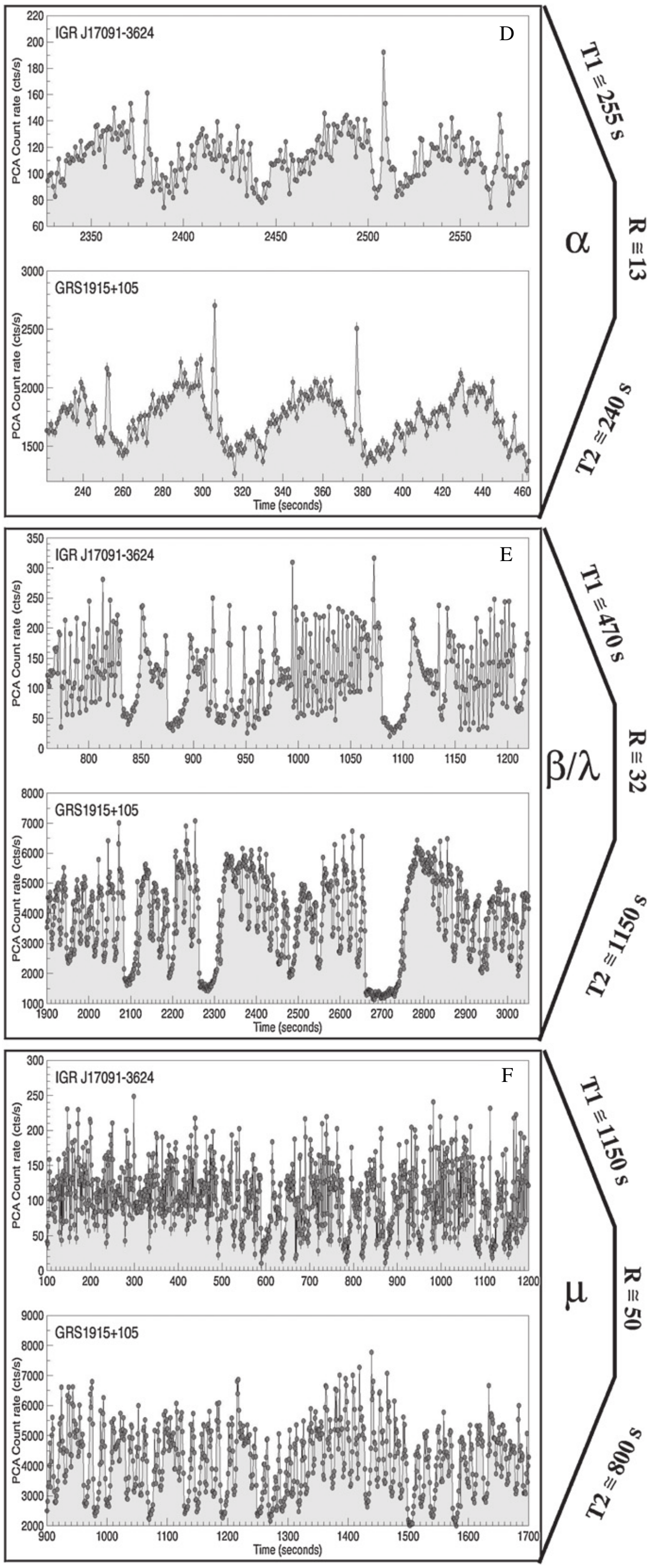

Figure 3. Similar to Figure 2. The IGR J17091–3624 D–F intervals come from observations 96420-04-03, -08-03, and -09-06, respectively. For GRS 1915+105 they come from observations 20187-02-01-00, 95701-01-31-00, and 10258-01-10-00, respectively.

of seconds (e.g., Markwardt et al. 1999; Belloni et al. 2000; Done et al. 2004; Soleri et al. 2008) is prevented by the combination of relatively low count rate and faster variability in IGR J17091–3624.

Given that we find the ν and ρ variability classes (panels A–C) in about 35% of our observations (another $\sim$35% of the light curves are flat, and the remaining $\sim$30% are a mix of the α, β, μ, λ, and unclassified ones) and that ρ is one of the best studied classes in GRS 1915+105, in the rest of this Letter we constrain ourselves on further comparison of the ν and ρ classes between sources. More detailed comparison of the other variability classes will be presented in upcoming papers.

Some of the observations clearly show only the ρ or the ν types of flares, while some show a mix, and sometimes differentiating the two classes is difficult due to the low statistics. In any case, these flares can occur as fast as every few (2–5) seconds (e.g., ObsID: 96420-01-22-04, MJD 55768), and as slow as every $\sim$100 s (e.g., ObsID: 96420-01-03-01, MJD 55634). This means that the oscillations in IGR J17091–3624 can be faster than those in GRS 1915+105, but not as slow. The fractional rms amplitude of the flares covers a range from $\sim$2% to up to 50%–60%. If one assumes that the minimum period that a quasi-periodic feature can reach scales proportional to some power of the mass of the compact object (see, e.g., Belloni et al. 1997; Frank et al. 2002), and that a 2–5 s recurrence time of the ρ/ν flares IGR J17091–3624 versus $\sim$40 s in GRS 1915+105 is due to a difference in mass, then our results suggest the black hole in IGR J17091–3624 could be a factor of a few less massive than the $14 \pm 4.4\, M_\odot$ of GRS 1915+105.

The variability classes are known to exhibit distinctive spectral evolution (e.g., Belloni et al. 2000). In a color–color diagram (CD) or hardness–intensity diagram (HID), one observes that each flare from the ρ (and sometimes ν) class traces a loop (or "ring;" see Vilhu & Nevalainen 1998; Belloni et al. 2000). Figure 4 (bottom left) shows the HID for 10 consecutive flares from a single observation of GRS 1915+105 (inset shows a representative flare). The loop in the HID is always traversed clockwise.

The HIDs and CDs from *single* flares of IGR J17091–3624 are dominated by low statistics, so we could neither exclude nor confirm loop-like patterns similar to those observed in GRS 1915+105. To improve statistics, we used intervals where more than 10 flares occurred approximately periodically and folded each interval at the best average period. Although this process washed out some of the structure in the light curves (due to the quasi-periodicity of the signal and the profile differences between flares), all the HIDs we created using the same energy bands as in GRS 1915+105 (which are fixed by the observing modes used) always showed a loop resembling that seen in GRS 1915+105. In the upper-left panel of Figure 4 we show a representative example (inset shows the average profile of the flare). However, in all cases the loop is traversed in a counterclockwise sense, i.e., opposite to what we see in GRS 1915+105. As the hardness ratios are a crude characterization of the spectrum, detailed spectral modeling of these loops (e.g., Neilsen et al. 2011) are needed to understand whether there is a physical difference between the ρ class seen in both sources.

Figure 4 (right panels) shows representative power spectra of the ρ variability class in IGR J17091–3624 and GRS 1915+105. The power spectra share the same main features: (1) a low-frequency QPO (with high harmonic content) due to the "flares" and (2) a QPO with characteristic frequency between 6–10 Hz (e.g., Muno et al. 1999). In addition, for both sources we

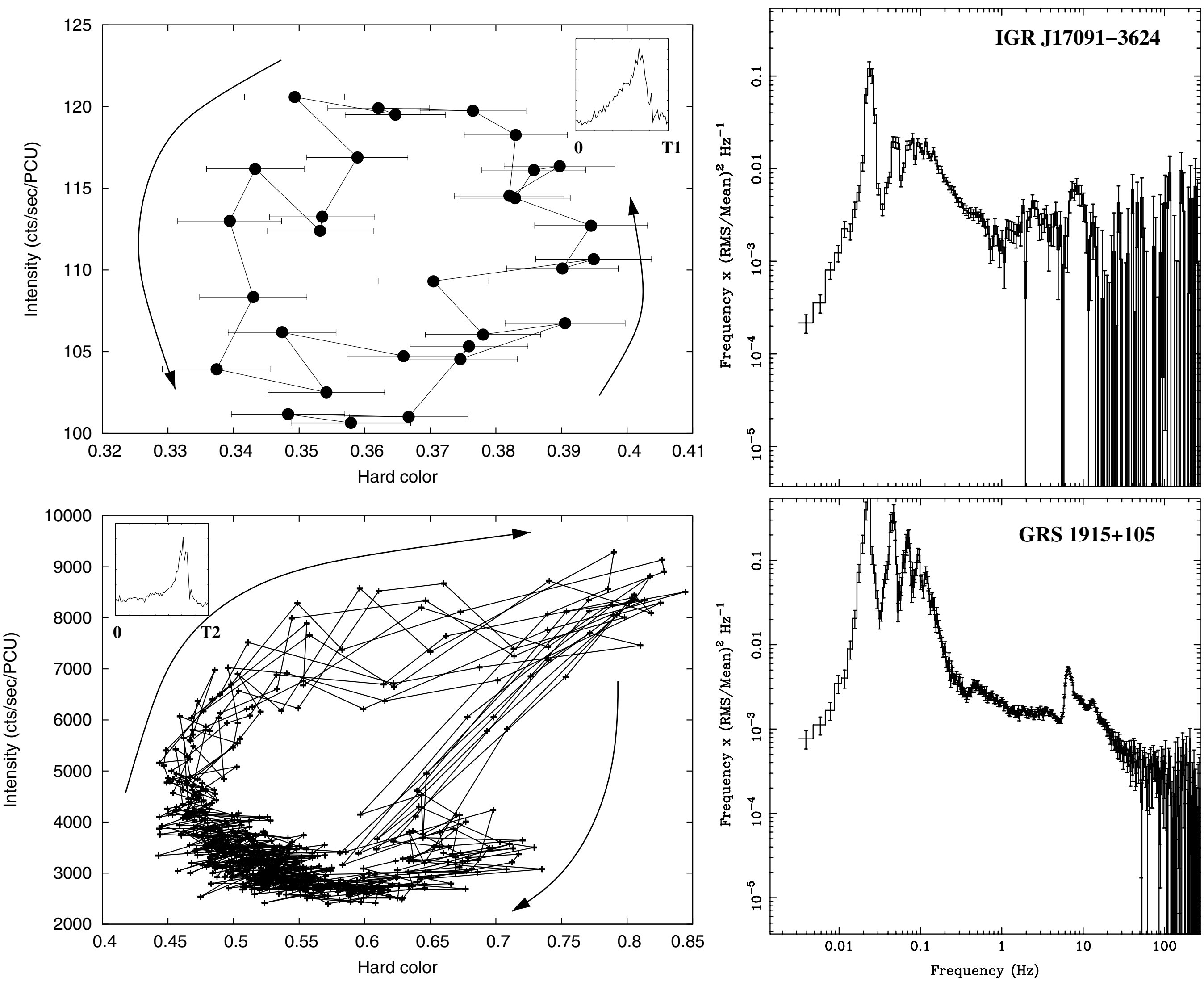

Figure 4. Left panels show the hardness–intensity diagram for flares observed during the ρ variability class in IGR J17091–3624 (top; ObsID: 96420-01-04-03) and GRS 1915+105 (bottom; ObsID: 96378-01-01-00) occurring at an average period of $T1 = 70.96$ s and $T2 = 63.72$ s, respectively. Arrows mark the time evolution. Inset shows representative flares. Light curves and colors are estimated from 1 s averages. Intensity is the count rate in the 2–60 keV range (absolute channels 0–240) and hard color is the 6.5–15.0 keV/2–6.5 keV count rate ratio (channels 15–35 and 0–14, respectively). Right panels show representative power spectra from averages of 512 s segments during the ρ variability class for IGR J17091–364 (top; ObsID: 96420-01-05-000, MJD 55647.9) and for GRS 1915+105 (bottom; ObsID: 40703-01-07-00, MJD 51235.3).

sometimes find a "bump" with characteristic frequency between 1 and 5 Hz.

4. DISCUSSION

Extensive literature exist attempting to understand the complex variability observed in GRS 1915+105. Some authors propose that the high luminosity (close to, or super-Eddington) of GRS 1915+105 is the determining factor (e.g., Belloni et al. 1997, 2000; Vilhu & Nevalainen 1998; Nayakshin et al. 2000; Janiuk et al. 2002; Done et al. 2004; Neilsen et al. 2011, and references therein). Although it is generally accepted that the complex X-ray variability in GRS 1915+105 results from disk instabilities, the exact nature of the instability remains unknown. The lack of at least a second source showing similar characteristics has prevented definite conclusions.

In this Letter we show for the first time that another source, the BHC IGR J17091–3624, can show the same broad variety of complex light curves as GRS 1915+105 (at least 7 of the 12 variability classes observed in GRS 1915+105, in addition to unclassified ones; note that at the time of submission of this Letter IGR J17091–3624 is still active). Although the comparisons presented in this Letter constitute only a first step, the observed similarities suggest that the complex light curves of the two sources are produced by the same physical mechanisms. If true, the low flux of IGR J17091–3624 compared with GRS 1915+105 combined with the circumstance that currently neither the distance to IGR J17091–3624 nor the mass of its compact object are known raises the fundamental question: is IGR J17091–3624 close to Eddington or not during the times when it shows the same characteristic X-ray variability?

A scenario in which IGR J17091–3624 is not emitting at close to Eddington but only at a few percent is at variance with models where the variability is explained as due to disk instabilities that *only* occur at high luminosity (e.g., Vilhu & Nevalainen 1998; Belloni et al. 2000; Nayakshin et al. 2000; Janiuk et al. 2002; Done et al. 2004; Neilsen et al. 2011, and references therein). However, in this scenario, IGR J17091–3624 would follow

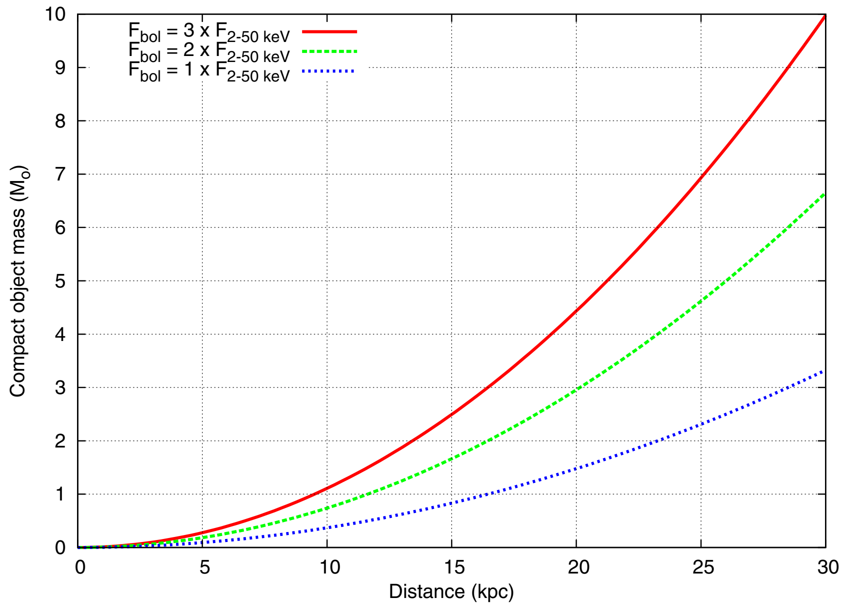

Figure 5. Mass of the compact object vs. distance to the binary system assuming IGR J17091–3624 is emitting at Eddington. The three curves correspond to different (1, 2, and 3) correction factors between the 2–50 keV and the bolometric flux.

(A color version of this figure is available in the online journal.)

radio/X-ray correlation of some or most BHCs (depending if the distance is closer to ~11 kpc or ~17 kpc, respectively; Rodriguez et al. 2011b).

A scenario in which IGR J17091–3624 is emitting at close to the Eddington limit puts constraints on its mass and distance. Although this scenario would imply that, independently of the distance, IGR J17091–3624 does not follow the standard radio/X-ray luminosity plane for BHCs (Rodriguez et al. 2011b), this would be similar to GRS 1915+105, as it does not follow the radio/X-ray flux plane either (see, e.g., Figure 4 in Rodriguez et al. 2011b and references therein).

We therefore made a rough estimate of the source flux in each observation by calculating the average-per-observation energy spectrum. In the upper panel of Figure 1, we plot the 2–50 keV unabsorbed flux. In IGR J17091–3624 we observe the α, β, ν, ρ, and μ classes when the flux is between ~2 and ~3.7 10^{-9} erg cm^{-2} s^{-1} (the `diskbb` temperature kT vary between 1 and 2 keV while the power-law index between 2 and 3). Assuming that IGR J17091–3624 is emitting at Eddington rates, we derived the mass of the compact object as a function of distance (Figure 5) for a 2–50 keV flux of 4×10^{-9} erg cm^{-2} s^{-1}. Given that the correction factor linking the 2–50 keV and the bolometric flux is not exactly known, we plot curves for factors of 1, 2, and 3. Figure 5 implies that if IGR J17091–3624 emits at Eddington, then either it harbors the lowest mass black hole known today ($<3\,M_{\odot}$ for distances lower than 17 kpc), or it is very distant. Such a large distance, together with its $b \simeq 2\overset{\circ}{.}2$ Galactic latitude, would imply a significant, but not necessarily implausible, altitude above the disk (e.g., $b \simeq -2\overset{\circ}{.}8$ and $d > 25$ kpc for the BHC GS 1354–64; Casares et al. 2009).

Clearly, constraining the distance to IGR J17091–3624 is fundamental for understanding the physical processes that govern the X-ray variability in IGR J17091–3624, and hence those in GRS 1915+105. The interstellar absorption in the direction of IGR J17091–3624 is high ($\sim 1 \times 10^{22}$ cm^{-2}; see Rodriguez et al. 2011b), implying that optical studies when the binary system is in quiescence (e.g., Casares et al. 2004) might be challenging. However, accurate parallax distance estimates like those reported for the black hole X-ray binary V404 Cyg (Miller-Jones et al. 2009) could still be possible.

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