

# The enigmatic black hole candidate and X-ray transient IGR J17091–3624 in its quiescent state as seen with *XMM–Newton*

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Accepted 2012 February 27. Received 2012 February 27; in original form 2012 February 2

## ABSTRACT

We report on two short *XMM–Newton* observations performed in 2006 August and 2007 February during the quiescence state of the enigmatic black hole candidate system IGR J17091–3624. During both observations the source was clearly detected. Although the errors on the estimated fluxes are large, the source appears to be brighter by several tens of per cent during the 2007 February observation compared to the 2006 August observation. During both observations, the 2–10 keV luminosity of the source was close to  $\sim 10^{33}$  erg s<sup>-1</sup> for an assumed distance of 10 kpc. However, we note that the distance to this source is not well constrained and it has been suggested it might be as far as 35 kpc which would result in an order of magnitude higher luminosities. If the empirically found relation between the orbital period and the quiescence luminosity of black hole transients is also valid for IGR J17091–3624, then we can estimate an orbital period of >100 h (>4 d) for a distance of 10 kpc but it could be as large as tens of days if the source is truly much further away. Such a large orbital period would be similar to GRS 1915+105 which has an orbital period of  $\sim 34$  d. Orbital periods this large could possibly be connected to the fact that both sources exhibit the same very violent and extreme rapid X-ray variability which has so far not yet been seen from any other black hole system. Alternatively the orbital period of IGR J17091–3624 might be more in line with the other systems (<100 h), but we happened to have observed the source in an episode of elevated accretion which was significantly higher than its true quiescent accretion rate. In that case, the absence or presence of extreme short-term variability properties as is seen for IGR J17091–3624 and GRS 1915+105 is not related to the orbital periods of these black hole systems.

**Key words:** accretion, accretion discs – black hole physics – binaries: close – X-rays: binaries – X-rays: individual: IGR J17091–3624.

## 1 INTRODUCTION

Accretion neutron stars and black holes in X-ray transients are systems which are typically found in a dormant, quiescent state during which they cannot be detected in X-rays or only at very low luminosities. In such quiescent states no or hardly any accretion occurs on to the compact stars. However, occasionally they go in outbursts during which their X-ray luminosities increase by several orders of magnitude and such systems become visible as X-ray binaries. This huge increase in brightness is caused, presumably, by a similarly large temporary increase in accretion rate on to the accretors. Typically X-ray binaries are divided into two general subclasses: (i) low-mass X-ray binaries in which the donor mass is lower than the mass of the accretor and matter transfer occurs

because the donor fills its Roche lobe and (ii) high-mass X-ray binaries in which the donor mass is higher than the mass of the accretor and matter transfer occurs via the strong stellar wind of the companion or due to a Be excretion disc. Often, when a new transient X-ray binary is discovered it is not directly clear what kind of accretor and donor it has and the system is classified based on its similarities with other known types of systems.

When in outburst the X-ray transients can easily be studied due to the large number of photons observed from those systems. However, only a few X-ray satellites have the sensitivity to detect the very faint X-ray emission during the quiescent state of these systems. *Chandra* and *XMM–Newton* have proven crucial to make significant progress in detecting many systems in quiescence and have allowed the study of several of the brightest ones in great detail. One of the main findings is that black hole transients are systematically (albeit not always) significantly fainter in quiescence than the neutron stars systems, especially when comparing them at the

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**Table 1.** The log of the *XMM-Newton* observations.

ObsID	Date of observation	Useful exposure <sup>1</sup> (ks)	Energy range (keV)	Observed flux ( $\times 10^{-14}$ erg s <sup>-1</sup> cm <sup>-2</sup> )	Unabsorbed flux ( $\times 10^{-14}$ erg s <sup>-1</sup> cm <sup>-2</sup> )
0406140101	2006 August 25	5.3	2–10	$8.4 \pm 2.3$	$9.2 \pm 2.3$
0406140401	2007 February 19	11.1	0.5–10	$9 \pm 2$	$13.6^{+3.4}_{-3.9}$
			2–10	$11^{+2}_{-3}$	$12 \pm 3$
			0.5–10	$12^{+2}_{-3}$	$18 \pm 2$

<sup>1</sup> The exposure time per EPIC camera could be slightly different due to variations in the exact moments when the detectors were switched on and off.

same orbital period (Narayan, Garcia & McClintock 1997; Garcia et al. 2001; Kong et al. 2002). This difference has been used as evidence that black holes have event horizons while neutron stars have solid surfaces (e.g. Narayan et al. 1997; Garcia et al. 2001; Narayan, Garcia & McClintock 2002; McClintock, Narayan & Rybicki 2004; Narayan & McClintock 2008). This hypothesis is consistent with the observed fact that in many neutron star systems a soft thermal component (with blackbody temperatures below 0.2–0.3 keV) has been observed (Asai et al. 1996a,b; Rutledge et al. 1999, and references to those papers), presumably from the neutron star surface. Such soft components have never been seen in the quiescent state of black hole transients (McClintock et al. 2004) which would be consistent with the absence of a solid surface. The quiescent X-ray spectra of black hole transients can typically be described with a single power-law model with a photon index of around 2 (e.g. Kong et al. 2002) albeit usually with large error bars because of the often very low number of photons detected from those systems.

The origin of the X-ray emission of quiescent black hole transients is not very well understood. The most frequently used model assumes that there is still residual accretion occurring on to the black hole even in quiescence, but that the accretion occurs through a so-called advection-dominated accretion flow (ADAF; see Narayan et al. 1997, and references therein) type of flow which is very inefficient in radiating its energy away and most of the energy from the infalling matter is advected beyond the event horizon. Therefore, the black hole X-ray transients can be very faint. If indeed this is the correct explanation for the quiescent emission of black hole transients, the X-ray emission of these systems is predicted to be correlated with the orbital period of the binary: the luminosity should be larger for larger orbital periods (Menou et al. 1999). Such a trend, albeit with significant scatter, has indeed been observed (Garcia et al. 2001; Kong et al. 2002; McClintock et al. 2004) giving weight to the ADAF interpretation for the quiescent X-ray emission of black holes.

To further test and constrain the ADAF interpretation, more black holes in quiescence must be detected and studied in detail. An excellent candidate would be IGR J17091–3624. This source was discovered in 2003 April using *INTEGRAL* (Kuulkers et al. 2003). Another outburst was seen in 2007 (Kennea & Capitanio 2007; Capitanio et al. 2009) and archival studies showed that the source had been previously active during several other occasions (in ’t Zand et al. 2003; Revnivtsev et al. 2003). Based on its outbursts properties (i.e. its X-ray spectral and timing behaviour), the source was suggested (Capitanio et al. 2006) to harbour a black hole as the accretor, although a neutron star could not be excluded. In 2011 February, the source was detected again in outburst (using *Swift*; Krimm & Kennea 2011; Krimm et al. 2011) but this time the source stayed on until at least the time of writing this Letter (recent *Swift* observations showed the source still to be active at least until 2012 February 11; see also Altamirano et al. 2012). The 2011 outburst of

the source has caused quite some excitement because in the X-rays it suddenly displayed very unusual X-ray variability which so far had only been seen in the enigmatic very bright black hole X-ray transient GRS 1915+105 (e.g. see Altamirano et al. 2011; Pahari, Yadav & Bhattacharyya 2011; Altamirano & Belloni 2012, for details about its variability and its comparison with GRS 1915+105). Capitanio et al. (2009) reported on two *XMM-Newton* observations taken in 2006 and 2007 during which IGR J17091–3624 was in its quiescent state. They claim that the source could not be detected during these observations; however, we have re-examined those *XMM-Newton* observations and we clearly detect a source in both observations. In this Letter we report on those observations and discuss how the source fits in within the general picture of quiescent black hole transients.

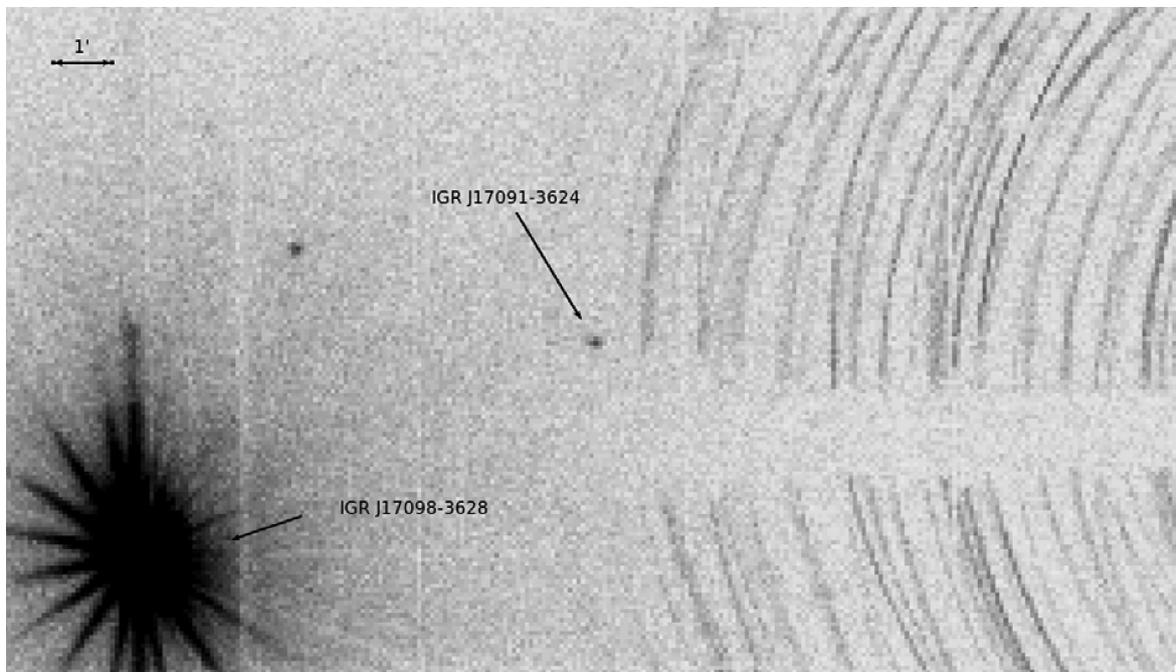
## 2 OBSERVATIONS, ANALYSIS AND RESULTS

*XMM-Newton* observed the field containing IGR J17091–3624 on 2006 August 25 and 2007 February 19 (see Table 1; see also Capitanio et al. 2009). For all EPIC cameras the medium filter was used. We do not analyse the RGS data in this Letter since the source was too faint (see below) to result in any significant flux from the source using this instrument. The data were analysed using *SAS* version 11 and following the standard analysis threads.<sup>1</sup> To apply the most up-to-date calibration we reprocessed the original data files using the programs *EPPROC* and *EMPROC*. We searched for the presence of background flares in the EPIC data using only the data above 10 keV and found none during the 2006 observation but a small flare occurred at the end of the 2007 observation. This flare was removed from the data; Table 1 lists the resulting exposure times.

Fig. 1 shows the combined 0.5–10 keV image of all data (including both observations and all three EPIC instruments; the contaminating arcs are due to the bright neutron star X-ray binary GX 349+2 which is outside the field of view of the telescope). Contrary to the findings by Capitanio et al. (2009), we clearly detect a source close to the radio position reported for IGR J17091–3624 (Corbel et al. 2011). The source was most clearly visible in the pn images, so we used the pn data and the tool *edetect\_chain* to extract the source position (using only the 0.5–10 keV data). The best source position was obtained from the 2007 observation: RA = 17<sup>h</sup>09<sup>m</sup>07.674 and Dec. = –36°24′25.3 (epoch J2000) with a statistical error of 0.9 arcsec and  $\sim 2$  arcsec ( $1\sigma$ ) absolute astrometry error.<sup>2</sup> This position (as well as the position obtained during the 2006 *XMM-Newton* observation) is fully consistent with the radio position of the source

<sup>1</sup> <http://xmm.esac.esa.int/sas/current/documentation/threads/>

<sup>2</sup> The *XMM-Newton* calibration documents can be found at [http://xmm.vilspa.esa.es/external/xmm\\_sw\\_cal/calib/documentation.shtml](http://xmm.vilspa.esa.es/external/xmm_sw_cal/calib/documentation.shtml).

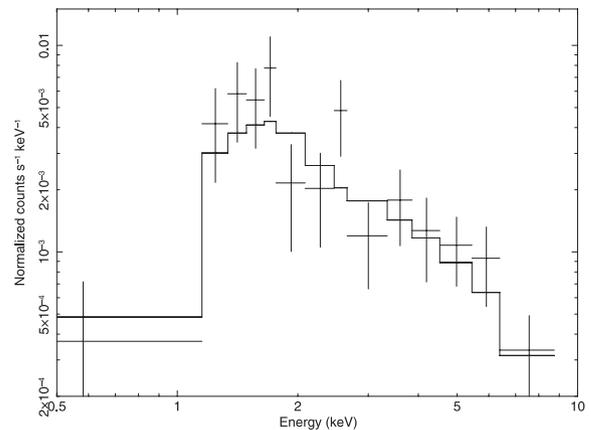


**Figure 1.** *XMM–Newton* images (both observations and all EPIC detectors combined) of IGR J17091–3624. The source and the close-by active transient IGR J17098–3628 are indicated by arrows. The arcs at the right are due to the bright persistent neutron star X-ray binary GX 349+2 which is outside the field of view.

and it is very likely that the detected source is the quiescent X-ray counterpart of IGR J17091–3624. The 0.5–10 keV count rates (using the pn) of the source during the first and second observations were  $0.012 \pm 0.003$  and  $0.020 \pm 0.002$  count  $s^{-1}$ , respectively. This difference in count rate indicates that during the second observation the source was slightly brighter than during the first observation. We searched for variability in the light curves during each observations but the statistics were very limited inhibiting any conclusion on this.

To extract the source spectrum we used a circle of 10 arcsec on the source position. To estimate the background we used a circle of 25 arcsec on a region of the CCD which was free of sources and also free of the contaminating arcs in the image. We only report here on the pn spectra because very limited number of photons were recorded using the MOS cameras (e.g. in the MOS2 data of the first observation the source could not conclusively be detected). The spectra were extracted using the tool *especget*. The spectra were rebinned to have at least 10 photons per bin. The spectral data were analysed using *XSPEC* version 12.7.0. The pn spectrum obtained during the 2007 observation is shown in Fig. 2. The quality of the data is insufficient to perform a detailed spectral analysis and we only tried to fit the data with single component models. However, since quiescent spectra of black hole transients are typically fitted with a simple power-law model, we focus only on that model but we note that a blackbody or a multicolour disc blackbody model could equally well fit the data.

We fitted the spectra with an absorbed power-law model in which the column density was fixed to the outburst value of  $1.1 \times 10^{22}$   $cm^{-2}$  (Rodríguez et al. 2011) and the photon index was tied between the observations. The limited quality of the data does not allow us to constrain those parameters independently. The normalization was left free in order to investigate possible variability between the two observations. This model could fit the data adequately with a reduced  $\chi^2$  of 0.7 with 13 degrees of freedom. The obtained photon index was  $1.6 \pm 0.5$  and the obtained fluxes are reported in



**Figure 2.** *XMM–Newton* pn spectrum of the 2007 observation. The solid line through the data points is the best-fitting absorbed power-law model.

Table 1. The fluxes also show (similar to the count rates) that the source likely was fainter during the 2006 observation compared to the 2007 observation although the errors on the fluxes are large and formally the fluxes are consistent with each other.

### 3 DISCUSSION

We report on the X-ray detection (using *XMM–Newton*) of the enigmatic X-ray transient and black hole candidate IGR J17091–3624 in its quiescent state. The X-ray spectrum of the source could be described with a simple absorbed power-law model with a photon index of  $1.6 \pm 0.5$ . This is consistent with what is observed for other black hole transients in their quiescent states (e.g. Kong et al. 2002). The obtained fluxes are listed in Table 1. Due to lack of constraints on the source distance, it is not possible to estimate accurately the quiescent X-ray luminosity of IGR J17091–3624, making it rather

difficult to compare our results to those of other quiescent black hole systems. Therefore, we will discuss several scenarios based on different assumptions.

The location of the source in the Galactic bulge might suggest a distance of only 8–10 kpc similar to what is typically assumed for sources in the bulge. For 10 kpc, the 0.5–10 keV luminosity would be  $1\text{--}2 \times 10^{33} \text{ erg s}^{-1}$  (the range is due to the errors on the fluxes and the observed flux variation between the two observations). However, it is possible that the source might be significantly further away than 10 kpc. IGR J17091–3624 displayed atypical behaviour during its 2011 outburst. In many ways it resembles another enigmatic black hole system, namely GRS 1915+105. Both showed a large variety of variability phenomena in their light curves although IGR J17091–3624 displayed variability on a time-scale of about a factor of 40–50 faster than seen in GRS 1915+105 (Altamirano et al. 2011). This kind of extreme variability behaviour is not understood, but for GRS 1915+105 it has been postulated to be related to the high X-ray luminosities (Eddington to possibly even super-Eddington luminosities) of the source (see the discussion and references in Altamirano et al. 2011). The X-ray flux of IGR J17091–3624 during outburst is considerably lower than that of GRS 1915+105 (by a factor of 30). If also IGR J17091–3624 is accreting near the Eddington limit it must have a black hole mass of only  $3 M_{\odot}$  for the source to be located within our Galaxy ( $<20$  kpc), or the source must be at  $>35$  kpc if it would harbour a black hole with a mass of  $\sim 15 M_{\odot}$  (similar to the black hole mass of GRS 1915+105). For such distances, the quiescent 0.5–10 keV X-ray luminosity of IGR J17091–3624 would be  $5\text{--}10 \times 10^{33} \text{ erg s}^{-1}$  or  $1\text{--}3 \times 10^{34} \text{ erg s}^{-1}$  for 20 and 35 kpc, respectively. Irrespective of the source distance, the X-ray luminosity of this source is likely to be among the highest observed for quiescent black hole transients.

To explain the quiescent X-ray emission of black hole transients, several models have been proposed but the most commonly used model is that of residual accretion on to the black hole through an ADAF-like accretion flow. A profound and testable aspect of this model is that the quiescent luminosity of black hole transients should increase with the orbital period of the systems (Menou et al. 1999). Although the observations are still quite limited, a trend of increasing quiescent luminosities with increasing orbital periods is indeed suggested by the observations (Garcia et al. 2001; Kong et al. 2002; McClintock et al. 2004). Using the data presented by (Reynolds & Miller 2011, see their fig. 4; see also McClintock et al. 2004), we estimate that the orbital period of the system should be  $>100$  h ( $>4$  d) for a source distance of 10 kpc but it could be up to tens of days for larger distances. We cannot offer stronger constraints since no black holes have been observed in their quiescent states with an orbital period  $>200$  h and the empirically found relation might break down for larger orbital periods. If its orbital period indeed turns out to be this large, the quiescent behaviour of IGR J17091–3624 provides strong support for an ADAF-like interpretation of the quiescent X-ray emission of black hole transients.

It is not truly unexpected that IGR J17091–3624 could have such a large orbital period because of its similarities during outburst with GRS 1915+105. This system has a measured orbital period of  $\sim 34$  d and therefore quite a large accretion disc. Such a large disc could be related to or may be even the cause of the very high accretion luminosities of this system (e.g. Done, Wardziński & Gierliński 2004). If it is indeed true that the violent variability seen in GRS 1915+105 only can occur at such high luminosities, IGR J17091–3624 must also be accreting at (near-)Eddington luminosities and possibly a large disc and a large orbital period might also be required in this system. In this assumed scenario it remains unclear

if IGR J17091–3624 harbours a low-mass black hole at  $\sim 20$  kpc or a more massive black hole at  $>35$  kpc (Altamirano et al. 2011). If the frequency of the recently discovered high-frequency quasi-periodic oscillations found in IGR J17091–3624 indeed scales with mass, the black hole mass of this system should be similar to that of GRS 1915+105 (see Altamirano & Belloni 2012, for a discussion) and the source should be at very large distance (i.e. outside the Galaxy) with a very high quiescent luminosity. We expect that if GRS 1915+105 would turn quiescent again in the future, it should also exhibit a rather high quiescent luminosity. Together with IGR J17091–3624, GRS 1915+105 would also be an excellent candidate to test the ADAF explanation for the quiescent luminosities of black hole transients.

It is possible that we have not observed IGR J17091–3624 truly in its quiescent state. During our two *XMM-Newton* observations, we might have caught it in an anomalous faint accretion rate regime which is orders of magnitude lower than when in outburst but which is also several orders of magnitude higher than during a true quiescent state. In this respect it is interesting to note that the source has a rather short recurrence time of only a few years compared to many years to decades for the majority of black hole transients. Before the *XMM-Newton* observations, the source was active until 2004 April and it was only quiescent until 2007 July (Capitanio et al. 2006, 2009). It is possible that during such short quiescent periods the source never reaches true quiescence. Recently such a subluminescent accretion state was also possibly observed for the black hole transient GS 1354–64 (Reynolds & Miller 2011) and several neutron star systems (both transients as well as persistent sources) have also shown enigmatic subluminescent accretion behaviour (e.g. Wijnands, Miller & Wang 2002; in’t Zand, Cornelisse & Méndez 2005; Degenaar & Wijnands 2009, 2010; Degenaar et al. 2010; Degenaar, Wijnands & Kaur 2011). The photon index of the observed spectra is consistent with such an interpretation but the errors are large and as discussed above it is also fully consistent with the spectra typically observed for quiescent black hole transients. Our physical understanding of such long-lived low-level accretion states is still quite limited and is not easily explained using the disc instability model which has been used to explain X-ray binary outbursts (see Lasota 2001, for a review). The likely variability we have seen between the two observations might hint at the fact that the source is not yet quiescent; however, quiescent variability has been observed for several other black hole transients (e.g. Kong et al. 2002; Hynes et al. 2004). If the orbital period of the system is indeed very large, it is plausible that the source was indeed in quiescence, but if the orbital period turns out to be very similar to the majority of black hole transients ( $<100$  h), then it is very likely that IGR J17091–3624 was indeed in a subluminescent accretion state and that its quiescent state could be quite fainter than what we have observed during our *XMM-Newton* observations. Clearly, the distance towards the source and the orbital period of this system need to be determined more accurately before this source can be put more clearly within the context of the other black hole transients and with GRS 1915+105 in particular.

## ACKNOWLEDGMENTS

RW acknowledges support from a European Research Council (ERC) starting grant. RW and YJY acknowledge support from The European Community’s Seventh Framework Programme (FP7/2007–2013) under grant agreement number ITN 215212 Black Hole Universe. We thank Nathalie Degenaar for giving valuable comments on an earlier version of this Letter. We acknowledge the use of data obtained through the *XMM-Newton* data archive.

This research has made use of NASA’s Astrophysics Data System Bibliographic Services.

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