SPECTRAL STATES OF THE X-RAY BINARY IGR J17091–3624 OBSERVED BY INTEGRAL AND RXTE

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Received 2005 August 12; accepted 2006 January 20

ABSTRACT

IGR J17091–3624 was discovered in 2003 April by IBIS, the gamma-ray imager on board the INTEGRAL satellite, during its Galactic Center Deep Exposure program. The source was initially detectable only in the 40–100 keV range but after 2 days was also detected in the 15–40 keV range. Its flux had by then increased to 40 and 25 mcrab in the 15–40 and 40–100 keV bands, respectively. RXTE observed the source simultaneously on 2003 April 20, with an effective exposure of 2 ks. We report here the spectral and temporal evolution of the source, which shows a transition between the hard and soft states. We analyze in detail the RXTE/INTEGRAL Comptonized spectrum of the hard state, as well as the JEM-X detection of a blackbody component during the source softening. Even though the source spectral behavior and time variability show a similarity with the outburst of the black hole candidate IGR J17464–3213 (=H1743–322), observed by INTEGRAL in 2003, the nature of its compact object (BH vs. NS) remains controversial.

Subject headi

1. INTRODUCTION

A new source was discovered by IBIS, the imager on board the International Gamma-Ray Astrophysics Laboratory (INTEGRAL), during a pointed observation on 2003 April 14–15. It was designated IGR J17091–3624 based on its position of R.A. (J2000.0) = 17°09′10″, decl. = −36°24′5″, with an error box of 3′ at 90% confidence (Kuulkers et al. 2003).

Initially, its flux was ∼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 ∼10 mcrab. A week earlier, the source did not appear in either energy band, with upper limits of ∼10 mcrab (Kuulkers et al. 2003). During subsequent observations of the Galactic Center Deep Exposure (GCDE) program on 2003 April 15–16, the source flux increased to ∼25 mcrab in the 40–100 keV band. The source was also included in the IBIS ISGRI (INTEGRAL Soft Gamma-Ray Imager) Galactic plane survey catalog (Bird et al. 2004) and classified as unknown. Observations with the Very Large Array revealed the presence of a possible radio counterpart with a steeply falling spectrum typical of synchrotron emitters (Rupen et al. 2003); this was also confirmed by a subsequent observation with the Giant Meterwave Radio Telescope (Pandey et al. 2006).

Immediately after the INTEGRAL discovery, a Rossi X-Ray Timing Explorer (RXTE) observation was performed. The analysis of the RXTE data showed a relatively stable source flux with

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out features associated with quasi-periodic oscillations (QPOs) in the power spectrum. On the basis of the energy and power spectra, Lutovinov & Revnivtsev (2003) suggested that IGR J17091–3624 is an X-ray binary in the low/hard state and probably a black hole system. IGR J17091–3624 was then searched for in the X-ray catalogs and detected in the archival data of both the TTM telescope on board Mir-Keant orbital station (Revnivtsev et al. 2003), and in the BeppoSAX Wide Field Camera (WFC; in’t Zand et al. 2003). Following this, Lutovinov et al. (2005) performed a preliminary study of the IBIS ISGRI spectrum of the source, showing that its flux changed by a factor of ∼2 between 2003 April and 2003 August–September. During 2003, the source spectrum was described by a simple power law with a photon index of Γ ≃ 2.2 in the 20–150 keV energy band, i.e., softer than the RXTE spectrum. As the source flux in the hard X-rays increased in 2004, the spectrum became harder with Γ ≃ 1.6. From the above investigations, IGR J17091–3624 appears as a moderately bright variable (probably a transient) source with flaring activity in 1994 October (Mir-Keant TTM), 1996 September (BeppoSAX WFC), 2001 September (BeppoSAX WFC; in’t Zand et al. 2003), and 2003 April (INTEGRAL IBIS; Kuulkers et al. 2003).

1.1. Improvements over Previous Analysis

We have performed a more accurate spectral analysis of this source compared to those previously reported, analyzing all the INTEGRAL data available while the source was detectable (until the end of 2004 April). The new set of data allowed us to fit a joint RXTE/INTEGRAL spectrum of IGR J17091–3624 in the low/hard state. The improved version of the INTEGRAL data analysis software (Off-line Scientific Analysis [OSA] ver. 4.2; Goldwurm et al. 2003) has allowed us to obtain INTEGRAL spectra up to 150 keV. An initial test with the newly delivered OSA version 5 software has shown a substantial agreement with the former OSA version 4.2 results.

We have fitted the data with detailed models, thus obtaining new information on the geometry of the source and on the accretion disk optical depth and temperature. We have also extracted a JEM-X spectrum that confirms the previous hypothesis of a
transition to the soft state (Lutovinov et al. 2005), and furthermore we have found suggestions of a hysteresis-like behavior in the source spectral evolution, with the hard-to-soft state transition occurring at higher luminosity than the soft-to-hard transition. We then speculate on the source nature, even if the final picture is still not evident.

2. DATA ANALYSIS

In this paper, we analyze the data set consisting of all INTEGRAL (Winkler et al. 2001) Core Program and public observations in which IGR J17091−3624 was within the IBIS field of view, and of the RXTE Proportional Counter Array (PCA; Bradt et al. 1993) data collected during the 2 ks observation performed on 2003 April 20. The INTEGRAL observations, although not continuous, cover a period of 1 year from 2003 April to 2004 April. The RXTE observation corresponds to a period between INTEGRAL revolution 61 (2003 April 14–16) and the beginning of revolution 63 (2003 April 21). In general, all INTEGRAL observations are divided into uninterrupted 2000 s time intervals, called science windows (SCWs). Table 1 summarizes the INTEGRAL observations of the source. Light curves, hardness ratio, and spectra are then obtained for each individual SCW. We use here INTEGRAL data from the coded mask imager, IBIS (Ubertini et al. 2003). Then, in order to obtain broadband spectra, we add the lower energy data from the PCA, and, whenever available, those from the INTEGRAL X-ray Monitor, JEM-X (Lund et al. 2003).

Figure 1 shows the 20–150 keV INTEGRAL image of IGR J17091−3624 during the period of the RXTE observation. The figure shows that the transient source IGR J17091.8−3628, detected 9/4 from IGR J17091−3624 on 2005 March 24 (Grebenev et al. 2005), was then not visible. This rules out any contamination of other sources in the field of view. The IBIS data were processed using OSA version 4.2, (Goldwurm et al. 2003) released by the INTEGRAL Science Data Center, ISDC (Courvoisier et al. 2003). The data set has been divided in two subsets according to the source position being either within the partially coded field of view (PCFOV, 19°×19°) or in the narrower fully coded field of view (FCFOV, 9°×9°). Both data sets have been used to produce the source light curves in different energy ranges, while only FCFOV data have been used for spectral extraction because of the better signal-to-noise ratio.

Since the IBIS spectra do not show any substantial variability during 2003 April 14–21, we have integrated over this observation period. The JEM-X spectra were derived with the ISDC version 5.0, using the latest available spectral matrices and extracting the source spectrum with the fixed position of the source. While IBIS provides a large FOV, >30°, that of JEM-X is narrower (>10°), thus providing only a partial overlap with the high-energy detector. In general, the effective JEM-X exposure is ~15% of that of IBIS. Therefore, a combined JEM-X/IBIS spectrum was possible only for a small fraction of the data.

2.1. Time Evolution

IGR J17091−3624 is a very faint source, which is often below the detection limits of the IBIS and JEM-X in a single 2000 s SCW (~5 mcrab in the 20–100 keV IBIS energy range, and ~23 mcrab in the 3–20 keV JEM-X energy range). Furthermore, most of the JEM-X data were not in its FCFOV, which is partly due to the pointing algorithm of the GCDE. As a result, the JEM-X effective exposure was ~10 times shorter than that of IBIS.

We have followed the IBIS evolution of the source flux from the first INTEGRAL detection of the source. First, a flux increase took place in the first SCWs of revolutions 61–63 (2003 April 14–21), as can be seen in Figure 2. We have also found a very faint signal in the data of revolution 60.

We have analyzed the data until revolution 185 (2004 April 19–20), as later observations do not show any signal in the direction of the source at least until revolution 232 (2004 September), the current limit of the public data set. We have produced IBIS light curves in two different energy bands, 20–40 and 40–100 keV (Fig. 2, top and middle panels, respectively). The light curves are derived from the flux and variance maps for each individual SCW by extracting values directly from the derived source positions. The flux maps are already corrected for off-axis effects, so this correction is automatically included in the light curves. Differences in the shape of the error bars on individual points are due to different SCW exposures and different source locations within the field of view. The bottom panel of Figure 2 shows the hardness ratio, HR = R_{40–100}/R_{20–40}, where R is the count rate. During MJD 52,860–52,924 (2003 August–October), the source was rather faint, especially in the 40–100 energy range, and the hardness ratio shows a weak indication of softening corresponding to 25%.

The RXTE observation lasted only 2 ks, so that it has not been possible to extract information on the long-term temporal

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**TABLE 1**

| Revolution | Start Date | End Date | ISGRI Exposure |
|------------|------------|----------|----------------|
| 61−63      | 2003 Apr 12 | 2003 Apr 21 | 15 |
| 100−119    | 2003 Aug 10 | 2003 Oct 04 | 77 |
| 164−185    | 2004 Feb 17 | 2004 Apr 02 | 77 |

* Including the 2 ks RXTE observation on 2003 April 20.

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**Fig. 1.—**The 20–150 keV IBIS image of the field near IGR J17091−3624. It can be seen that IGR J17098−3628 (1) is not visible during the RXTE/PCA observations of IGR J17091−3624 (2), which argues against any contamination in the PCA field of view.

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8 See http://heasarc.gsfc.nasa.gov/docs/xte/xte_public.html.
behavior. A detailed timing analysis of the 2 ks data set is given by Lutovinov & Revnivtsev (2003).

For the third observation period, during MJD 53,054–53,097 (2004 February–April), only IBIS data were available. The light curves are characterized by an increased flux with respect to the previous periods together with a faint tendency of source hardening.

3.2. Spectral Evolution of IGR J17091−3624

We have studied the spectral behavior separately for three epochs:

1. Revolutions 61–63 (2003 April 15–21, ~15 ks), which are the first INTEGRAL observations combined with the RXTE/PCA data.
2. Revolutions 100–119 (2003 August–October, ~77 ks), during which the IBIS spectrum softened, and which includes the only JEM-X detection.
3. Revolutions 165–179 (2004 April, ~77 ks), containing only the IBIS data.

The data sets have been fitted with XSPEC version 11.3.1. Several models have been tested for each of the data sets. In our fits, we have confirmed the constraint found by Lutovinov & Revnivtsev (2003), $N_H < 10^{22}$ cm$^{-2}$, which is also in agreement with the Galactic column density along the direction to the source, $\approx 8 \times 10^{21}$ cm$^{-2}$.

For revolutions 61–63, the relatively high brightness and the lack of variability have allowed us to obtain a combined IBIS/PCA spectrum (see Fig. 4). We use two thermal Comptonization models, COMPTT (Titarchuk 1994) and COMPPS (Poutanen & Svensson 1996), both assuming a slab geometry. The COMPPS model is an accurate iterative-scattering model, in which subsequent photon scatterings are directly followed. It has been extensively tested against Monte Carlo results (e.g., by Zdziarski et al. 2000). On the other hand, COMPTT is based on an approximate solution of the kinetic equation with some relativistic corrections, and the resulting spectra are also only approximate (see the Appendix of Zdziarski et al. 1996). For the COMPPS model, we assumed a viewing angle of $60^\circ$ and the source of seed photons to be at the slab bottom (the model geometry parameter was set equal to 1) with a blackbody distribution at $kT_{bb} = 0.1$ keV. For the COMPTT model, we used Wien seed photons with the temperature as above. The free parameters of each model are the electron temperature, $kT_e$, the Thomson optical depth, $\tau$, and the normalization, $N$. There is no evidence of a Compton reflection component, and the weak fluorescent Fe Kα line present in the spectrum appears mostly due to the Galactic ridge emission (Lutovinov & Revnivtsev 2003).

The results corresponding to revolutions 100–119 consist of the combined JEM-X (six SCWs) and ISGRI average spectra. Given the difference in the JEM-X and ISGRI exposures, we have also compared the ISGRI count rate for the six SCWs for which the JEM-X spectrum was obtained and found it is almost the same as the count rate averaged over the entire period of revolutions 100–119. We have analyzed in detail the JEM-X data in order to exclude any possible contamination from close by

![Fig. 2.—The 20–40 and 40–100 keV light curves (top and middle panels, respectively) and the corresponding hardness ratio (bottom panel), with the solid line representing a value of up to 1.

### Table 2

| Model  | $kT_e$ (keV) | $\tau$ | $\chi^2$/dof | $F(3–100$ keV) (ergs cm$^{-2}$ s$^{-1}$) |
|--------|--------------|--------|--------------|---------------------------------|
| COMPTT | 24$^{+5}_{-9}$ | 2.1$^{+0.3}_{-0.5}$ | 0.93 | 54 | $2.5 \times 10^{-16}$ |
| COMPPS | 31$^{+4}_{-12}$ | 2.3$^{+0.2}_{-0.4}$ | 0.96 | 54 | $2.4 \times 10^{-16}$ |

Note.—See the light gray spectrum in Figure 4.

* $N_H < 10^{22}$.
sources, being IGR J17091—3624 located in a crowded region near the Galactic center.

The source shows a bright component in soft X-rays, followed by a weak high-energy tail. Thus, we have used the model consisting of a disk blackbody (DISKBB; Mitsuda et al. 1984) and a power-law spectrum. Table 3 summarizes our results, and the spectrum is shown in the right panel of Figure 3 and in the dark gray curve in Figure 4.

We clearly see a transition from the hard to the soft state from the first to the second epoch. After this, the source returns to the hard state, as shown by the IBIS data for revolutions 164–179, the black spectrum in Figure 4. The epoch 3 IBIS data are fitted by COMPTT with \( kT \approx 21\pm4\) keV and \( \tau \approx 2.7\pm0.3 \); these values are similar to that of epoch 1 (Table 2).

The spectral evolution of IGR J17091—3624 shows both similarities and differences with respect to that of another black hole candidate observed by INTEGRAL, IGR J17464—3213 (Capitanio et al. 2005; Joinet et al. 2005). Therefore, we report here the spectra and fit results for that object as well. Table 4 shows fit results with both COMPTT and COMPPS for the hard state, and Figure 5 shows a comparison of its hard and soft states with those of IGR J17091—3624.

![Figure 3](image-url) **Left:** RXTE/IBIS count spectra for revolutions 61–63. **Right:** JEM-X/IBIS count spectra for revolutions 100–119.

4. DISCUSSION AND CONCLUSIONS

We have followed the evolution of an outburst of IGR J17091—3624. Within the course of less than 1 year, the source went from the hard to the soft state and then back to the hard state.

Although Markoff et al. (2005) have recently suggested that the hard state emission could be due to synchrotron self-Compton emission from the base of the jet, we have considered here the standard hard-state model with the dominant radiative process being thermal Comptonization of disk blackbody photons. An intriguing feature of our hard-state spectra is the rather low electron temperature, \( \sim 20\) keV, while the range of temperatures typical for black hole binaries is \( \sim 50–100\) keV (e.g., Zdziarski & Gierliński 2004). This low temperature is obtained using both the COMPPS and COMPTT models, and for both occurrences of the hard state, in the rise and decline. Such a low temperature may be a characteristic of the hard state of neutron-star low-mass X-ray binaries, although at present it is rather poorly constrained (e.g., Gierliński & Done 2002). On the other hand, we might have caught the source during transitional phases, with enhanced Compton cooling due to the increasing flux of disk blackbody emission and the correspondingly lower electron temperature.

During the soft state in epoch 2, the peak of the \( EF(E) \) emission is at several keV, as compared to the \( \sim 100\) keV peak in the hard state. There is a high-energy tail, but its weakness does not permit us to put constraints on its origin.

In § 3.2, we have also compared the evolution of IGR J17091—3624 with that of another transient source observed by INTEGRAL, IGR J17464—3213. This is a black hole candidate discovered by HEAO-1 in 1977, named then H1743–322. An outburst of that source was observed during the GCDE in 2003 (Capitanio et al. 2005). Both sources show similar spectral evolution during outbursts of similar duration. However, as shown in Figure 5, the hard-state spectrum of IGR J17464—3213 is substantially softer than that of IGR J17091—3624, although both

![Figure 4](image-url) **Figure 4:** Unfolded spectra showing the source evolution during the INTEGRAL and RXTE observations. The light gray spectrum (PCA/IBIS) corresponds to revolutions 61–63, the dark gray spectrum (JEM-X/IBIS) corresponds to revolutions 100–119, and the black spectrum (IBIS) corresponds to revolutions 164–179. The Fe Kα line, shown by the light gray dotted curve, is due to the Galactic ridge emission. The dark gray dotted curves denote the disk blackbody and power-law components of the models. [See the electronic edition of the journal for a color version of this figure.]

### Table 3

| Fit Parameters to the JEM-X/IBIS Spectrum of Revolutions 100–119 with the Disk Blackbody and a Power-Law Model |
| Model | \( kT_m \) (keV) | \( N_{\text{disk}} \) | \( \Gamma \) | \( N_{\text{pl}} \) | \( \chi^2/\nu \) | \( F(3–100\) keV) |
|-------|--------------------|-----------------|-------|----------|-----------------|-----------------|
| DISKBB+POW | \( 2.6^{+0.2}_{-0.3} \) | \( 1.9^{+0.7}_{-0.6} \) | \( 2.1^{+0.1}_{-0.3} \) | \( 0.2^{+0.4}_{-0.1} \) | 1.0 | 53 | \( 2 \times 10^{-9} \) |

**Note:** See the dark gray spectrum in Figure 4.

* keV\(^{-1}\) cm\(^2\) s\(^{-1}\) at 1 keV.
sources share the relatively low electron temperature of ~20 keV.

Furthermore, the relative normalization of the observed hard and soft state spectra is different. Curiously, the hard (revolutions 61–63) and soft state (revolutions 100–119), assuming a distance of 8.5 kpc and isotropy, are virtually identical. The various amplitudes of the hard and soft state spectra are often seen in X-ray transients (e.g., Zdziarski et al. 2004) and are due to the hysteretic behavior of the accreting systems.

IGR J17091−3624 is located 10′ from the Galactic center region, where the highest concentration of low-mass X-ray binaries in the Galaxy is present (White & van Paradijs 1996). The model unabsorbed bolometric (0.01–500 keV) luminosities in the hard (revolutions 61–63) and soft state (revolutions 100–119), assuming a distance of 8.5 kpc and isotropy, are $L \approx 1 \times 10^{37}$ erg s$^{-1}$ and $L \approx 2 \times 10^{37}$ ergs s$^{-1}$, respectively. These values are not far from those characteristic to the soft and hard states of black hole binaries (e.g., Zdziarski & Gierliński 2004), although the neutron star nature of the source cannot be excluded. On the other hand, the RXTE power spectrum, without QPO-like features and with band-limited noise (Lutovinov & Revnivtsev 2003), commonly observed in black hole binaries in the low/hard spectral state, as well as the probable correlation with a radio source (Pandey et al. 2006; Rupen et al. 2003) may also argue for the black hole nature of this source.

We acknowledge the ASI financial/programmatic support via contracts I/R/046/04. We thank the unknown referee for his/her useful comments, which helped us to improve the quality of this work. We also thank Catia Spalletta for the careful editing of the manuscript and Memmo Federici for supervising the INTEGRAL data analysis. A. A. Z. has been supported by grants 1P03D01827, 1P03D01128, and 4T12E04727.

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**TABLE 4**

| Model      | $kT_e$ (keV) | $\tau$ | $\chi^2$/dof | $F(3–100$ keV) (ergs cm$^{-2}$ s$^{-1}$) |
|------------|-------------|--------|--------------|----------------------------------|
| COMPTT     | 18.4$^{+2.1}_{-1.8}$ | 1.3$^{+0.4}_{-0.3}$ | 1.05 | 119 | 6$\times$10$^{-9}$ |
| COMPPS     | 20.3$^{+2.5}_{-2.0}$ | 2.0$^{+0.2}_{-0.3}$ | 1.04 | 119 | 4$\times$10$^{-9}$ |

Note.—See the black spectrum in Fig. 5.