THE TWO INTEGRAL X-RAY TRANSIENTS IGR J17091−3624 AND IGR J17098−3628: A MULTIWAVELENGTH LONG-TERM CAMPAIGN

F. Capitanio1, M. Giroletti2, M. Molina3, A. Bazzano1, A. Tarana1, J. Kennea4, A. J. Dean3, A. B. Hill3, M. Tavani1, and P. Ubertini1

1 Istituto Nazionale di Astrofisica Istituto di Astrofisica Spaziale e Fisica Cosmica-Roma, Via Fosso del Cavaliere 100, 00033 Rome, Italy
2 Istituto Nazionale di Astrofisica Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy
3 School of Physics and Astronomy, University of Southampton, Highfield Southampton, SO17 1BJ, UK
4 Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA

Received 2008 March 27; accepted 2008 August 14; published 2008 December 22

ABSTRACT

IGR J17091−3624 and IGR J17098−3628 are two X-ray transients discovered by INTEGRAL and classified as possible black hole candidates. We present here the results obtained from the analysis of mult wav e length data sets collected by different instruments from 2005 until the end of 2007 on both sources. IGR J17098−3628 has been regularly detected by INTEGRAL and RXTE over the entire period of the observational campaign; it was also observed with pointed observations by XMM-Newton and Swift/X-ray Telescope (XRT) in 2005 and 2006 and exhibited flux variations not linked with the change of any particular spectral features. IGR J17091 − 3624 was initially in quiescence (after a period of activity between 2003 April and 2004 April) and it was then detected again in outburst in the XRT field of view during a Swift observation of IGR J17098−3628 on 2007 July 9. The observations during quiescence provide an upper limit to the 0.2−10 keV luminosity, while the observations in outburst cover the transition from the hard to the soft state. Moreover, we obtain a refined X-ray position for IGR J17091−3624 from the Swift/XRT observations during the outburst in 2007. The new position is inconsistent with the previously proposed radio counterpart. We identify in VLA archive data a compact radio source consistent with the new X-ray position and propose it as the radio counterpart of the X-ray transient.

Key words: accretion, accretion disks – binaries: close – methods: data analysis – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

Among the sources included in the INTEGRAL IBIS/ISGRI survey catalog (Bird et al. 2007), the two X-ray transients IGR J17091−3624 and IGR J17098−3628 are remarkable because of their proximity, being only 9.6 away from each other. The two sources have been detected in different periods of time from 2003 April until the beginning of 2008. In particular, IGR J17091−3624 was detected by IBIS in 2003 and remained detectable for one year and, after a period of quiescence, it was again in outburst in 2007 July. IGR J17098−3628 was detected for the first time by INTEGRAL in 2005 (while IGR J17091−3624 was not visible) and it has then remained detectable with variable flux in the soft X-ray energy range ($E < 20$ keV) up to now. On the basis of their spectral behavior, both IGR J17091−3624 and IGR J17098−3628 are classified as probable black hole candidates (BHCs; Lutovinov & Revnivtsev 2003; Grebnev et al. 2007).

In this paper, we present the results of a long-term monitoring, primarily at high energy, of these two transients, and discuss the identification in archival data of a radio counterpart for IGR J17091−3624. The date, the exposure time, the instruments used, and the two sources’ detections of the different observations are summarized in Table 1. The paper is organized as follows: in Sections 1.1 and 1.2, we introduce the two BHCs; in Section 2, we describe our observations; in Section 3, we present the results; finally, we give a discussion and present our conclusions in Section 4.

1.1. IGR J17091−3624

IGR J17091−3624 was discovered by INTEGRAL/IBIS during a Galactic Center observation on 2003 April 14−15 (Kuulkers et al. 2003). Initially, the flux was $\sim 20$ mcrab in the 40−100 keV energy band exhibiting a hard spectrum, while it was not detected in the 15−40 keV band, with an upper limit of $\sim 10$ mcrab. During subsequent observations of the Galactic Center Deep Exposure (GCDE) on 2003 April 15−16, the source flux increased to $\sim 40$ mcrab in the 40−100 keV band and to 25 mcrab in the 15−40 keV (the IBIS flux statistical error is less than 10%).

Immediately after the INTEGRAL discovery, providing the position of IGR J17091−3624, an RXTE observation was performed and the source was then searched in the X-ray catalogs. IGR J17091−3624 was found in the archival data of both the TTM telescope on board the KVANT module of the Mir orbital station (Revnivtsev et al. 2003), and in the BeppoSAX WFC (in’t Zand et al. 2003). A first study of the IBIS/ISGRI spectral evolution of the source (Lutovinov & Revnivtsev 2003, 2005) showed a source hardening with a photon index changing from $\Gamma = 2.2 \pm 0.1$ to $\Gamma = 1.6 \pm 0.1$ from 2003 April to 2003 August. A subsequent detailed analysis of the IBIS, JEM-X, and RXTE/PCA data of the entire outburst duration (Capitanio et al. 2006) revealed an indication of a hysteresis-like behavior and the presence of a hot disk blackbody emission component during the source softening.

From the investigations reported above, IGR J17091−3624 appears as a moderately bright variable transient source, with a 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. In this paper, we report on the last episode of activity, as well as on limits on the quiescent state.
2. THE MULTIWAVELENGTH OBSERVATION CAMPAIGNS

We report here on the analyzed data collected by *INTEGRAL*, *Swift*, and *XMM* from 2005 till 2007. To illustrate the need for a multiwavelength campaign with good positional accuracy, we show in Figure 1 two *INTEGRAL* mosaic images of the region of the two BHCs. In the left panel, we show the region during the IGR J17091—3624 outburst in 2003 (IGR J17098—3628 was switched off), while in the right panel we show the same zone when only IGR J17098—3628 was visible.

The two sources are too close to each other to be resolved by X-ray and γ-ray monitors such us *RXTE/ASM* and *Swift/BAT*. Therefore, it is not possible to measure their flux separately and it is rather difficult to follow their individual activities. Observations with better positional accuracy are needed to assign each flux variation to one of the two sources with confidence. As an example, Figure 2 shows the contaminated *RXTE/ASM* IGR J17098—3628 plus IGR J17091—3624 light curve between 1.5 keV and 12 keV from 2001 until the beginning of 2008. The black and gray arrows represent the periods of BeppoSAX, *Swift/XRT*, and *XMM* observation campaigns that verified the activity of respectively IGR J17091—3624 and IGR J17098—3628.

The XRT on board *Swift* satellite is an imaging instrument operating in the 0.2–10 keV energy range with a single photon point spread function of 18′′ (half-power diameter) and a spectral resolution of 140 eV at 5.9 keV. We have collected all the XRT data available from the NASA HEASARC public archive. The XRT data were processed using the most recently available standard *Swift* tools: *XRT* software version 0.11.4, *FTOOLS* version 6.3.1, and *XSPEC* version 11.3.2. The ancillary response files were generated with the *xrtpipeline* task *xrtmkarf*. The channels of each spectrum were rebinned in order to achieve a minimum of 100 counts per bin. The *Swift/BAT* transient monitor light curve was provided by the *Swift/BAT* team.

We also analyzed two *XMM*-pointed observations performed on 2006 August 25 and 2007 February 19. *XMM* data were reprocessed using the *XMM-Newton* Standard Analysis Software (SAS) version 7.0, employing the latest available calibration files. Only single X-ray events (PATTERN = 0) were taken into account for the PN; the standard selection filter FLAG = 0 was applied. Exposures have been filtered for periods of high background. Since pile-up was present in both observations, source counts were extracted from annular regions of typically 90′′ external radius centered on the source, and the central 7′′ of the PSF have been excised; background spectra were extracted from circular regions close to the source or from source-free regions of typically 20′′ of radius. The ancillary response matrices (ARFs) and the detector response matrices (RMs) were generated using the *XMM*-SAS tasks *arfgen* and *rmfgen*; spectral channels were rebinned in order to achieve a minimum of 100 counts per each bin.

The analyzed *INTEGRAL* data set consists of all Key Program and public observations from 2005 May until the end of 2007. The *INTEGRAL* data reduction of both the X-ray monitor JEM-X (Lund et al. 2003) and the γ-ray telescope IBIS (Ubertini et al. 2003) were performed using the latest release of the standard Offline Scientific Analysis (OSA; Goldwurm et al. 2003) version 7.

---

### Table 1

| Start Date | End Date | Satellite | Detected Sources | Exposure |
|------------|----------|-----------|------------------|----------|
| 2003 Apr 12 | 2003 Apr 21 | *INTEGRAL* | IGR J17091—3624\(^{a}\) | 15 ks |
| 2003 Apr 20 | ... | *RXTE* | IGR J17091—3624\(^{b}\) | 4.5 ks |
| 2003 Aug 10 | 2003 Apr 2 | *INTEGRAL* | IGR J17091—3624\(^{a}\) | 154 ks |
| 2005 Feb 20 | 2005 May 1 | *INTEGRAL* | IGR J17098—3628\(^{a}\) | 300 ks |
| 2005 Mar 29 | ... | *RXTE* | IGR J17098—3628\(^{a}\) | 2.1 ks |
| 2005 May 1 | 2007 Feb 28 | *INTEGRAL* | IGR J17098—3628 | 450 ks |
| 2005 May 1 | 2005 Sep 14 | *Swift* | IGR J17098—3628 | 8.5 ks |
| 2006 Aug 25 | ... | *XMM* | IGR J17098—3628 | 8 ks |
| 2007 Feb 19 | ... | *XMM* | IGR J17098—3628 | 16 ks |
| 2007 Jul 19 | 2007 Aug 7 | *Swift* | IGR J17091/IGR J17098 | 11 ks |
| 2007 Aug 25 | 2007 Sep 30 | *INTEGRAL* | IGR J17091—3624 | 50 ks |

---

### References

\(^{a}\) Capitanio et al. (2006).

\(^{b}\) Lutovinov & Revnivtsev (2003).

\(^{c}\) Rupen et al. (2003).

\(^{d}\) Grebnev et al. (2007).

1.2. IGR J17098—3628

IGR J17098—3628 was detected for the first time with *INTEGRAL/IBIS* 9′4 off IGR J17091—3624 (Grebnev et al. 2005b) during deep Open Program observations of the Galactic Center region on 2005 March 24. The average fluxes were 28.2 ± 1.4 and 38.7 ± 2.8 mcrab in the 18–45 and 45–80 keV bands, respectively. Further analysis (Grebnev et al. 2005a) reported that the source was evolving in both brightness and spectral shape with an indication of softening.

From 2005 March 29 to April 4, an observational campaign was performed with *RXTE/PCA*. The spectral shape given by *INTEGRAL/IBIS* and *RXTE/PCA* varied throughout the observations and it is modeled by a soft blackbody emission component plus a hard tail and an absorption consistent with the Galactic one (Grebnev et al. 2007). The spectral variations suggested that this source was an X-ray nova going in outburst and probably a BHC (Grebnev et al. 2007).

The source was then observed with the *Swift* satellite (Kennea et al. 2005) with an exposure time of 2.8 ks on 2005 May 1; it was quite bright, with an estimated flux of $1.3 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$ in the 0.5–10 keV energy band. The analysis of the *Swift/X-ray Telescope* (XRT) data for IGR J17098—3628 refined the source coordinates as follows: R.A. 17°09′45″, decl. −36°27′57″ (J2000), with an uncertainty radius of about 5″ (Kennea et al. 2005). This position is 30″ from the *INTEGRAL* position reported by Grebnev et al. (2005b).

Following the soft X-ray detection of IGR J17098—3628 with *Swift/XRT*, a probable radio counterpart has also been found (Rupen et al. 2005). In particular, the first data set of four consecutive VLA radio observations, made on 2005 March 31, April 5, April 12, and May 4 at 4.86 GHz, showed only one significant radio source within the 2′ *INTEGRAL* error circle, located at R.A. 17°09′45″±0.011s, decl. −36°27′57″±0.55 (J2000) (Rupen et al. 2005).

Thanks to the radio observations, a probable optical/infrared identification has been found within the Two Micron All Sky Survey (2MASS) All-Sky Catalog and the SuperCOSMOS Sky Survey (Steeghs et al. 2005a, 2005b; Blustin et al. 2005; Rupen et al. 2005). On the basis of the optical identification, Grebnev et al. (2007) estimated the source distance as $d = 10.5$ kpc and an upper limit on the inclination angle $\geq 77°$.

---

5 http://heasarc.gsfc.nasa.gov/docs/archive.html

6 http://swift.gsfc.nasa.gov/docs/swift/results/transients/index.html
Figure 1. Left: 2003 IBIS/INTEGRAL 80 ks mosaic image (20–40 keV) of IGR J17091−3624 and IGR J17098−3628 zone: only IGR J17091−3624 is visible. Right: 2005 IBIS/INTEGRAL 120 ks mosaic image (20–40 keV) of IGR J17091−3624 and IGR J17098−3628 zone: only IGR J17098−3628 is visible. (A color version of this figure is available in the online journal.)

Figure 2. IGR J17098−3628 RXTE/ASM light curve contaminated by IGR J17091−3624 outbursts from 2001 till 2008 January. The black triangles and gray arrows represent the periods of BeppoSAX, Swift/XRT, and XMM observation campaigns that verified the activity of respectively IGR J17091−3624 and IGR J17098−3628. The time is expressed in Modified Julian Date (MJD) (52000 (MJD) = 2001 April 1; 53500 (MJD) = 2005 May 10; 54500 (MJD) = 2008 February 4).

We have also searched in the radio archives for data containing IGR J17091−3624 and IGR J17098−3628 observations. VLA\(^5\) observations were taken for a few epochs in 2003, following the outburst of IGR J17091−3624, and in 2005, after the IGR J17098−3628 detection. We have obtained and calibrated the data in AIPS with the standard procedures.

3. RESULTS

3.1. Swift 2005 Observations

The 2005 Swift observations were performed from May 1 until September 24, after the peak of the IGR J17098−3628 outburst. A detailed analysis of this outburst peak has been reported by Grebnev et al. (2007). We report here the spectral analysis of six pointings (about 2 ks each) that were performed in Window Timing (WT). Figure 3 shows the image of one XRT pointing observation performed in the photon counting mode in order to detect the refined position of the source; as the Figure shows, IGR J17098−3628 is quite bright while IGR J17091−3624 is not visible.

During all the Swift observations, IGR J17098−3628 showed a slightly variable flux of about 3% with a constant spectral shape. The best fit for each individual observation is a multicolor disk blackbody component (\texttt{diskbb} in XSPEC; Mitsuda et al. 1984) with an internal temperature of about 0.9 keV; the equivalent hydrogen column ($N_H = (0.88 \pm 0.02) \times 10^{22}$ cm$^{-2}$) is consistent with the galactic one. Table 2 shows the spectral parameters of the fit for each observation.

The INTEGRAL/IBIS analysis of the data collected in the same period of the Swift observation campaign did not reveal any source emission above 15 keV up to 3$\sigma$ level. The ASM monitor detected the source with an average flux of about 30 mcrab, that is a value slightly above the detection limit of the JEM-X monitor (about 20–25 mcrab). Moreover, the source has been observed only in the JEM-X partially coded field of view because of dithering strategy used for INTEGRAL observations. For these reasons, the X-ray monitor JEM-X did not detect the source in each single science window at the 3$\sigma$ level. However, adding the JEM-X science windows together

\(^5\) The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
yields a total exposure time of 450 ks which then provides a 3σ level detection of the source in the mosaic.

3.2. XMM 2006–2007 Observations

XMM observations of the field containing both sources were performed in 2006 August 29 and in 2007 February 19. These observations revealed that IGR J17091−3628 still did not show any detectable emission, while IGR J17098−3628 was in a relatively bright state (see Figure 4). INTEGRAL observed the field containing the two sources at the same time as XMM, with no detections from either sources; the INTEGRAL upper limit flux for a single pointing (2400 s) is about 20 mcrab in the range 20–100 keV.

3.2.1. IGR J17091−3624

No detectable emission was revealed from IGR J17091−3624. Since the distance of this source is still unknown, we assumed IGR J17091−3624 as located at the Galactic Center (8 kpc). The corresponding best upper limit luminosity, derived for the quiescent state of this source and based on the XMM observations (exposure time 7 ks), is \( L \leq 7 \times 10^{32} \) erg s\(^{-1}\) (Watson et al. 2001).

3.2.2. IGR J17098−3628

During 2006 August and 2007 February, the XMM spectral shape of the source did not show, once more, any important variation. The only noticeable difference was the flux decrease of about 20% between the two pointings. Both spectra are characterized by an absorbed multicolor disk blackbody emission with a constant inner temperature that varied from about 1 keV in the first pointing to about 0.9 keV in the second pointing (see Table 3). The equivalent hydrogen column, \( N_H = 8.0 \times 10^{22} \) cm\(^{-2}\), is in good agreement with that measured by XRT in 2005 and with the galactic value. Table 3 shows the fit parameters of both pointings. There is no evidence in the spectral shape of a reflection component or Fe emission line according to the 2005 XRT data set analysis. Figure 5 shows the unfolded spectrum of the two XMM/PN pointings.

This behavior is confirmed by the RXTE/ASM light curve from 2005 May 1 to 2007 April 10. In this period, IGR J17091−3624 was in quiescence and the ASM light curve is only due to IGR J17098−3628 flux emission. As Figure 6 shows, the RXTE/ASM hardness–intensity diagram confirms that the source varied only the flux with a constant hardness ratio.

3.3. The 2007 July Swift/XRT Monitoring: The New IGR J17091−3624 Outburst

On 2007 July 9, as a consequence of an increase in the Swift/BAT and RXTE/ASM light curves, a Swift/XRT 2.5 ks ToO was
Figure 4. XMM/EPN image (16 ks) of the 2007 February 19 pointing observation. IGR J17091−3624 is not visible while IGR J17098−3628 is bright and affected by pile up. (The dark bar in the image is due to the gap between two adjoining CCDs.)

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

Figure 5. XMM/PN unfolded spectra of IGR J17098−3628. Left panel: 2006 August 25 spectrum. Right panel: 2007 February 19 spectrum. The data are fitted with diskbb model. Fit parameter values are reported in Table 3.

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

granted. The observation was performed in the window timing mode in order to avoid the pileup and revealed the presence of two sources in the XRT field of view, both of which were causing the flux increase in the RXTE/PCA light curve. Another 500 s pointing observation, performed in the photon counting mode in order to locate the position of the two sources, revealed the presence of both IGR J17098−3628 and IGR J17091−3624, which was newly in outburst. Both sources were in relatively bright state as Figure 7 shows.

A Swift monitoring campaign was then requested for a total of three more observations, 2 ks each (one per week between 2007 July 24 and 2007 August 7) pointed on IGR J17091−3624. The key outcomes of this observation campaign for each source are summarized in the following sections.

3.3.1. IGR J17098−3628

IGR J17098−3628 has been observed during only three of the pointings associated with the observational campaign, for a total exposure of ~8 ks. The source flux only showed flux variations of about 30% in the range 0.5–10 keV as was inferred from the light curve shown in Figure 8. The source spectrum revealed only minor changes and the best overall fit is represented by a diskbb component with an inner temperature of about 0.9–1 keV.

3.3.2. IGR J17091−3624

This XRT ToO was a unique opportunity to catch the new outburst of IGR J17091−3624 from the very beginning and
Figure 6. RXTE/ASM hardness–intensity diagram of the period from 2005 May 1 until 2007 April 10. In this period, IGR J17091−3624 was in quiescence and the ASM flux emission is due only to IGR J17098−3628. The hardness ratio is defined as $HR = (flux_A / flux_B)$, where $A$ and $B$ are respectively the 1.5–3 keV and 3–5 keV energy bands. The plot clearly shows that the hardness value have not changed all over the observation period.

Figure 7. Swift/XRT 0.1–10 keV image of the 2007 July ToO Swift 500s observation. The observation has been performed in the photon counting mode in order to locate the position of the sources. IGR J17098−3628 is affected by pile up.

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

also provided the refined position of the source (Kennea & Capitanio 2007): R.A. 17h09m07s, decl. −36°24′24″9 (J2000), with an estimated uncertainty radius of 3.6″ (90% confidence), consistent with the INTEGRAL position. However, this X-ray position rules out the tentative radio counterpart previously proposed for IGR J17091−3624 (Rupen et al. 2005; Pandey et al. 2006), which lies outside the XRT error circle, approximately 86″ away. This location also rules out the optical counterpart suggested by Negueruela & Schurch (2006) which was also based on the radio counterpart. During the Swift observations the 0.5–10 keV flux of IGR J17091−3624 increased from $5 \times 10^{-10}$ (erg cm$^{-2}$ s$^{-1}$) to $2 \times 10^{-9}$ (erg cm$^{-2}$ s$^{-1}$). Figure 9 shows the 0.1–10 keV light curve of the 2007 XRT monitoring campaign.

In Figure 10, we show respectively the Swift/BAT 15–50 keV (top panel) and RXTE/ASM 2–10 keV (bottom panel) light curves at the time of the 2007 outburst. The luminosity peak present in both light curves is considered to be mainly due to the IGR J17091−3634 outburst, since the contamination from the IGR J17098−3628 flux should not imply such a strong variation
of the flux. In fact, as discussed before, IGR J17098–3628 showed a soft spectrum and a flux variation clearly lower than the one reported by the two light curves of Figure 10.

However, the BAT and ASM light curves show a behavior typical of that expected at the beginning of a black hole binary outburst, with the hard luminosity peak preceding the soft one. This behavior is also confirmed by the spectral analysis: a power-law component with a photon index of $1.4 \pm 0.1$ represents the best fit of the first two observations (July 9 and 2007 July 16). For the spectra of the subsequent observations, it is necessary to add a multicolor disk blackbody component to the power law.

Table 4 summarizes the spectral parameter values of the XRT 2007 observation campaign.

INTEGRAL detected this source only at the end of the outburst because of visibility constrains. Unfortunately the source was outside the field of view of the INTEGRAL X-ray monitor JEM-X, thus only the IBIS high-energy data were available. Figure 11 shows the 20–100 keV IBIS image of the field of view which includes the two sources between August and 2007 September (for a total exposure time of $\sim 50$ ks). As Figure 11 shows IBIS detected above 20 keV only IGR J17091–3624.
The first INTEGRAL IGR J17091−3624 observation of the two source fields (2007 August 25) was performed 18 days after the last XRT observation (2007 August 07). However, as Figure 12 shows, XRT and IBIS spectra are in good agreement. The INTEGRAL observations, after the end of the XRT campaign, revealed that the spectrum of the source continued its softening with a photon index that varied from 2 to $\Gamma \simeq 3$. The INTEGRAL observations from 2005 in the region of IGR J17091−3624 region in the Swift/XRT position. A radio source is clearly revealed in a position consistent with the high-energy error circle. This component is present in the three epochs at 8.4 GHz, and shows an increase in total flux. Data at 5 GHz are also available at three epochs; the source is marginally detected in the first one (3$\sigma$), 5 GHz data only), and clearly revealed in the next two. For the epochs where simultaneous data are available, we show an 8.4 GHz image of the IGR J17091−3624 region in Figure 14, superimposed to the Swift/XRT position. A radio source is clearly revealed in a position consistent with the high-energy error circle. This component is present in the three epochs at 8.4 GHz, and shows an increase in total flux. Data at 5 GHz are also available at three epochs; the source is marginally detected in the first one (3$\sigma$, 5 GHz data only), and clearly revealed in the next two. For the epochs where simultaneous data are available, a comparison to the 8.4 GHz flux reveals an inverted spectrum. Table 5 reports on the measured flux densities; the position of the radio source is R.A. 17h09m07s5 $\pm$ 0:5, decl. $-36^\circ 24' 24'' \pm 3''$.  

3.4. Radio Counterparts

A plot of the NVSS data in the region of IGR J17091−3624 and IGR J17098−3628 is shown in Figure 13 together with the position and associated uncertainties of the INTEGRAL and Swift/XRT measurements (marked by vertical and diagonal crosses, respectively) and the tentative radio counterparts from VLA literature data (Rupen et al. 2003, 2005). In the region of IGR J17098−3628, there is clearly an excellent agreement between the radio and X-ray positions, which gives a high confidence identification. The NVSS contours themselves show some emission in this region, although it is quite extended and only significant at the 2.5$\sigma$ level. In the region of IGR J17091−3624, the refined Swift/XRT position is clearly not consistent with the proposed radio counterpart. No signal is detected in the NVSS image in that region.

We have therefore searched the VLA archive for higher resolution images of these regions, primarily to find a radio counterpart to IGR J17091−3624 but also in order to study the time and the spectral evolution of the sources. We have found archival data from 2003 in the region of IGR J17091−3624 and from 2005 in the region of IGR J17098−3628. The data from 2003 were taken in the compact D configuration on April 23, April 26, May 6, and May 9, with exposures of a few minutes. We show an 8.4 GHz image of the IGR J17091−3624 region in Figure 14, superimposed to the Swift/XRT position. A radio source is clearly revealed in a position consistent with the high-energy error circle. This component is present in the three epochs at 8.4 GHz, and shows an increase in total flux. Data at 5 GHz are also available at three epochs; the source is marginally detected in the first one (3$\sigma$, 5 GHz data only), and clearly revealed in the next two. For the epochs where simultaneous data are available, a comparison to the 8.4 GHz flux reveals an inverted spectrum. Table 5 reports on the measured flux densities; the position of the radio source is R.A. 17h09m07s5 $\pm$ 0:5, decl. $-36^\circ 24' 24'' \pm 3''$.  

![Figure 10](image-url)

Figure 10. Top panel: IGR J17091−3624 Swift/BAT (15–50 keV) light curve. Bottom panel: IGR J17091−3624 RXTE/ASM (2–10 keV). Both curves are contaminated by the IGR J17098−3628 flux emission. The time is expressed in MJD (54000 (MJD) = 2006 September 22; 54200 (MJD) = 2007 April 10; 54400 (MJD) = 2007 October 27).

![Table 4](table-url)

**Table 4** The Fit Parameters of the Observed Spectra of IGR J17091−3624 During 2007 Swift/XRT Monitor Campaign (Errors are at 90% Confidence Level)

| Pointing (date) | Exposure (ks) | $T_\text{in}$ (keV) | $N_{\text{disk}}$ | $\Gamma$ | $N_{\text{pow}}$ (photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$) | Flux$_{0.5-10}$ (erg cm$^{-2}$ s$^{-1}$) | $\chi^2_{\text{red}}$ |
|----------------|--------------|---------------------|-----------------|--------|--------------------------------|---------------------|---------|
| 2007 Jul 9     | 2.4          | 1.4$^{+0.1}_{-0.1}$ | $0.05^{+0.01}_{-0.01}$ | 9.0$^{+4.0}_{-4.0}$ | $4.7 \times 10^{-10}$ | 0.96 |
| 2007 Jul 16    | 3.4          | 1.3$^{+0.1}_{-0.1}$ | $0.02^{+0.005}_{-0.005}$ | 9.0$^{+4.0}_{-4.0}$ | $3.0 \times 10^{-10}$ | 1.10 |
| 2007 Jul 24    | 2.6          | 1.6$^{+0.1}_{-0.1}$ | $0.12^{+0.02}_{-0.02}$ | 9.0$^{+4.0}_{-4.0}$ | $1.8 \times 10^{-9}$ | 1.20 |
| 2007 Aug 7     | 1.9          | 2.0$^{+0.1}_{-0.1}$ | $0.23^{+0.03}_{-0.03}$ | 9.0$^{+4.0}_{-4.0}$ | $2.1 \times 10^{-9}$ | 1.08 |

Note. $T_\text{in}$, disk inner temperature; $N_{\text{disk}}$, diskbb model normalization constant; $\Gamma$, power-law photon index; $N_{\text{pow}}$, power-law model normalization constant; Flux$_{0.5-10}$, unabsorbed model flux between 0.5–10 keV; $\chi^2_{\text{red}}$, reduced $\chi^2$.  

The NVSS data from 2003 in the region of IGR J17091−3624 and from 2005 in the region of IGR J17098−3628. The data from 2003 were taken in the compact D configuration on April 23, April 26, May 6, and May 9, with exposures of a few minutes. We show an 8.4 GHz image of the IGR J17091−3624 region in Figure 14, superimposed to the Swift/XRT position. A radio source is clearly revealed in a position consistent with the high-energy error circle. This component is present in the three epochs at 8.4 GHz, and shows an increase in total flux. Data at 5 GHz are also available at three epochs; the source is marginally detected in the first one (3$\sigma$, 5 GHz data only), and clearly revealed in the next two. For the epochs where simultaneous data are available, a comparison to the 8.4 GHz flux reveals an inverted spectrum. Table 5 reports on the measured flux densities; the position of the radio source is R.A. 17h09m07s5 $\pm$ 0:5, decl. $-36^\circ 24' 24'' \pm 3''$.  

![Figure 12](image-url)

Figure 12. A plot of the NVSS data in the region of IGR J17091−3624 together with the position and associated uncertainties of the INTEGRAL and Swift/XRT measurements (marked by vertical and diagonal crosses, respectively) and the tentative radio counterparts from VLA literature data (Rupen et al. 2003, 2005). In the region of IGR J17098−3628, there is clearly an excellent agreement between the radio and X-ray positions, which gives a high confidence identification. The NVSS contours themselves show some emission in this region, although it is quite extended and only significant at the 2.5$\sigma$ level. In the region of IGR J17091−3624, the refined Swift/XRT position is clearly not consistent with the proposed radio counterpart. No signal is detected in the NVSS image in that region.
4. DISCUSSION AND CONCLUSIONS

The huge amount of data collected and the broad energy coverage allowed us to perform a detailed spectral analysis of these two sources, following their evolution during more than two years and fixing upper limits when one of the sources was not visible. In the following a detailed summary of the results for both sources can be found.
Figure 13. NVSS image of the region of IGR J17091−3624 and IGR 17098−3628, contours traced at (−1, 1, 2, 4, ...) × 1 mJy beam$^{-1}$ (thin gray lines). Darker bold symbols represent IBIS positions (big plus signs), Swift/XRT positions (circles, 90% confidence), and previously proposed radio counterparts (crosses). The key in the bottom right corner shows the radio beam size (45″ × 45″ HPBM).

Figure 14. VLA 8.4 GHz image of the region of IGR 17091−3624, taken on 2003 May 9. Contours are traced at (−0.3, 0.3, 0.6, 1.2) mJy beam$^{-1}$; the gray-scale range is 0.2−1.1 mJy beam$^{-1}$. The circle shows the refined Swift position (90% confidence), and the cross shows the previously proposed radio counterpart. The key in the bottom left corner shows the radio beam size (40″4 × 7″3 HPBM in P.A. 30°, measured north to east).

4.1. IGR J17098−3628

Our analysis, spanning from 2005 May to 2007 September, proves that the source spectrum shows a soft blackbody component with an internal temperature of about ∼1 keV and an internal radius comparable to the last stable orbit of the accretion disk. The luminosity due to soft component (assuming $d = 10.5$ kpc; Grebnev et al. 2007) varied during the two
years of our observational campaign from $\sim 2 \times 10^{37}$ to $\sim 5 \times 10^{38}$ erg s$^{-1}$. The flux variation range and the spectral parameters are comparable with those reported by Grebnev et al. (2007) during the first phases of the outburst on 2005 April. In our data set each flux variation seems not to be correlated with any relevant spectral features, as confirmed by the lack of evident variation of the RXTE/ASM hardness–intensity diagram (Figure 6). However respect to the previous 2005 April observations, we did not detect any power-law emission at higher INTEGRAL/IBIS energy band. This indicates that the spectral shape was evolved from the first phase of the outburst being dominated only by a thermal disk component coming from the accretion disk around the compact object.

We can conclude that this source seems to have spent 2.5 years in the high soft state with a disk blackbody component substantially identical to the one previously observed at the beginning of the outburst (Grebnev et al. 2007). Curiously the only difference is the lack of any high energy emission. In fact the hard component fell below the detection limit of IBIS after about three months from the beginning of the outburst. Hence the geometry and the temperature of the accretion disk have not shown any significant variation up to now, on the other end the power-law emission quenched probably because of the electron temperature of the corona fallen below the disk seed photons temperature making the inverse Compton scattering processes inefficient.

### 4.2. IGR J17091–3624

Previous studies have demonstrated that the X-ray luminosity of the BHCs in quiescence is lower than that of neutron star X-ray binaries and falls below $\sim 10^{32}$–$10^{33}$ erg s$^{-1}$ (Campana et al. 2001). In the quiescent state, neutron star X-ray binaries are normally detected and hence the XMM upper limit of IGR J17091–3624 is a good indication that the source is a BHC.

The Swift ToO caught the source at the beginning of its outburst when it was still in a low/hard state. The best fit of the first observation (2007 July 9/2007 July 16) is a power-law spectrum with $\Gamma = 1.4 \pm 0.1$. The source spectrum substantially softened and the blackbody component became dominant with an increasing temperature and a steeper power law. INTEGRAL continued to monitor the source with IBIS after the end of the XRT observational campaign, up to the end of 2007 September. These observations confirm the softening of the source. A power-law component without an energy cutoff provided the best fit of the IBIS spectra between 20 and 80 keV, probably due to jets or corona reprocessing of disk seed photons. The power-law photon index varied during two month period from about 1.4 (beginning of July) to about 3 (end of September).

Unfortunately the relatively low source flux at high energies ($7 \times 10^{10}$ erg cm$^{-2}$ s$^{-1}$ between 20 keV and 100 keV) and the variation of the spectral shape did not provide sufficient statistics to extend the spectra up to 80 keV and to verify the presence or not of a high energy cutoff in the spectrum.

Thanks to the XRT-refined position, we found the radio counterpart of the source. As soon as 9 days after the detection by IBIS in 2003, a radio source at the sub-mJy level was detected at 5 GHz. The source has been detected also at 8.4 GHz, and it showed an increase in flux over the subsequent two weeks. The spectrum is inverted, characteristic of selfabsorbed synchrotron radiation from a compact jet. This behavior is typical of BHC in low hard states. Although it is difficult to guess the spectral shape at higher frequencies, it is reasonable to estimate that the total radiative luminosity of the compact jet is of the order of $10^{31}$ erg s$^{-1}$, assuming the distance to the Galactic Center. No information is available after the 2007 outburst, and it will be clearly valuable to obtain new radio observations after future episodes of activity.

Chaty et al. (2008), on the basis of ESO NTT observations, report on two possible infrared counterparts of IGR J17091–3624 consistent with the Swift/XRT error box. Our refined position, based on the radio observations, could support the identification of the real infrared counterpart of this source.

Little is known about nature, duration, and recurrence of outbursts in transient X-ray binaries. It is probable that the outbursts are due to randomly acting factors such as the mass transfer variations or truncation of the inner disk radius. However for IGR J17091–3624 five outbursts are known from 1994 to 2007. Thus, it appears that this source goes in outburst every three or five years. Generally the flux varies from 5 mcrab to about 20 mcrab in the range 2–10 keV over a period of a few months. The 2003 outburst was the first detected at higher energy range (20–150 keV) for one year period. Comparing the two hard states of respectively the 2003 and 2007 outbursts, the last one seems to be the hardest. In fact it was possible to determine the high-energy power-law cutoff of the 2003 hard state ($\sim 49$ keV; Capitano et al. 2006) while in the 2007 hard state the cutoff is not detectable up to 80 keV. Concerning the soft state the 2003 outburst has a higher temperature blackbody emission (Capitano et al. 2006) that does not appear to be present in the 2007 outburst. However the XRT monitoring campaign observed the source only at the beginning of its transition to the soft state and unfortunately in the subsequent INTEGRAL monitoring the source was outside the JEM-X field of view and so it was not possible to follow the entire evolution of the blackbody temperature.

This work has been supported by the Italian Space Agency through grants I/008/07/0 and I/088/06/0. We acknowledge the use of public data from the Swift data archive and all the Swift team for its support and Memmo Federici for supervising the INTEGRAL data analysis. Particular thanks are due to Erick Kuulkers for making his private data available for analysis.

### REFERENCES

Bird, A. J., et al. 2007, ApJS, 170, 175
Blustin, A. J., et al. 2005, Astron. Telegram, 479, 1
Campana, S. A. N., Parmar, & Stella, L. 2001, A&A, 372, 241
Capitano, F., et al. 2006, ApJ, 643, 376
Chaty, S., Rahoui, F., Poelimi, C., Tomsick, J. A., Rodriguez, J., & Walter, R. 2008, A&A, 484, 783
Goldwurm, A., et al. 2003, A&A, 411, 1223

#### Table 5

| Date       | $S_{5\,GHz}$ (mJy) | $S_{24\,GHz}$ (mJy) | Spectral Index |
|------------|---------------------|---------------------|---------------|
| 2003 Apr 23 | 0.32                |                     |               |
| 2003 Apr 26 | 0.48                | 0.56                | -0.3          |
| 2003 May 06 | 0.42                | 0.67                | -0.8          |
| 2003 May 09 |                     | 0.73                |               |

Note. The observation of 2003 April 23 was at 5 GHz only and is a 3$\sigma$ detection; 2003 May 9 is only at 8.4 GHz. Spectral index is defined according to $S(\nu) \propto \nu^{-\alpha}$.
Grebnev, S. A., Molkov, S. V., Revnivtsev, M. G., & Sunyaev 2007, ESA SP, 622, 373
Grebnev, S. A., Molkov, S. V., Revnivtsev, M. G., & Sunyaev, R. A. 2005a, Astron. Telegram, 447
Grebnev, S. A., Molkov, S. V., & Sunyaev, R. A. 2005b, Astron. Telegram, 444
in’t Zand, J. J. M., Heise, J., Lowes, P., & Ubertini, P. 2003, Astron. Telegram, 160
Kennea, J. A., & Capitanio, F. 2007, Astron. Telegram, 1140, 1
Kennea, J. A., et al. 2005, Astron. Telegram, 476, 1
Knulkers, E., et al. 2003, Astron. Telegram, 149, 1
Lund, N., Budz-Joergensen, C., & Westgaard, N. I. 2003, A&A, 411, L231
Lutovinov, A., & Revnivtsev, M. 2003, Astron. Lett., 29, 719
Lutovinov, A., Revnivtsev, M., Molkov, S., & Sunyaev, R. 2005, A&A, 430, 997
Mitsuda, K., et al. 1984, PASJ, 36, 741
Negueruela, I., & Schurch, M. P. E. 2006, A&A, 461, 631
Pandey, M., Manchanda, R. K., Rao, A. P., Durouchoux, P., & Ishwara Chandra, 2006, A&A, 453, 83
Revnivtsev, M., Gilfanov, M., Churazov, E., & Sunyaev, R. 2003, Astron. Telegram, 150, 1
Rupen, M. P., Mioduszewski, A. J., & Dhawan, V. 2003, Astron. Telegram, 152, 1
Rupen, M. P., Mioduszewski, A. J., & Dhawan, V. 2005, Astron. Telegram, 490, 1
Steeghs, D., et al. 2005a, Astron. Telegram, 494, 1
Steeghs, D., et al. 2005b, Astron. Telegram, 478, 1
Ubertini, P., et al. 2003, A&A, 411, L131
Watson, M. G., et al. 2001, A&A, 364, L51