INTEGRAL and RXTE/ASM Observations on IGRJ17098–3628

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Abstract

To further probe the possible nature of the unidentified source IGR J17098–3628, we have carried out a detailed analysis of its long-term time variability, as monitored by Rossi X-ray Timing Explorer/All Sky Monitor (RXTE/ASM), and of its hard X-ray properties, as observed by the International Gamma-Ray Astrophysics Laboratory (INTEGRAL). INTEGRAL has monitored this sky region for years, and significantly detected IGR J17098–3628 only when the source was in its dubbed active state. In particular, at \( \geq 20 \)keV, Imager on Board of the INTEGRAL Satellite/INTEGRAL Soft Gamma-Ray Imager (IBIS/ISGRI) caught an outburst in 2005 March, lasting for \( \sim 5 \)d with a detection significance of \( 73\sigma \) (20–40keV) and with emission at \( <200 \)keV. ASM observations have revealed that the outburst of the soft X-ray lightcurve is similar to that detected by INTEGRAL; however the peak of the soft X-ray lightcurve lags behind, or is preceded by, the hard X-ray (\( >20 \)keV) outburst by \( \sim 2 \)d. This resembles the behavior of X-ray novae like XN 1124, and hence further suggests a Low-Mass X-ray Binary (LMXB) nature for IGR J17098–3628. While the quality of the ASM data prevents us from drawing any definite conclusions, these discoveries are important clues that, coupled with future observations, will help us to resolve the nature of IGR J17098–3628 that is unknown so far.

Key words: gamma rays: bursts — X-ray: individual (IGR J17098–3628)

1. Introduction

INTEGRAL has detected roughly 500 sources at energies \( \geq 20 \)keV (Bodaghee et al. 2007). Among them, X-ray binary systems were identified for 32\% at that time, and another 26\% remained unidentified. As one of the unidentified sources, IGR J17098–3628 was discovered (Grebenev et al. 2005a) at the end of 2005 March by INTEGRAL/IBIS during the private Open Program observation dedicated to a deep view to the Galactic center. The source was located at RA(J2000.0) = 17\(^{h}\)09\(^{m}\)48\(^{s}\) and Dec = –36\(^{\circ}\)28\('\)12\(\prime\)', with an error box of 2\(\prime\) at the 90\% confidence. The source had a peak flux at \( \sim 60 \) and 95 mCrab for 18–45 and 45–80 keV, respectively. The 20–60 keV flux evolved from \( \sim 50 \) mCrab at 2005 March 26 00:00 to \( \sim 9 \) mCrab at April 3 23:30 (UTC) (Mowlavi et al. 2005). The preliminary spectral analysis (Grebenev et al. 2005b) showed that the source spectrum became quite soft along with this evolution. After INTEGRAL, IGR J17098–3628 was observed by Rossi X-ray Timing Explorer (RXTE) on 2005 March 29, and was detected at 80 mCrab in the 3–20 keV band, with a hard power-law tail of a spectral index \( \sim 2.5 \). The source was thus assumed to be a black-hole candidate (BHC) and X-ray nova (Grebenev et al. 2007). The column density was found to be less than \( 1 \times 10^{22} \) atoms cm\(^{-2}\).

Later on, Swift observed this source on 2005 May 1, and refined its location to RA(J2000.0) = 17\(^{h}\)09\(^{m}\)45\(^{s}\)9 and Dec = –36\(^{\circ}\)27\('\)57\(\prime\)', with the 90\% confidence, and an uncertain radius of 5\(\prime\) (Kennea et al. 2005). This made a search for potential counterparts in the optical and infrared bands. From the 2MASS ALL-SKY Catalog, a possible counterpart was found, J17094612–3627573 (Kong 2005). However, the most recent optical and infrared observations, made with the 6.5 m Magellan-Baade telescope, revealed that 2MASS J17094612–3627573 is in fact composed of several sources (Steeghs et al. 2005). Furthermore, Very Large Array (VLA) observations of IGR J17098–3628 were made on 2005 March 31, April 5, and May 4 at 4.86 GHz (Rupen et al. 2005), which led to the discovery of a radio transient at 0.8 from the Swift XRT position, and is hence regarded as a possible radio counterpart. Finally, on July 9, Swift/XRT observed IGR J17098–3628 again, and found that the spectrum could be fitted by an absorbed disk blackbody model. The obtained column density was \( (0.89 \pm 0.02) \times 10^{22} \) atoms cm\(^{-2}\) (Kennea & Capitanio 2007).

In this paper, we report on an analysis of all available observations on IGR J17098–3628, carried out by IBIS/ISGRI and Joint European Monitor for X-rays (JEMX) on board INTEGRAL, and the All Sky Monitor (ASM) on board RXTE. This allows us to trace the source behavior in X-rays back to 1996 with ASM, and back to 2002 with INTEGRAL. We put the outburst in 2005 in this context.
2. Time Variability Monitored by ASM

ASM is one of the three detectors on board the RXTE satellite (Swank 1994; Gruber et al. 1996), which has been used to track the long-term behavior of the source in the energy band of 1.5–12 keV since 1996 February. The target source was usually observed several times per day, within the “dwells”, of duration 96 s each. The extracted source light curves are presented for the energy bands of 1.5–3, 3–5, 5–12, and 1.5–12 keV, respectively. IGR J17098–3628 has been monitored by ASM as one of the most active sources ever seen since 2002. As shown in figure 1, the 1.5–12 keV lightcurves, retrieved in a time period from 1996 January to 2008 May, show the variability, where each bin represents a dwell, or — in the middle panel — the average over a monthly time scale. Many individual burst-like events existing in the dwell lightcurve can be spotted, and the flux maxima can sometimes reach 65.5 counts s$^{-1}$ [the dwell at Modified Julian Day (MJD) = 51958.219410], corresponding to 873 mCrab in the 1.5–12 keV band. We have consulted with the ASM team about such a feature. It turns out that the source IGR J17098–3628 is only 1° away from GX 349+2, a very strong X-ray source. The angular resolution of each of the ASM cameras is much better in one coordinate, $\phi$ ($\sim$3°), than in the other coordinate, $\theta$ ($\sim$15°). It is (understandably) difficult for the ASM analysis system to properly handle this kind of problem; similar problems have arisen with other sources. But, in general GX 349+2 is stable in the 1.5–12 keV band observed by ASM (see figure 1, the bottom panel). In short, the analysis software has incorrectly attributed the flux from GX 349+2 to IGR J17098–3628 only on those relatively few occasions. Actually, the big uncertainty in this lightcurve is contamination from a neighboring source, IGR J17091–3624, located (only 0°17 away) too close to IGR J17098–3628 to be resolved by ASM. As a result, the burst events on monthly time scale, as shown in the middle panel of figure 1, may be sometimes attributed to IGR J17091–3624. Fortunately, this problem can be well solved via INTEGRAL’s mapping of this region with either ISGRI or JEMX. In the monthly lightcurve there are several well-established outbursts with a duration of several months. The first one occurs around MJD 52800 (2003 June), with an averaged peak flux reaching to the 40 mCrab level. We will see later that this outburst came from IGR J17091–3624 (Grebenev et al. 2007), and those thereafter observed by INTEGRAL did from IGR J17098–3628. IGR J17091–3624 seems to have been in the quiet most of the time since MJD 52800 (Grebenev et al. 2007). A sequence of outbursts has occurred since MJD 53455 (2005 March), and the 1.5–12 keV flux has kept staying at the flux level of $\sim$50 mCrab over a period of years. These results, accompanying the INTEGRAL results, which will be shown later on, suggest that IGR J17098–3628 has been in an active phase within the last several years.
Table 1. INTEGRAL IBIS/ISGRI observations.*

| Label | Revolution | Start date  | End date   | Exposure (ks) | IGRJ17091–3624 counts s⁻¹ (significance) | IGRJ17098–3628 counts s⁻¹ (significance) |
|-------|------------|-------------|------------|--------------|-------------------------------------------|-------------------------------------------|
| T1    | 0037–0063  | 2003-02-01  | 2003-04-22 | 593          | 0.35 (8.6)                                | —                                         |
| T2    | 0100–0120  | 2003-08-09  | 2003-10-07 | 652          | 1.64 (41.8)                               | —                                         |
| T3    | 0164–0185  | 2004-02-16  | 2004-04-19 | 360          | 2.51 (44.9)                               | —                                         |
| T4    | 0224–0246  | 2004-08-15  | 2004-10-20 | 477          | —                                         | —                                         |
| T5    | 0286–0297  | 2005-02-15  | 2005-03-22 | 456          | —                                         | —                                         |
| T6    | 0298–0299  | 2005-03-23  | 2005-03-28 | 152          | —                                         | 6.08 (73.4)                              |
| T7    | 0300–0307  | 2005-04-02  | 2005-04-21 | 341          | —                                         | 0.96 (16.9)                              |
| T8    | 0345–0370  | 2005-08-10  | 2005-10-26 | 386          | —                                         | —                                         |
| T9    | 0406–0423  | 2006-02-09  | 2006-04-03 | 337          | —                                         | 0.49 (7.8)                               |

* INTEGRAL IBIS/ISGRI Observations of IGRJ17091–3624 and J17098–3628 in the 20–40 keV band for those with the detection significance (signal to noise ratio) larger than 3σ.

Fig. 2. 20–40 keV significance map from IBIS/ISGRI of IGR J17091–3624. The contours start at a detection significance level of 10σ, with a step of 10σ for the time period during the hard X-ray outburst (2005 March 23–28).

3. Hard X-Ray Properties Revealed by INTEGRAL

3.1. Observations and Data Analysis

INTEGRAL is an ESA scientific mission (Winkler et al. 2003) dedicated to spectroscopy ($E/\Delta E \simeq 500$; SPI: see Vedrenne et al. 2003) and imaging (angular resolution, 12' FWHM; source location accuracy, $\sim 1–3'$; IBIS: see Ubertini et al. 2003) of celestial gamma-ray sources in the energy range of from 15 keV to 10 MeV, with simultaneous monitoring in the X-ray (3–35 keV; angular resolution, 3'); JEMX: see Lund et al. 2003) and optical ($V$-band, 550 nm; OMC: see Mas-Hesse et al. 2003) energy ranges. All of the instruments on board INTEGRAL, except for the Optical Monitoring Camera (OMC), work with coded masks. The observational data from the detectors IBIS/ISGRI (15–200 keV) and JEMX have been adopted in our analysis of IGRJ17098–3628.

The available INTEGRAL observations when IGR J17098–3628 falls into the Fully Coded Field of View (FCFoV) of ISGRI comprise about 2400 science windows (scw's, typically 2000 s each), adding to a total exposure of 3700 ks. Most of these observations are carried out in a $5 \times 5$ dithering mode. The data are subdivided into 9 groups according to the sequence in observational time. The groups T5, T6, and T7 represent observations made one month prior to the hard X-ray outburst, during the outburst (for six days in 2005 March 23–28), and one month after the outburst, respectively (see table 1 for a summary of the individual observational groups).

The analysis of JEMX and ISGRI data is performed by using the INTEGRAL Offline Scientific Analysis (OSA) software, version 6.0. All of the sources within the FoV that are brighter than, or comparable to, IGRJ17098–3628 are taken
into account in extracting the source spectrum. An additional 2% systematic error is added to the spectra because of calibration uncertainties. The ISGRI spectrum was normalized to the JEMX spectrum by a factor $0.77^{+0.07}_{-0.06}$ derived from the fit. The spectra are fitted with XSPEC v12.3.1 and the model parameters are estimated at the 90% confidence level.

3.2. INTEGRAL Results

3.2.1. Sky maps

We have looked into the sky maps of both ISGRI and JEMX to see the situation for each of the 9 time zones concerning about which source was on active. The detection significances from ISGRI in the $20-40$ keV band are summarised in table 1. We find that IGR J17091–3624 was in the active phase within 2003 April and 2004 April (T1–T3), and IGR J17098–3628 took the role, since 2003 March in T6. After 2003 August (in T4), IGR J17091–3624 was not detectable by INTEGRAL in the X-ray region.

IGR J17098–3628 was detected by ISGRI at energies $\geq 20$ keV during 2003 March 24–28 when the source had an outburst in hard X-rays. The detection significances were $73.4\sigma$ in the $20-40$ keV band (for the mosaic image seen in figure 2), $38\sigma$ in the $40-60$ keV, $21\sigma$ in the $60-100$ keV, and $8\sigma$ in the $100-200$ keV. The source was still visible in its decaying phase during the following one month (T7), with the detection significances dropping to $16.9\sigma$ in the $20-40$ keV. For all other INTEGRAL observations, only marginal detections or upper limits were obtained at energies $\geq 20$ keV; for the time
Fig. 6. Light curves from ASM (1.5–3 keV), JEMX (3–6 keV, 6–10 keV, 10–15 keV), and ISGRI (20–40 keV, 40–60 keV), with each bin averaged over the individual data group T5–T9. The hard X-ray outburst is marked by the circle.

Table 2. Spectral index and reduced $\chi^2$ resulting from the fitting of ISGRI data in the 20–200 keV band with different models.

| Date (phase) | Power law $\alpha$ ($\chi^2/v$) | Cutoff power law $\alpha$ ($\chi^2/v$) | Broken power law $\alpha$ ($\chi^2/v$) |
|--------------|---------------------------------|----------------------------------------|----------------------------------------|
| 03-23 03:13–03-25 02:35 (rising phase) | $1.74^{+0.27}_{-0.25}$ (0.71) | $1.61^{+0.3}_{-1.8}$ (<464 keV) (0.78) | $1.74^{+0.25}_{-0.25}$ (>3.7 keV) (0.88) |
| 03-25 23:03–03-27 00:51 (peaking phase) | $2.13^{+0.06}_{-0.06}$ (1.49) | $1.54^{+0.27}_{-0.27}$ (<82 keV) (0.95) | $2.13^{+0.06}_{-0.06}$ (>5.5 keV) (1.60) |
| 03-27 00:53–03-28 11:15 (decaying phase) | $2.66^{+0.08}_{-0.08}$ (0.86) | $2.16^{+0.33}_{-0.36}$ (<95 keV) (0.72) | $2.60^{+0.08}_{-0.08}$ (>7.4 keV) (0.93) |

period T9, the source was detected only in the 20–40 keV band with significance at the $\sim 8\sigma$ level (see table 1). Since JEMX overlaps with ASM in most of its working energies, the detections at $\leq 15$ keV in general follow the same trend indicated by the ASM light curves. Figure 3 shows the most significant JEMX detection of IGR J17098–3628 in 2005 March 31–April 21, which gives $\sim 22\sigma$ in the 3–6 keV band.

3.2.2. Light curves

We used version 6.0 of the INTEGRAL Offline Scientific Analysis (OSA) software to construct a $>20$ keV ISGRI X-ray lightcurve of this outburst, and to compare it to the 1.5–12 keV ASM lightcurve from the same period. Unfortunately, IGR J17098–3628 was either prohibitively faint or out of the FoV for JEMX for most of the INTEGRAL observations, and the remaining data were contaminated by a strong source in the JEMX field-of-view (this is a known issue for JEMX data extraction — INTEGRAL Help Desk Priv. Comm.) to prevent from producing the proper lightcurve through running the pipeline. We therefore generated the JEMX light curves via reading out the flux at the source position from the mosaic map. A comparison of the JEMX and ASM light curves at the 3–12 keV is shown in figure 4, where the trends are consistent with each other. We find that the outburst of the soft X-ray light curve is similar to that detected by INTEGRAL; however, the peak of the soft X-ray light curve lags behind the hard X-rays by $\sim 2$ d (figure 5). We note, however, that no hard X-ray data cover the peak outburst observed in the ASM data. If there is a hard X-ray peak that coincides with the soft X-ray peak,
then, since there is no evidence for two peaks in the ASM data, the earlier hard X-ray peak may well be interpreted as a precursor event to a wider band concurrent X-ray outburst, rather than evidence for a lag between the hard and soft X-ray bands. Figure 6 shows a comparison of the flux variability in the time zones T5–T9, as obtained with ASM in the 1.5–3 keV band, JEMX in the 3–6, 6–10, and 10–15 keV, and ISGRI in the 20–40 and 40–60 keV.

3.2.3. Spectra

Since there is a quite difference in behavior between the light curves of the higher and lower energy bands, it would be interesting to investigate the spectrum at different periods of the outburst, i.e., the time evolution of the spectrum along the outburst, although the overall spectra have been presented in Grebenev et al. (2007) from ISGRI data of the outburst, supplemented by the available PCA (Proportional Counter Array)/RXTE data. For investigating the spectrum of the source, the time zone where the outburst was recorded by INTEGRAL (T6) was subdivided into three shorter periods according to observations: March 23 03:13 to 25 02:35 (the rising phase), 25 23:03 to 27 00:51 (the peaking phase), and 27 00:53 to 28 11:15 (UTC) (the decaying phase). Due to the relatively small FoV of the JEMX, its data are only available during the decaying phase, which is then combined with the corresponding ISGRI data for a broader spectral fitting. Firstly, we have tried different fitting models in the 20–200 keV band using only the ISGRI data: simple power-law, power-law with cutoff, and broken power-law shapes. The goodness of each trial is shown in table 2. We find that the relatively poor statistics of the data from the rising of the hard X-ray outburst prevents from discriminating among the models; the power-law with the cutoff model might be the best choice when the outburst reached the maximum; and the power-law model shows a good fit to the data from the decay of the outburst onwards. From the fit of a simple power-law model, the spectral index changes from $\sim 1.7$ when rising to roughly 2.6 when decaying. We also tried a disk blackbody model for the decaying phase (the broad band 5–200 keV spectrum), and found the reduced $\chi^2$ ($\sim 1.36$) becomes worse than that from the best-fit model of a broken power law (see figure 7). The best-fit parameters of the proper model for the three phases are thus presented in tables 3, 4, and 5, respectively. That the different episodes of the outburst have to be described by different models might suggest a rather strong time evolution. By taking a distance of 10.5 kpc, as estimated by Grebenev et al. (2007), the source had a luminosity of $\sim 9.8 \times 10^{36}$ erg s$^{-1}$ averaged over the whole outburst in the 20–200 keV energy region. The luminosities in individual phase are $5.3 \times 10^{36}$ erg s$^{-1}$ (the rising), $1.6 \times 10^{37}$ erg s$^{-1}$ (the peaking), and $8.9 \times 10^{36}$ erg s$^{-1}$ (the decaying).

4. Discussion and Summary

IGR J17098–3628 may have stepped into an active phase at the beginning of 2005. INTEGRAL detected a days’ continuous outburst extending up to energies of $\sim 200$ keV. A similar outburst is detected in the soft X-ray (1.5–12 keV) band; however the onset of the outburst lags behind the hard X-ray outburst by $\sim 2$ d, in a fashion reminiscent of X-ray novae like XN 1124–683 (Chen et al. 1997). The spectral analysis of the initial stages of the outburst detected by INTEGRAL supports the association with X-ray novae (Grebenev et al. 2007); also, the cool disk temperature and the small inner radius of the...
accretion disk both suggest that IGR J17098−3628 is a newly discovered black hole system. Current theoretical models concerning the formation of X-ray novae include the mass transfer instability (MTI) model (Hameury et al. 1986) and the disk thermal instability (DTI) model (Cannizzo et al. 1982; Faulkner et al. 1983; Meyer & Meyer-Hofmeister 1984; Huang & Wheeler 1989; Mineshige & Wheeler 1989; Ichikawa et al. 1994). Unfortunately, the only way to discriminate between these models relies on detailed differences in the observed soft energy spectrum of the source, and so the lack of any detailed X-ray spectra of the IGR J17098−3628 outburst in this energy band prevents us from drawing any conclusions on the detailed X-ray spectra of the IGR J17098−3628. That the three episodes of the hard X-ray outburst observed by INTEGRAL have to be described by different models might suggest rather strong time evolution, i.e., the spectral index changed from 0.06 to 0.71 from the rising phase to the peaking phase and then dropped to 0.07 from the decaying phase.

Although no clear statement can be made regarding their nature, the discovery of the lag/precursor event revealed by the concurrent RXTE/ASM and INTEGRAL observations in 2005 is an important piece of the IGR J17098−3628 puzzle that will help us to resolve the nature of this perplexing source that is unknown so far.

| Model              | $N_{\text{keV}^{-1}\text{cm}^{-2}\text{s}^{-1}}$ at 1 keV | $\alpha$ | $\chi^2/\nu$ | d.o.f | $F_{(20-200\text{keV})}$ erg cm$^{-2}$ s$^{-1}$ |
|--------------------|----------------------------------------------------------|----------|---------------|-------|-----------------------------------------------|
| Power law          | 0.036$^{+0.064}_{-0.036}$                                | 1.74$^{+0.27}_{-0.25}$ | 0.71 | 10   | $4.0 \times 10^{-10}$                        |

Table 3. Modeling to the ISGRI data from the rising phase of the hard X-ray outburst.

| Model               | $N_{\text{keV}^{-1}\text{cm}^{-2}\text{s}^{-1}}$ at 1 keV | $E_k$ keV | $\chi^2/\nu$ | d.o.f | $F_{(20-200\text{keV})}$ erg cm$^{-2}$ s$^{-1}$ |
|---------------------|----------------------------------------------------------|---------|---------------|-------|-----------------------------------------------|
| Cutoff power law    | 0.12$^{+0.14}_{-0.07}$                                   | 82$^{+65}_{-26}$ | 1.54$^{+0.27}_{-0.27}$ | 0.95 | 27   | $1.2 \times 10^{-09}$                        |

Table 4. Modeling to the ISGRI data from the peaking phase of the hard X-ray outburst.

| Model               | $N_{\text{keV}^{-1}\text{cm}^{-2}\text{s}^{-1}}$ at 1 keV | $E_{\text{break}}$ keV | $\chi^2/\nu$ | d.o.f | $F_{(5-200\text{keV})}$ erg cm$^{-2}$ s$^{-1}$ |
|---------------------|----------------------------------------------------------|------------------------|---------------|-------|-----------------------------------------------|
| Broken power law    | 0.08$^{+0.14}_{-0.06}$                                   | 0.85$^{+0.53}_{-0.79}$ | 7.19$^{+0.28}_{-0.49}$ | 2.66$^{+0.07}_{-0.07}$ | 1.07 | 133   | $1.9 \times 10^{-09}$                        |

Table 5. Modeling to the combined ISGRI/JEMX data from the decaying phase of the hard X-ray outburst.
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